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ASSESSMENT OF MAXIMAL OXYGEN UPTAKE IN RUNNERS: NEW CONCEPTS ON AN OLD THEME

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ABSTRACT

This thesis aimed to establish why the incidence of a $\dot{V}O_2$-plateau is typically high (>80%) for a discontinuous test but not for a continuous test, how treadmill grade influences $\dot{V}O_{2peak}$ and the incidence of a $\dot{V}O_2$-plateau for a speed incremented test, and whether it is possible to develop a continuous protocol for which the incidence of a plateau in the $\dot{V}O_2$-running speed relationship is >80%.

Study 1 was a large study that addressed several issues. Each subject (n = 10) completed a discontinuous test (DCT) in which running speed was increased every 3 min, a continuous test in which the speed was increased every 3 min (CT), a ramp test in which the speed was increased every 5 s (5%RT60), and a run to exhaustion at a speed calculated to elicit 105% $\dot{V}O_{2peak}$ (105%T). For each test, the treadmill grade was set at 5%, and the sampling period was set at 60 s. Each subject also completed 2 further tests: a ramp test (5% grade) for which the sampling period was 30 s (5%RT30); and a ramp test (60 s samples) for which the treadmill grade was set at 0% (0%RT). The peak $\dot{V}O_2$ (mean ± SD) was higher for the 5%RT60 than for the DCT (59.9 ± 7.9 vs. 57.8 ± 8.1 ml.kg^{-1}.min^{-1}; $p < 0.05$), but the incidence of a $\dot{V}O_2$-plateau was higher for the DCT (80% vs. 50%). The incidence of a plateau was also higher for the 5%RT60 than for the 0%RT (50% vs. 30%), as was the peak $\dot{V}O_2$ (59.9 ± 7.9 vs. 57.8 ± 7.9 ml.kg^{-1}.min^{-1}; p = 0.003). The peak $\dot{V}O_2$ was lower for the 105%T than for the 5%RT60, and the difference between the two values was negatively correlated with the duration of the 105%T (r = -0.89, p = 0.001). The incidence of a plateau was lower for the 5%RT30 than for the 5%RT60 (20% vs. 50%); the reason for this appeared to be that the variability in $\dot{V}O_2$ was higher for the 30 s samples. It was concluded that discontinuous tests should not be used for the assessment of $\dot{V}O_{2max}$ and that factors which influence the variability in $\dot{V}O_2$ might be important determinants of the incidence of a plateau.

Study 2 evaluated the effect of sampling period and exercise intensity on the variability in $\dot{V}O_2$. Eight subjects completed 4 runs at ~70% $\dot{V}O_{2peak}$, during which 12 samples of expirate were taken over periods of 30, 60, 90, or 120 s. In addition, $\dot{V}O_2$ was determined over twelve 30 s periods during runs at ~70 and ~96% $\dot{V}O_{2peak}$ (n = 6). The SD for $\dot{V}O_2$ decreased as sampling period increased from 30 to 60 s (1.3 ± 0.7 vs. 0.6 ± 0.2 ml.kg^{-1}.min^{-1}; $p < 0.05$), but no further decrease was observed as the sampling period increased beyond 60 s. This SD also decreased as exercise intensity increased (1.1 ± 0.2 vs. 0.6 ± 0.3 ml.kg^{-1}.min^{-1}; p = 0.005), such that the SD for 30 s samples taken during the run at ~96% was the same as that for the 60 s samples taken at ~70% $\dot{V}O_{2peak}$ (p = 0.96). It was concluded that the only valid approach to defining a $\dot{V}O_2$-plateau is one in which the sampling period decreases as exercise intensity increases.

Study 3 evaluated three ramp tests for the assessment of $\dot{V}O_{2max}$ in runners. Each subject (n = 12) completed 3 tests: a constant speed, increasing grade test (IGT); a constant grade, increasing speed test on a level treadmill (0%T); and a constant grade, increasing speed test conducted at a 5% grade (5%T). For each test, the sampling period decreased as the exercise intensity increased and the individual $\dot{V}O_2$ data were fit to both a linear model and a (two-piece) plateau model. For each test, the SEE was lower for the plateau model than for the linear model ($p < 0.0005$) and a $\dot{V}O_2$-plateau was observed in >90% of subjects. However, $\dot{V}O_{2max}$ was higher for the 5%T (64.0 ± 4.7 ml.kg^{-1}.min^{-1}) than for the 0%T (62.6 ± 4.6 ml.kg^{-1}.min^{-1}), and higher still for the IGT (65.1 ± 4.3 ml.kg^{-1}.min^{-1}) ($p < 0.05$). It was concluded that whilst an upper limit for $\dot{V}O_2$ is typically reached when trained runners perform a treadmill ramp test, the $\dot{V}O_2$ at which this limit is reached depends on the conditions under which the test is performed.

LIST OF ABSTRACTS

The following abstracts of conference papers related to this thesis have been published:

Draper, S.B., Wood, D.M., and Fallowfield, J.L. (1999) The effect of test protocol on $\dot{V}O_{2peak}$ and the incidence of a $\dot{V}O_2$-plateau. *Journal of Sports Sciences* 17: 31.

Draper, S.B., Wood, D.M., and Fallowfield, J.L. (1998) Comparison of three protocols for the assessment of maximal oxygen uptake in runners. *Proceedings of the Third Annual Congress of the European College of Sports Science*: 271.

Wood, D.M., Myers, S.D., and Fallowfield, J.L. (1998) Variability in $\dot{V}O_2$ decreases as exercise intensity increases: implications for the identification of a $\dot{V}O_2$-plateau. *Proceedings of the Third Annual Congress of the European College of Sports Science*: 502.

Copies of these abstracts can be found in Appendix 1.

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PART I

STATEMENT OF THE PROBLEM AND REVIEW OF LITERATURE

CHAPTER 1: INTRODUCTION

The English physiologists, A.V. Hill and Hartley Lupton, are widely credited with being the first to propose that there is a limit to the rate at which an individual can take up and use oxygen. This they did, noting that in the case of running "there is clearly some critical speed for each individual ... above which ... the maximum oxygen intake is inadequate" (Hill and Lupton, 1923, p. 151). But in fact they did much more than this. They went on to propose that there is also a limit to the amount of energy that can be generated anaerobically (they termed this limit the maximum oxygen debt), and they then developed what was probably the first physiological model of running performance. Ultimately though, what is perhaps most remarkable about their work is that it has influenced exercise physiologists for the majority of this century and continues to do so today. Indeed, so influential has their work been that in the 75 years that have passed since their classic paper was published only minor revisions have been made to their original model of running performance.

Hill and Lupton (1923, p. 158) noted that "a man may fail to be a good runner by reason of a low oxygen intake, a low maximum oxygen debt, or a high oxygen requirement". They then went on to show, using data on A.V. Hill himself, that as long as the maximum oxygen intake, the maximum oxygen debt, and the relationship between oxygen requirement and running speed are known for a given individual it is possible to make a reasonably accurate prediction of the highest speed that this individual will be able to sustain for any distance between 0.25 and 2 miles (i.e. for any middle-distance race). Thus, effectively at least, they defined the determinants of performance in middle-distance running as the maximum oxygen intake, the maximum oxygen debt, and the relationship between oxygen requirement and running speed.

Seventy years later, di Prampero et al. (1993) presented what appears to be a much more sophisticated model of running performance. This model, which assumes the determinants of performance in middle-distance running to be maximal oxygen uptake ($\dot{V}O_{2max}$), the oxygen equivalent of the anaerobic capacity, the oxygen cost of running, and the rate at which oxygen uptake ($\dot{V}O_2$) increases towards $\dot{V}O_{2max}$, might not seem much like Hill and Lupton's basic model. However, the two models are actually very similar. Indeed, if it is accepted that maximal oxygen uptake is synonymous with maximum oxygen intake, that the oxygen equivalent of the anaerobic capacity is synonymous with the maximum oxygen debt, and that the oxygen cost of running is synonymous with the oxygen requirement, it can be concluded that di Prampero et al.'s contemporary model is basically the same as Hill and Lupton's traditional model.

Di Prampero et al. did adapt Hill and Lupton's model slightly, but this adaptation simply involved introducing an additional term to account for the fact that $\dot{V}O_{2max}$ is not attained immediately at the onset of severe exercise. The original model has also been extended so that it can be applied to distance running (Péronnet and Thibault, 1989). But once again, this extension simply involved introducing an additional term. Indeed, Péronnet and Thibault's model of running performance, which they apply to middle-distance and distance running, is essentially the same as that of di Prampero et al. (1993) for middle-distance races. For distance races they simply make the further assumption that the % $\dot{V}O_{2max}$ that can be sustained decreases with increasing distance.

Physiological models of running performance are used by practitioners and researchers alike. Practitioners use them to determine which variables they should focus on when they conduct a physiological assessment of a middle-distance or a distance runner and which variables they should encourage such a runner to target in training, whilst researchers use them to ensure that the research they conduct has as its focus those factors that are most likely to exert a meaningful effect on performance in middle-distance or distance running. All of these models consider $\dot{V}O_{2max}$ to be an important determinant of performance, so it is perhaps not surprising that a " $\dot{V}O_{2max}$ test" is almost always performed when a middle-distance or a distance runner serves as a subject in a research project or is assessed by a practitioner. The test used is typically a continuous test in which the speed is held constant while the grade is progressively increased, and the highest $\dot{V}O_2$ observed in the test is typically taken as $\dot{V}O_{2max}$.

The rationale for the use of a progressive test can be traced back to the work of Hill and Lupton (1923). It was these authors who first proposed that the $\dot{V}O_2$-running speed relationship should plateau at high speeds. For example, in reference to some observations on A.V. Hill himself, Hill and Lupton (1923, p. 156) wrote: "The rate of oxygen intake ... increases as the speed increases, reaching a maximum, however, for speeds beyond about 260 metres per min. ... However much the speed be increased beyond this limit, no further increase in oxygen intake can occur". Data presented by Hill et al. (1924b) show, however, that Hill's own $\dot{V}O_2$-running speed relationship did not actually plateau at high speeds. These authors presented data on 5 subjects, but a plateau in the $\dot{V}O_2$-running speed relationship was evident in only 1 of the 5. What is surprising is that, in the years since this paper was published, very few researchers have attempted to establish the incidence of such a plateau. The likely reason for this is that, since 1955, the recommended protocol for the assessment of $\dot{V}O_{2max}$ has been one in which the speed is held constant while the grade is progressively increased.

Taylor et al. (1955) found that a plateau in $\dot{V}O_2$ could be identified in 94% of subjects for a test in which the belt speed was held constant while the grade was progressively increased. They also reported that the incidence of a $\dot{V}O_2$-plateau was higher for this constant speed, increasing grade (CSIG) test than for a constant grade, increasing speed (CGIS) test, and on the basis of this they recommended the use of a CSIG for the assessment of $\dot{V}O_{2max}$. More recent guidelines for the assessment of $\dot{V}O_{2max}$ (Bird and Davison, 1997; McConnell, 1988; Thoden, 1991) make a similar recommendation. However, the assumption made by contemporary models of running performance is that the $\dot{V}O_2$-running speed relationship plateaus. It is important that this assumption is tested, and the obvious way to do this would be to determine whether or not $\dot{V}O_2$ typically plateaus in the closing stages of a CGIS test.

The test used by Taylor et al. was discontinuous (i.e. rest periods were allowed between stages), whereas the tests that are currently in routine use are continuous. The incidence of a plateau is typically only ~50% for a continuous version of a CSIG test (Duncan et al., 1997; Rivera-Brown et al., 1994; Sheehan et al., 1987), and the data of Taylor et al. (1955) suggest that this incidence would be lower still for a continuous version of a CGIS test. The peak $\dot{V}O_2$ is, however, generally the same for a continuous and a discontinuous test (Duncan et al., 1997; McArdle et al., 1973; Rivera-Brown et al., 1994; Sheehan et al., 1987; Shephard et al., 1968; Stamford, 1976; Wyndham et al., 1966). It is presumably this finding, coupled with the fact that the incidence of a $\dot{V}O_2$-plateau has been reported to be >80% for a discontinuous test (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979; Rivera-Brown et al., 1994; Taylor et al., 1955), that has provided the rationale for treating the highest $\dot{V}O_2$ attained in a continuous test as a maximal $\dot{V}O_2$ even when a $\dot{V}O_2$-plateau is not observed. However, it has recently been suggested (Noakes, 1997) that a plateau observed in a discontinuous test (DCT) might be an artefact of the test protocol. If this is the case then the fact that a $\dot{V}O_2$-plateau is typically observed in only ~50% of subjects for a continuous test (CT) even when the test is a CSIG test is of major significance. This is certainly the view held by Noakes (1998, p. 1389), who has suggested that the "the plateau phenomenon probably qualifies as the single most influential concept in modern exercise physiology."

The aims of this thesis were:

- to establish whether a $\dot{V}O_2$-plateau that occurs in a DCT is a real phenomenon or an artefact of the test protocol;
- to identify those factors that exert the greatest influence on the incidence of a $\dot{V}O_2$-plateau for a progressive test;
- to investigate how treadmill grade influences the peak physiological responses and the incidence of a $\dot{V}O_2$-plateau for a CGIS test;
- to determine whether it is possible to develop a continuous CGIS protocol for which the incidence of a $\dot{V}O_2$-plateau is similar to that which has been reported for a discontinuous CSIG test (i.e. >80%).

If it could be demonstrated not only that the incidence of a $\dot{V}O_2$-plateau is high (i.e. >80%) for a DCT but also that the peak $\dot{V}O_2$ attained in such a test cannot be exceeded in any of the other commonly used tests, it would be reasonable to conclude that the peak $\dot{V}O_2$ attained in a DCT is in fact a maximal $\dot{V}O_2$. Given this scenario, it would still be of interest to establish whether it is possible to develop a continuous protocol for which the incidence of a plateau is similar to that which has been reported for a DCT because it is continuous tests that are in routine use. However, regardless of whether such a protocol could be developed, there would be no need for contemporary models of running performance to be revised.

On the other hand, were it to be demonstrated that whilst the incidence of a plateau is high for a DCT the peak $\dot{V}O_2$ attained in such a test can be exceeded in one or more of the other commonly used tests, the only reasonable conclusion would be that the plateau that is observed in a DCT is an artefact of the test protocol. Given this scenario, the question of whether it is possible to develop a continuous protocol for which the incidence of a plateau is similar to that which has been reported for a DCT would assume extreme importance. If such a protocol could be developed, there would be no need for contemporary models of running performance to be revised. If not, these models would need to be revised, and new factors would need to be considered as potential determinants of performance in middle-distance and distance running.

There are 5 parts to this thesis. Part I reviews the literature on the assessment of $\dot{V}O_{2max}$ and presents arguments for and against the notion that an upper limit for $\dot{V}O_2$ is typically reached during progressive exercise. Part II covers technical considerations for the determination of $\dot{V}O_2$ and RER during treadmill running and outlines the steps that were taken to assure the quality of the derived data reported in parts III and IV. Part III comprises a large study that was designed to address the issues that arose from the review of literature and establish what factors might be important in determining whether a $\dot{V}O_2$-plateau is observed during a progressive test. Part IV comprises 2 studies which were designed to address the issues that arose from Part III. The first evaluates the effect of sampling period and exercise intensity on the variability in $\dot{V}O_2$ and highlights the need for a new approach to defining a $\dot{V}O_2$-plateau. The second adopts one such approach to establish the incidence of a $\dot{V}O_2$-plateau for three different progressive tests. Finally, in Part V, the findings are discussed and recommendations are given for the assessment of $\dot{V}O_{2max}$ in runners.

CHAPTER 2: THE WORK OF A.V. HILL AND HIS COLLEAGUES

2.1 Introduction

Archibald Vivian Hill was a brilliant physiologist, who in his youth had been a competent middle-distance runner. He worked in the US for a while in the mid 1920s, and while he was there he delivered a series of lectures, which he later put into a book. In the introduction to this book, Hill (1927, p. 3) recounts how he has often been asked why he bothers to study athletics. He explains that athletics is well suited to being studied by a physiologist because "the processes of athletics are simple and measurable" and "athletes themselves ... can be experimented on without danger and can repeat their performances exactly again and again". But then he adds "I might perhaps state a third reason and say ... that the study of athletes and athletics is "amusing": certainly to us and sometimes I hope to them."

It is remarkable that Hill's work on the physiology of running, which to him was simply "amusing", has influenced exercise physiologists for the majority of this century. But it has, and it is for this reason that a whole chapter of this thesis has been devoted to the work of Hill and his colleagues.

2.2 The contribution of "his colleagues"

A.V. Hill was an Englishman, and most of his theories about the physiology of running were based on data collected when he was working in Manchester, England. Starting in 1922, he produced, in collaboration with several colleagues, what he later described as "a long series of papers on the physiology of severe exercise" (Hill, 1965, p. 86). The colleagues involved were Hartley Lupton, C.N.H. Long, and K. Furusawa, but whilst Hill shared the Nobel prize in 1922 and went on to have a long and distinguished career, producing hundreds of papers on various aspects of physiology before he died in 1977, Hartley Lupton died in September 1924, aged 32, and neither Long nor Furusawa featured on any of Hill's papers after 1929. Moreover, throughout the 1920s, Hill gave many lectures, some of which were published (Hill, 1925a, 1927, 1933), in which he presented and expanded upon the data he had collected and the theories he had devised with Lupton.

Given this background, it is perhaps not surprising that these theories are often attributed solely to Hill. It is probably true that he was the driving force behind much of this work. One thing that is certainly true is that he was a subject for most of the studies on running. But it should be remembered that this work would never have been completed without the assistance of his co-workers. Indeed, as Hill (1925a, p. 110) said, at the end of a lecture on 'The recovery process after exercise in man', "the work I have described to you today is largely due to the devotion and enterprise of my friend and colleague Hartley Lupton. He did not live to see the published account of his investigations, but I hope that they will remain associated with his name." It is hoped that including the above quote here will go some way towards ensuring that Lupton's name continues to be associated not just with the classic 1923 paper by Hill and Lupton but also with those by Hill et al. (1924a, b) and Furusawa et al. (1924), to which he undoubtedly contributed a great deal.

2.3 The concept of a maximal $\dot{V}O_2$

The work of A.V. Hill and his colleagues has long been associated with the concept of a maximal $\dot{V}O_2$. It was the ideas put forward by Hill's group that provided the basis for the classic 1950s studies on the assessment of $\dot{V}O_{2max}$, and it is these same ideas that have been scrutinised in several recent critiques of the $\dot{V}O_{2max}$ concept. The studies in question are those of Taylor et al. (1955), who opened their discussion with a reference to Hill's book Muscular Activity (Hill, 1925a), Mitchell et al. (1958), who opened their paper with a quote from the same book, and Wyndham et al. (1959), whose paper opened with a reference to Hill and Lupton's 1923 paper. The critiques are those of Noakes (1988, 1997, 1998), who argues that Hill's group were guilty of circular reasoning and failed to demonstrate the existence of a maximal $\dot{V}O_2$, and Bassett and Howley (1997), who take an opposing position and argue that Hill's group did in fact demonstrate that a maximal $\dot{V}O_2$ could be attained.

The significance of Hill's group's work is certainly acknowledged by Tim Noakes, the South African physiologist who in recent years has been a persistent critic of the $\dot{V}O_{2max}$ concept. When Noakes delivered the J.B. Wolfe Memorial Lecture at the American College of Sports Medicine's 1996 conference, he questioned some of the fundamental theories on which modern exercise physiology is based and challenged other physiologists to respond. Much of his questioning was directed at Hill's group's notion of a maximal $\dot{V}O_2$, and much of this built on what he had argued previously (Noakes, 1988). His major point was that whilst Hill's group proposed that the $\dot{V}O_2$-running speed relationship would plateau at high speeds, they did not demonstrate that such a plateau actually occurred in the subjects they studied. However, when this lecture was published (Noakes, 1997), it was accompanied by a response from the American physiologists David Bassett and Edward Howley. These authors claimed that Noakes was wrong and that Hill's group had in fact "conducted experiments that clearly demonstrated the $\dot{V}O_2$ plateau" (Bassett and Howley, 1997, p. 592).

Bassett and Howley (1997) presented data from Hill et al. (1924b) showing the $\dot{V}O_2$ associated with various running speeds for 6 subjects, 3 of whom were the authors of the paper. These data were not mentioned by Noakes (1997), although he did present some of them in his 1988 paper (figure 3 in Noakes, 1988). They are important because at no other time did Hill or any of his colleagues present data on the relationship between $\dot{V}O_2$ and running speed for a range of speeds and a range of subjects. Bassett and Howley presented the data exactly as Hill et al. had done, producing a table in which individual data were given and a graph on which data from all 6 subjects were plotted. This graph is given below (figure 2.1).

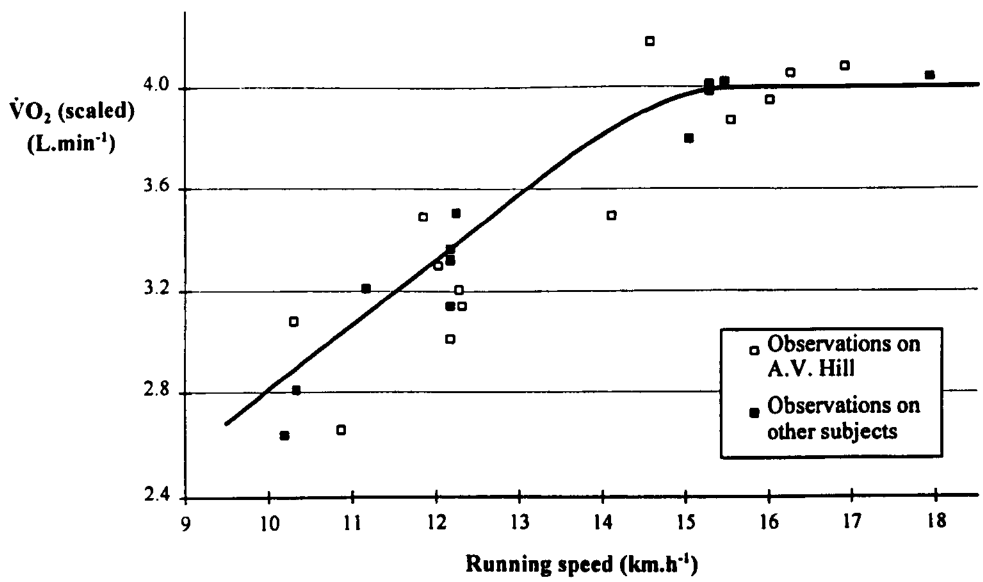

Figure 2.1. Relationship between running speed and $\dot{V}O_2$ for the subjects studied by Hill et al. (1924b) (re-drawn from the original data).

The way the data are presented in figure 2.1 above is consistent with the way in which these data were originally presented (figure 1 in Hill et al., 1924b). Hill et al. distinguished between the observations on Hill himself and those on other subjects, but they fitted the entire set of data with a function that reached an asymptote at a $\dot{V}O_2$ of 4 L.min^{-1}. They also "scaled" the $\dot{V}O_2$ data for two of their subjects (who had body masses of 68 and 58 kg) so that these data could be compared with the corresponding data for the other 4 subjects (all of whom had a body mass of ~73 kg). They gave no details of how they actually performed this scaling, and Noakes (1998, p. 1383) has criticised them for this, claiming that they failed to "explain ... whether that transformation influenced their conclusions".

In compiling figure 2.1, which is in good agreement with figure 1 in Hill et al. (1924b), it was assumed that this scaling simply involved calculating the $\dot{V}O_2$ per kg body mass (L.kg^{-1}.min^{-1}) and multiplying this by 73 to obtain a value (in L.min^{-1}) representative of the $\dot{V}O_2$ that would be obtained by a 73 kg person [i.e. $\dot{V}O_2$ (L.min^{-1}) for a 73 kg person = actual $\dot{V}O_2$ (L.min^{-1}) $\div$ actual body mass (kg) $\times$ 73]. Since there is good agreement between the two figures, it seems reasonable to conclude that in making "that transformation" Hill et al. scaled their data according to the procedure described above, which is simply equivalent to expressing all $\dot{V}O_2$ data in ml.kg^{-1}.min^{-1}. It is hard to conceive that in so doing they would have "influenced their conclusions" in any way, and it would seem, therefore, that Noakes' criticism is unwarranted.

On the basis of the data presented in figure 2.1, Hill et al. (1924b, pp. 156-157) concluded that "at high speeds ... the oxygen intake attains its maximum value, which in athletic individuals of about 73 kg ... is strikingly constant (in the case of running) at about 4 litres per minute. The oxygen intake fails to exceed this value, not because more oxygen is not required, but because the limiting capacity of the circulatory-respiratory system has been attained." Hill et al. (1924b, p.157) explained that they made no attempt to determine $\dot{V}O_2$ at speeds above 18 km.h^{-1}, partly because "greater speeds were not comfortable" on their small (90 m) grass track, and partly because "much higher speeds could not be maintained long enough to allow a sufficient foreperiod and collection interval" (i.e. they could not be sustained long enough for a steady state $\dot{V}O_2$ to be attained). They then added (Hill et al., 1924b, p. 157) that "the form ... of the oxygen intake curve ... , approaching a constant level of 4 litres per minute, makes it obvious that no useful purpose would be served by investigating higher speeds in this way."

According to Noakes (1998), these comments indicate that Hill's group believed not that $\dot{V}O_2$ would plateau at a value characteristic of the individual but rather that it would not exceed ~4 L.min^{-1} in any individual. However, in an earlier paper, Hill and Lupton (1922) had noted that whilst the 73 kg Hill, who was able to reach a $\dot{V}O_2$ of 4.175 L.min^{-1} (57 ml.kg^{-1}.min^{-1}) during running, was "fairly fit", he was not, and never had been, a "first-class runner". They suggested (Hill and Lupton, 1922, p. xxxii) that a champion middle-distance runner would attain "considerably higher values (e.g. 5000 c.c. or more)". It would seem, therefore, that in this instance Noakes has done what he so often accuses others of doing and misinterpreted Hill's group's work.

Given that Hill's group have been accused of employing circular reasoning (Noakes, 1988, 1997), it is important to establish whether Hill et al. (1924b) fitted their data with a function that reached an asymptote at 4 $L.min^{-1}$ because they were convinced that the $\dot{V}O_2$-running speed relationship would plateau at a $\dot{V}O_2$ of ~4 $L.min^{-1}$ in this group of subjects, or whether such a function really provides an accurate description of their data. Bassett and Howley (1997) did not comment on this. Instead they focused on the individual data (table 1 in Bassett and Howley, 1997), noting (p. 592) that "A.V. Hill did demonstrate a plateau in himself and also in subject J" (i.e. in 2 of the 5 subjects on whom $\dot{V}O_2$ data were presented for more than one speed). They then went on to conclude that Hill et al. (1924b) "clearly demonstrated the $\dot{V}O_2$ plateau".

Noakes, on the other hand, has recently issued a rebuttal to Bassett and Howley's paper (Noakes, 1998), in which he points out that Hill et al. (1924b) presented the data from all six subjects on one graph (see figure 2.1), and that this makes interpretation of these data difficult. In this 1998 paper, Noakes re-presented a graph which he had originally presented ten years previously (Noakes, 1988). This graph included just those data from Hill et al. (1924b) that were collected on Hill himself, data which Noakes suggested could be well described by a linear function. Bassett and Howley (1997, p.592) criticised Noakes' re-interpretation of Hill et al.'s original data, claiming it was "biased towards the view that a plateau does not exist."

The initial question that needs to be addressed is whether the $\dot{V}O_2$ attained by Hill at the faster speeds falls below that which would be predicted on the basis of the data obtained at the slower speeds. For the function that Hill et al. (1924b) fitted to their data, there is essentially no increase in $\dot{V}O_2$ for speeds above 15.5 $km.h^{-1}$ (see figure 2.1), so in order to establish whether it is appropriate to fit such a function to the data obtained on Hill it is necessary to establish whether the $\dot{V}O_2$ attained at speeds above 15.5 $km.h^{-1}$ falls below that which would be predicted on the basis of the data obtained at speeds below 15.5 $km.h^{-1}$. In figure 2.2 (below), the data on Hill that were presented previously (figure 2.1) have been presented again, but this time the $\dot{V}O_2$ data have been expressed relative to body mass ($ml.kg^{-1}.min^{-1}$) and the data for speeds below 15.5

km.h^{-1} (filled squares) have been used to derive a (linear) regression equation (solid line) which has been extrapolated to speeds above 15.5 km.h^{-1}. The broken lines represent the 95% confidence limits for the predicted $\dot{V}O_2$.

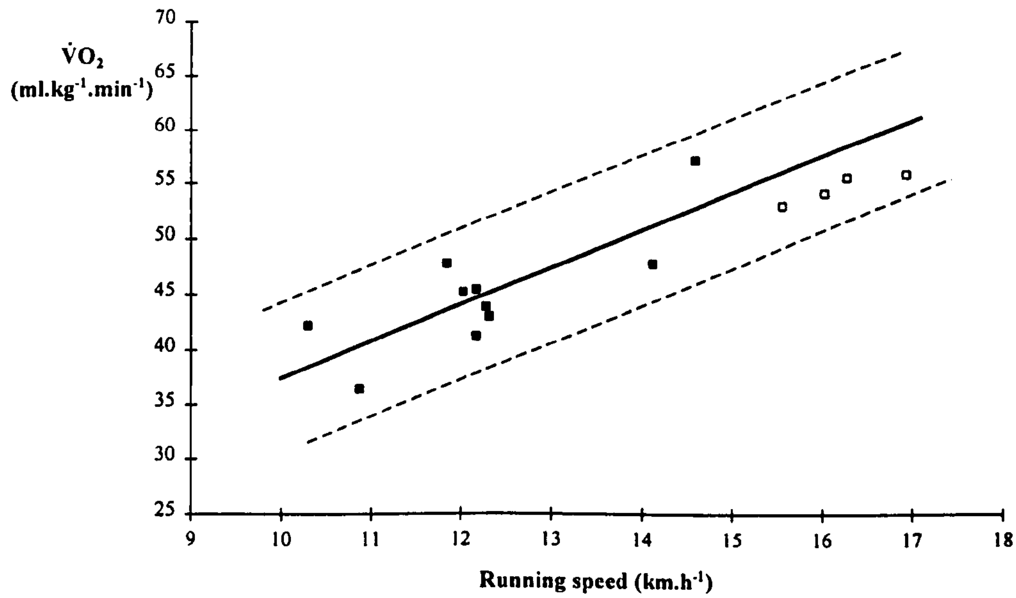

Figure 2.2. Data from Hill et al. (1924b) showing the relationship between running speed and $\dot{V}O_2$ for Hill himself.

Figure 2.2 shows that whilst all of the data points for speeds above 15.5 km.h^{-1} are below the regression line, each of them is within the 95% confidence limits of the predicted $\dot{V}O_2$. The problem, as Noakes (1998) has suggested, is that the variability in the data is considerable. The data reported in figure 2.2 were collected on Hill over several days. Recent studies on the day to day variability in the $\dot{V}O_2$ required to run at a given speed (Morgan et al., 1994; Pereira and Freedson, 1997) suggest that the coefficient of variation (CV) for this $\dot{V}O_2$ should be between 1 and 3%. In contrast, the standard error of estimate for the regression line given in figure 2.2 is 3.5 ml.kg^{-1}.min^{-1}, which corresponds to a CV of ~9% (for a $\dot{V}O_2$ of 40 ml.kg^{-1}.min^{-1}). This high variability causes the confidence limits for the predicted $\dot{V}O_2$ to be wide (see figure 2.2), and the fact that these limits are wide means that even if a $\dot{V}O_2$-plateau was present in the data it would be difficult to identify. If these were the only relevant data, there would be no option but to agree with Noakes (1988, 1997) that the data to show a plateau in the $\dot{V}O_2$-running speed relationship were lacking. But they are not. Data were also presented (Hill et al., 1924b) on the relationship between $\dot{V}O_2$ and running speed for 4 other subjects (S, W, CNHL, and J). These data are given in figure 2.3 (below).

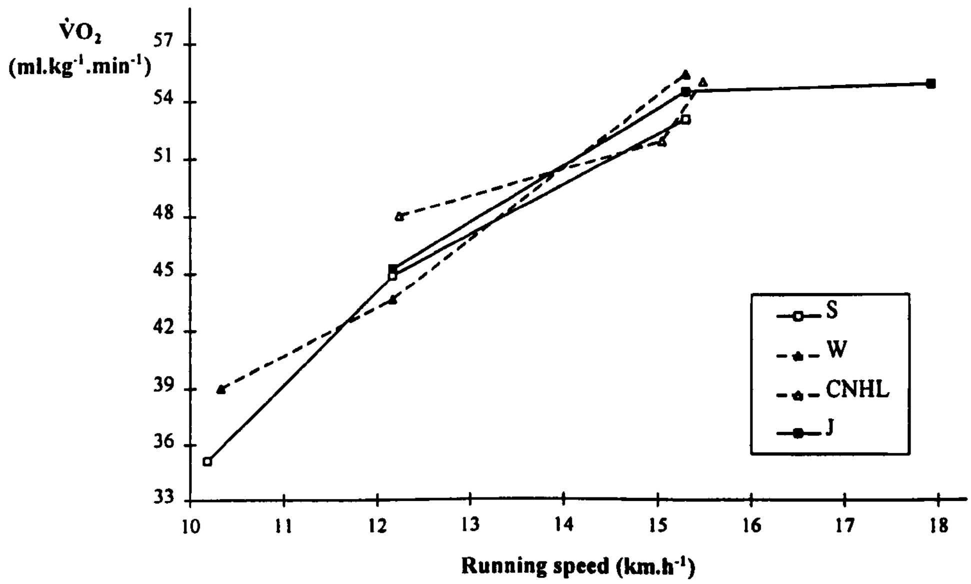

Figure 2.3. Data from Hill et al. (1924b) showing $\dot{V}O_2$ as a function of running speed for the remaining 4 subjects.

The above figure shows that a plateau in the $\dot{V}O_2$-running speed relationship was evident in only one of these four subjects. It is noteworthy that this subject (J) appears to have been able to run at a much higher speed than the other subjects. It is not known whether this reflects his superior capabilities as a runner or whether he was simply more skilled at running fast around a small grass track.

Whilst it would be fair to say that Hill's group failed to demonstrate that a plateau in the $\dot{V}O_2$-running speed relationship typically occurred in their subjects, there is no reason to believe that this is because they lacked the technical capabilities to determine $\dot{V}O_2$ accurately. The basis for this claim is that in terms of the $\dot{V}O_2$ required to run at a given speed, there is good agreement between the data presented by Hill's group (figure

2.1) and those derived from more recent studies of treadmill running (Léger and Mercier, 1984). For instance, for a speed of 13 km.h^{-1} (the lowest speed for which data are available on all 5 subjects), Hill et al.'s data (figure 2.1) show an average $\dot{V}O_2$ of ~48 ml.kg^{-1}.min^{-1}, whilst the "average" equation presented by Léger and Mercier (1984) predicts a $\dot{V}O_2$ of 44.5 ml.kg^{-1}.min^{-1}. This equation was derived from the results of 10 treadmill studies and adapted for track running by introducing an additional term to account for the effect of air resistance (after Pugh, 1970).

The agreement between the two figures may not seem particularly good, but it should be kept in mind that whilst Léger and Mercier's equation applies to unrestricted running on a tartan track, Hill et al.'s data were collected from subjects who ran on a grass track and carried a rubber Douglas bag while they ran. For a given running speed, $\dot{V}O_2$ would probably be higher for running on grass than for treadmill running because of the limited elastic properties of grass (particularly wet/muddy grass). Furthermore, the mass of a rubber Douglas bag is considerable, and carrying such a bag, together with the associated valves and taps [combined mass of ~5 kg (Sargent, 1926)], would therefore increase the $\dot{V}O_2$ required to run at a given speed. Hence it may be concluded that there is good agreement between the data presented by Hill et al. (1924b) and those presented by Léger and Mercier (1984). This is remarkable considering that in the intervening period there have been major advances in both the equipment and the techniques used for the collection and analysis of expired gases.

The above conclusion has implications in so far as it shows that Hill's group possessed the technical capabilities required to determine $\dot{V}O_2$ accurately. However, it does not change the fact that they managed to demonstrate a plateau in the $\dot{V}O_2$-running speed relationship in only 1 out of 5 subjects, and that in this subject the plateau was defined by only two data points (only 3 speeds were studied in subject J). Nor does it change the fact that when they made a concerted effort to demonstrate such a plateau (in Hill himself) the data they collected showed such high variability that it would be very hard to identify a plateau even if one were present.

It is likely that this high variability reflects the problems inherent in trying to collect reliable data outside of a controlled laboratory environment. What is not so easy to explain is why, despite the fact that they presented no convincing data to support one of their key theories, namely that there is a limit to the $\dot{V}O_2$ that can be attained, the work of Hill's group has had such a profound influence on so many physiologists. It can only be assumed that these physiologists have been swayed by the authoritative nature of the writing to the extent that they have not felt the need to scrutinise this group's data. Of relevance here is that Hill's group did much more than present the idea that there is a limit to the $\dot{V}O_2$ an individual can attain. They also speculated on what factors might limit this maximal $\dot{V}O_2$. Indeed, they even went so far as to calculate that a cardiac output of ~30 $L.min^{-1}$ would be required to support a "maximal" $\dot{V}O_2$ of 4 $L.min^{-1}$ (Hill and Lupton, 1923; Hill et al., 1924b). But what is perhaps more important is that they built a physiological model of performance around the idea that there is a limit to the $\dot{V}O_2$ an individual can attain, a model which they ultimately showed was capable of predicting performance in individual runners with a reasonable degree of accuracy.

2.4 The concept of a required and an attainable $\dot{V}O_2$

The term oxygen requirement, as distinguished from oxygen intake, was first used in Hill and Lupton's 1923 paper. On oxygen intake, Hill and Lupton (1923, p. 156) wrote the following in reference to some observations on Hill himself. "The rate of oxygen intake ... increases as the speed increases, reaching a maximum, however, for speeds beyond about 260 metres per min. ... However much the speed be increased beyond this limit, no further increase in oxygen intake can occur: the heart, lungs, circulation, and the diffusion of oxygen to the active muscle-fibres have attained their maximum activity." On oxygen requirement they wrote: "the oxygen requirement rises continuously, at an increasing rate, as the velocity increases, attaining enormous values - far beyond the possibility of satisfying them contemporaneously - at the higher speeds" (pp. 157-158). Finally, on the relationship between the two they wrote: "At high speeds the accumulation of acid is rapid, the oxygen requirement exceeding considerably the maximum oxygen intake" (p. 158).

Hill and Lupton's oxygen requirement is really an energy requirement, representative of the total (aerobic + anaerobic) energy production. Moreover, if it is accepted that there is a "critical speed ... above which ... the maximum oxygen intake is inadequate" (Hill and Lupton, 1923, p. 151), then it must also be accepted, given Hill and Lupton's reasoning, that energy has to be produced anaerobically at a considerable rate for all speeds above this "critical" speed. Hill and Lupton did not refer to aerobic and anaerobic metabolism though. Instead they wrote about oxygen intake and "oxygen debt", arguing that an O_2 debt could be incurred during exercise and "paid off" during recovery.

The idea of an O_2 debt was introduced by Hill and Lupton (1922), and in 1923 the same authors outlined how both the O_2 debt and the O_2 requirement could be determined by monitoring $\dot{V}O_2$ during, and in the initial stages of recovery from, a given exercise bout. Hill et al. (1924a) and Furusawa et al. (1924) elaborated upon the procedures involved, explaining that the O_2 debt should be calculated as the difference between the total volume of O_2 taken in during the first 30 min of recovery and that which would have been taken in during this period had the subject been at rest (O_2 debt = total O_2 intake in 30 min of recovery - resting $\dot{V}O_2 \times 30$), whilst the O_2 requirement (above resting) should be determined by dividing the total volume of O_2 taken in during exercise and recovery by the exercise duration [O_2 requirement ($L.min^{-1}$) = (total (exercise) O_2 intake above resting (L) + O_2 debt (L)) ÷ exercise duration (min)]. (It should be noted that whilst Hill's group frequently referred to oxygen intake, they used this term in a way which suggests that they were in fact referring to oxygen uptake.)

The general assumption implicit in this approach is that, for a given exercise bout, the extent to which the O_2 uptake is increased above baseline during recovery is representative of the extent to which energy was derived from anaerobic metabolism during the exercise. Specifically, the assumption is that the amount of energy derived from anaerobic metabolism during exercise (expressed as an equivalent O_2 uptake) and the amount of excess O_2 taken up during recovery are equal. There is a problem, however, in that since Hill's group first presented their ideas, data have been published that show this assumption to be incorrect.

Bangsbo et al. (1990) showed that the amount of energy generated anaerobically during a high intensity exercise bout is much smaller than would be predicted on the basis of the post-exercise O_2 uptake. These investigators studied one-legged, dynamic, knee extensor exercise because the active muscle mass can be quantified reasonably accurately for this type of exercise. They determined the amount of energy that was derived from anaerobic metabolism during the exercise from changes in the muscle concentrations of ATP, CP, IMP, various glycolytic intermediates, and lactate, as well as measurements of lactate efflux, and found that the O_2 equivalent of this anaerobic energy production represented only ~30% of the excess O_2 uptake. Thus they demonstrated that the elevated O_2 uptake that is observed during recovery from severe exercise cannot be considered to represent simply the repayment of an O_2 debt that was incurred during the exercise.

The implications of Bangsbo et al.'s data are 1) that it is inappropriate to use the term "oxygen debt" to refer to an elevated post-exercise O_2 uptake, and 2) that Hill's group must have dramatically overestimated the extent to which anaerobic metabolism actually contributes to energy provision in high intensity exercise. In reference to the first point, it should be pointed out that a more appropriate term, "excess post-exercise oxygen consumption" (EPOC), has been proposed (Gaesser and Brooks, 1980, 1984), and that this term is now typically adopted in preference to "oxygen debt" (Almuzaini et al., 1998; Laforgia et al., 1997; Short and Sedlock, 1997; Trost et al., 1997). As for the second, it is important to recognise that since Hill's group used their estimates of the total anaerobic energy production to determine the $\dot{V}O_2$ required to run at a given speed [O_2 requirement (L.min^{-1}) = (total O_2 intake (L) + O_2 debt (L)) ÷ exercise duration (min)], they would also have overestimated the true O_2 requirement, especially for the higher speeds. This would explain why Hill and Lupton (1923) were still able to predict Hill's middle-distance running performances with a reasonable degree of accuracy even though their estimates of the anaerobic contribution to energy production and the total energetic requirement were much too high (see section 2.6).

2.5 The concept of an anaerobic capacity

Hill's group never actually used the term "anaerobic capacity", but in effect they did propose that there is an upper limit to the amount of energy that can be derived from anaerobic metabolism. What they actually proposed was that there is an upper limit to the O_2 debt that an individual can incur (the "maximum oxygen debt" - Hill and Lupton, 1923). But as was stated previously, the assumption that the amount of excess O_2 taken up during recovery (the O_2 debt) and the amount of energy derived from anaerobic metabolism during exercise (expressed as an equivalent O_2 uptake) are equal was implicit in their approach. Hence it seems reasonable to argue that Hill and Lupton's maximum oxygen debt was equivalent, conceptually at least, to a maximum amount of anaerobically derived energy (i.e. an anaerobic capacity).

The idea that there is a limit to the amount of energy that can be generated anaerobically is still popular among contemporary physiologists (Bangsbo et al., 1993; Gastin, 1994; Gastin and Lawson, 1994a, b; Medbø et al., 1988; Oleson et al., 1994; Saltin, 1986, 1990a; Scott et al., 1991; Tabata et al., 1996). It is fundamental to the "critical power" concept (Hill, 1993; Monod and Scherer, 1965; Morton and Hodgson, 1996; Poole et al., 1988) and, together with the idea that there is a maximal $\dot{V}O_2$, it provides the basis for contemporary models of middle-distance running performance (di Prampero, 1986; di Prampero et al., 1993; Péronnet and Thibault, 1989). Problems have arisen, however, when attempts have been made to quantify this anaerobic capacity.

Hill et al. (1924a) attempted to quantify anaerobic capacity by determining the "maximum oxygen debt". They found that the O_2 debt incurred during moderate intensity exercise was small, regardless of the duration of the exercise, but that exercise of a slightly higher intensity, provided it was prolonged, was associated with a substantial O_2 debt. Then, having noted that the highest O_2 debts were generally recorded after exercise which was so severe that it could only be maintained for 2 to 4 min, Hill et al. (1924a) presented data on the highest O_2 debt they had observed for each of 15 subjects (13 males and 2 females). For the male subjects, none of whom it appears undertook specific anaerobic training, the "maximum oxygen debt" (expressed relative to body mass) averaged 0.132 $L.kg^{-1}$ (132 $ml.kg^{-1}$), whilst the individual values ranged from 0.095 to 0.216 $L.kg^{-1}$ (95 to 216 $ml.kg^{-1}$).

Hill's group's "oxygen debt" method is conceptually very neat, but Bangsbo et al.'s data suggest that it produces estimates for the amount of energy that can be generated anaerobically which are far too high (see section 2.4). More recently, attempts have been made to quantify anaerobic capacity by determining the "accumulated oxygen deficit" (AOD) (Craig et al., 1995; Gastin and Lawson, 1994a, b; Gastin et al., 1995; Hermansen and Medbø, 1984; Medbø and Tabata, 1989, 1993; Medbø et al., 1988; Oleson et al., 1994; Scott et al., 1991). Typically the subject is required to complete several exercise bouts at various sub-$\dot{V}O_{2peak}$ WRs and one exhaustive bout at a particular supra-$\dot{V}O_{2peak}$ WR. A regression equation relating $\dot{V}O_2$ to WR is derived from the sub-$\dot{V}O_{2peak}$ bouts, and this equation is used to predict a theoretical $\dot{V}O_2$ (analogous to Hill's group's O_2 requirement) for the supra-$\dot{V}O_{2peak}$ WR (Hermansen and Medbø, 1984; Medbø et al., 1988). This predicted $\dot{V}O_2$ is then used to calculate the total O_2 demand for the duration of the supra-$\dot{V}O_{2peak}$ bout and the AOD is calculated by subtracting the total amount of O_2 taken up in the course of the bout from this O_2 demand.

Medbø et al. (1988) studied exhaustive treadmill running lasting from ~15 sec to ~9 min and found that the AOD increased with increasing exercise duration for exercise bouts lasting less than 2 min but was constant for all exercise bouts lasting longer than 2 min. Moreover, they found that breathing a hypoxic gas mixture had no effect on the AOD. These results can be explained if it is assumed that each individual has a fixed capacity to generate ATP anaerobically but that the rate of anaerobic ATP production is limited in such a way that ~2 min is required to exhaust this capacity. It should be acknowledged, however, that much controversy surrounds the AOD concept (Bangsbo, 1992, 1996,a, b, 1998; Graham, 1996; Green and Dawson, 1995, 1996; Green et al., 1996; Medbø, 1996a, b). There are two important points here. First, both the $\dot{V}O_2$-power output relationship for cycling (Green and Dawson, 1995; Zoladz et al., 1995,

1998) and the $\dot{V}O_2$-speed relationship for running (Bangsbo et al., 1993; Wood et al., 1997) have been shown to be non-linear. Second, there is evidence to suggest that a steady state $\dot{V}O_2$ might not be attained during exercise at intensities close to that at which $\dot{V}O_{2peak}$ is attained (Poole et al., 1988; Roston et al., 1987).

There is no doubt that these are important points. However, it is noteworthy that when one-legged knee extensor exercise has been studied (Bangsbo et al., 1990) good agreement has been found between the AOD and the O_2 equivalent of the anaerobic ATP production as determined from changes in [ATP], [CP], [IMP], and [lactate]. What is also noteworthy is that whereas Hill et al. (1924a) reported an average value of 137 $ml.kg^{-1}$ for the maximum oxygen debt, with individual values ranging from 95 to 216 $ml.kg^{-1}$, Medbø et al. (1988) found that the maximal AOD averaged 72 $ml.kg^{-1}$, with individual values ranging from 52 to 90 $ml.kg^{-1}$. Medbø et al. studied 11 male subjects from diverse sporting backgrounds and obtained data which agree well with those from other recent studies [see Green and Dawson (1993) for a review].

Good agreement with the O_2 equivalent of the anaerobic ATP production as determined from changes in [ATP], [CP], [IMP] and [lactate] has been reported for the AOD but not the O_2 debt (Bangsbo et al., 1990). It seems reasonable to suggest, therefore, that Hill's group's estimates of anaerobic capacity, which are ~100% larger than the corresponding estimates that have been derived from the AOD, are likely to be ~100% too large. The consequence of this, as Noakes (1998) has pointed out, is that Hill's group would have overestimated the $\dot{V}O_2$ required to run at high speeds. For instance, whereas Hill and Lupton [figure 3 (p.157) in Hill and Lupton (1923)] proposed that Hill's oxygen requirement would be ~94 $ml.kg^{-1}.min^{-1}$ for a speed of 18 $km.h^{-1}$, the equation presented by Léger and Mercier (1984) (see section 2.3) predicts that the required $\dot{V}O_2$ should be ~62 $ml.kg^{-1}.min^{-1}$ for this speed. This is a large discrepancy considering that when Hill et al. (1924b) determined the $\dot{V}O_2$ that Hill actually sustained when he ran at 13 $km.h^{-1}$ they obtained a value that was within 10% of Léger and Mercier's predicted value. However, as was mentioned in section 2.4 and will be shown in the next section, the way in which Hill and Lupton modelled running performance was such that that they were still able to predict performance with a reasonable degree of accuracy even though they seriously overestimated the extent to which energy is generated anaerobically during exercise.

2.6 A physiological model of middle-distance running performance

Hill and Lupton (1923, p. 158) noted that "a man may fail to be a good runner by reason of a low oxygen intake, a low maximum oxygen debt, or a high oxygen requirement". They then performed some calculations, using data they had collected on Hill himself, from which they derived a theoretical relationship between race distance and average running speed for distances from 0.25 to 2 miles (400 m to 3.2 km). For each race they assumed that the maximum O_2 intake was sustained throughout and that a maximal O_2 debt was incurred. They presented Hill's best times for a range of distances and for each distance they calculated the total amount of O_2 that would be taken in over the duration of the race [total O_2 intake (L) = maximal O_2 intake ($L.min^{-1}$) ÷ race duration (min)]. They then added the maximum O_2 debt to this figure and divided the result by the race duration to determine the O_2 requirement that would be sustainable for this duration [O_2 requirement ($L.min^{-1}$) = (total O_2 intake (L) + O_2 debt (L)) ÷ race duration (min)]. Finally they referred to the relationship between O_2 requirement and running speed that they had previously derived for Hill (see section 2.4) to determine the running speed that would be associated with this O_2 requirement.

For Hill they assumed a maximum O_2 debt of 10 L (137 $ml.kg^{-1}$) and a maximum O_2 intake of 4 $L.min^{-1}$ above resting. They chose this value for the maximum O_2 debt simply because it was close to the highest value that they had observed at the time the paper was written [in a later paper (Hill et al., 1924a), they report a maximum oxygen debt of 150 $ml.kg^{-1}$ for Hill]. In selecting a value for the maximum O_2 intake they took account of the fact that the race times they used were achieved by Hill some 10 years prior to the experiments they reported. The highest $\dot{V}O_2$ they attained in the course of these experiments was 4.175 $L.min^{-1}$ (~3.8 $L.min^{-1}$ above resting), and the value they used in their calculations was 0.2 $L.min^{-1}$ higher than this (i.e. they assumed that Hill's maximum O_2 intake had dropped by 0.2 $L.min^{-1}$ over this 10 year period).

Hill and Lupton determined the O_2 requirement that should be sustainable for race distances of 0.25, 0.33, 0.5, 1.0, and 2.0 miles. However, when they related these O_2 requirements to running speeds they found that the speeds they obtained were higher than those that Hill had actually sustained. To overcome this problem they proposed that for a given O_2 requirement the speed should be reduced by 15% to account for the effect of carrying the respiratory apparatus (the relationship between O_2 requirement and running speed they derived for Hill was derived from experiments in which he carried a Douglas bag while he ran). Whilst this might seem like "fudging" the figures to make the data fit the theory, there is good reason to believe that their adjustment was reasonable.

First, it should be emphasised that Hill's group's data on O_2 intake suggest that carrying the respiratory apparatus did indeed increase the O_2 cost of running. These data show that for the experimental set-up used by these investigators, the actual $\dot{V}O_2$ associated with running at a given speed was higher than would be expected for unrestricted running [$\dot{V}O_2$ was ~8% higher than expected for a speed of 13 $km.h^{-1}$ (see section 2.3)]. Second, it should be pointed out that because they assumed that Hill attained his maximum O_2 intake immediately at the start of exercise Hill and Lupton would have overestimated the total O_2 intake and thus the sustainable O_2 requirement. By assuming that $\dot{V}O_2$ increases exponentially at the start of exercise and using realistic values (Williams et al., 1998), for the time constant, τ, it is possible to calculate that Hill and Lupton would have overestimated the actual O_2 requirement by between 4 and 8%. The effect would have been greatest for the ¼ mile (400 m) and smallest for the 2 mile (3.2 km) race.

Hill (1925b) acknowledged that the assumption that $\dot{V}O_2$ reaches its maximum immediately at the onset of exercise was false. He claimed that it was made so that the calculation of the total O_2 intake could be kept simple, noting that "for a more accurate calculation the gradual rise of the oxygen intake at the beginning of exercise can be taken into account" (Hill, 1925b, p. 482 (footnote)). In 1926 Sargent published a report of an experiment in which he attempted to circumvent not only the problems associated with assuming that the maximal $\dot{V}O_2$ is reached immediately but also those associated with carrying the respiratory apparatus. His subject, N, a well-trained middle-distance runner, covered a set distance [120 yards (110 m)] at a range of speeds. He did not carry any respiratory apparatus; rather he held his breath while he ran. He was handed the mouthpiece as soon as he stopped running, and his expirate was collected for the first 30-60 min of recovery. For each speed, Sargent determined the O_2 debt associated with the exercise and calculated the O_2 requirement by dividing this O_2 debt by the duration of the exercise. From these data he was able to derive a relationship between O_2 requirement and running speed, but he also determined the "maximum oxygen debt" and the "maximum oxygen intake" for N. Thus he obtained all the data necessary to apply Hill and Lupton's model of running performance. However, he also derived a curve relating $\dot{V}O_2$ to time for the first few minutes of exercise. In contrast to Hill and Lupton, he made use of this curve when he calculated the total amount of O_2 that could be taken in over a given duration. Using this revised version of Hill and Lupton's model, Sargent was able to predict N's best time to within 2 s for all distances from 300 yards (275 m) to 2 miles (3.2 km).

Hill (1933) presented Sargent's data in a lecture he delivered late in 1926. As he had done previously (Hill, 1925b), he drew an analogy with a bank account. He emphasised that an individual had a limited "income" (oxygen intake could not, he believed, exceed the maximum oxygen intake), and that high speeds could only be supported by running up an "overdraft" that would then have to be paid off once the exercise was over. Given that the model he presented was so straight forward, and that it was apparently capable of predicting performance very accurately, it is perhaps not surprising that the theories which underpinned it were readily accepted by the majority of physiologists. It is important to recognise, however, that Hill's group presented very few data in support of their theories. Of particular relevance to the present thesis is the fact that a plateau in the $\dot{V}O_2$-running speed relationship was observed in only one of their 5 subjects (see section 2.3). Thus they left room for debate over whether a maximal $\dot{V}O_2$ in fact exists, and despite the fact that many subsequent studies have attempted to resolve the issue, no consensus has yet been reached (Noakes, 1997, 1998; Bassett and Howley, 1997). The literature relevant to this debate is reviewed in the following two chapters (chapters 3 and 4).

CHAPTER 3: EVIDENCE THAT AN UPPER LIMIT FOR $\dot{V}O_2$ IS, OR AT LEAST SHOULD BE, REACHED DURING PROGRESSIVE EXERCISE

3.1 Introduction

It is now 75 years since Hill and Lupton (1923) first proposed that there is a limit to the $\dot{V}O_2$ an individual can attain (i.e. a maximal $\dot{V}O_2$), and many studies have now been published which have attempted to establish whether such a maximal $\dot{V}O_2$ does in fact exist. The focus of these studies has been the question of whether the $\dot{V}O_2$-WR relationship typically plateaus at high WRs. However, in recent years, a theoretical argument to suggest that such a maximal $\dot{V}O_2$ should exist has also developed, and many studies have been conducted as researchers have sought evidence to support this argument. Both types of study will be reviewed in this chapter, but it should be kept in mind that there are several problems associated with the $\dot{V}O_{2max}$ concept that will not be dealt with in detail. These problems are the focus of Chapter 4.

3.2 Studies on the assessment of maximal oxygen uptake

3.2.1 *Discontinuous protocols*

The first published account of a systematic attempt to determine the maximal oxygen uptake is that of Åstrand (1952). This was a large study (n = 225), which was primarily concerned with the effect of ageing on various factors related to oxygen uptake (the age of the subjects ranged from 4 to 33 years). All subjects were tested on a motorised treadmill (some of the adults were also tested on a cycle ergometer), and whilst the treadmill grade was set at 1° (1.75%) for the subjects over 20, all of the younger subjects ran on a level treadmill. Each subject completed a series of runs spread over a period of ~3 weeks. The speed was progressively increased over the course of this series, from an initial speed of 7-8 $km.h^{-1}$ (children) or 10-12 $km.h^{-1}$ (adults) to a final speed that was sufficient to exhaust the subject in 4 to 6 min. Oxygen uptake was determined by the Douglas bag method and expirate was generally collected after 4-5 min of work, although for some of the fastest runs the collection of expirate began after just 3 min of exercise.

The incidence of a plateau was evaluated only for those subjects whose age was between 14 and 18 years (n = 40). For this group, Åstrand noted that a plateau in the $\dot{V}O_2$-running speed relationship was observed in 19 (47.5%) of the subjects. However, no information was given concerning how such a plateau was defined, and all that can be assumed is that Åstrand simply examined a plot of $\dot{V}O_2$ vs. running speed to see whether a plateau was evident. The age of the subjects may also be of some significance. The incidence of a $\dot{V}O_2$-plateau has been reported to be particularly low in children (Cunningham et al., 1977; Rivera-Brown et al., 1992; Rowland, 1993), and it has been suggested (Cunningham et al., 1977; Rowland, 1989) that the reason for this is that the anaerobic capacity of children is typically low. Indeed, on the basis of cross-sectional data on the blood lactate concentration following maximal work, Cunningham et al. (1977) suggested that anaerobic capacity increases with age between the ages of 10 and 23 years.

Taylor et al. (1955) reported a comparison of two treadmill protocols for the assessment of $\dot{V}O_{2max}$. Both were discontinuous, but one was a speed incremented, constant (zero) grade test and the other was a grade incremented, constant speed test. They reported that whereas a plateau in the $\dot{V}O_2$-WR relationship was observed in 108 (94%) of 115 subjects for the increasing grade protocol, such a plateau was observed in only 9 (69%) of 13 subjects for the increasing speed protocol. They suggested that their subjects simply lacked the necessary skill to run at the speeds required to elicit a maximal $\dot{V}O_2$ on a level treadmill and concluded (p. 75) that "raising the grade, with the speed held constant (7 mph), is the most satisfactory method of increasing the work load with the motor driven treadmill to attain a maximal oxygen intake".

Whilst the protocols that are currently in use differ from that of Taylor et al. in that they are continuous, their recommendation that a constant speed, increasing grade (CSIG) protocol be used for the assessment of $\dot{V}O_{2max}$ has been very influential. Indeed, a CSIG protocol has been used by various researchers for the assessment of $\dot{V}O_{2max}$ in middle-distance and distance runners (Boileau et al., 1982; Conley and Krahenbuhl, 1980; Costill, 1970; Costill and Fox, 1969; Costill and Winrow, 1970a, b; Costill et al., 1971, 1973; Daniels and Daniels, 1992; Daniels et al., 1978; Farrell et al., 1979; Foster et al., 1978; Morgan et al., 1989; Pollock, 1977; Saltin and Åstrand, 1967; Saltin et al., 1995; Spencer et al., 1996; Svedenhag and Sjödin, 1984, 1985). Moreover, published guidelines for the assessment of $\dot{V}O_{2max}$ during treadmill running consistently recommend that such a protocol is used, regardless of whether the athletes being assessed are trained runners (Bird and Davison, 1997; McConnell, 1988; Thoden, 1991) or athletes who specialise in sports other than running, for whom a general measure of $\dot{V}O_{2max}$ may be required (Thoden, 1991). However, what is most significant about Taylor et al.'s study is that it was the first in which a systematic approach was taken to defining a $\dot{V}O_2$-plateau and the first in which a plateau was identified in such a high proportion of the subjects.

The CSIG protocol used by Taylor et al. was one where the speed was held constant at 7 mph (11.3 $km.h^{-1}$) while the grade was increased in increments of 2.5%. To establish confidence limits for the amount by which $\dot{V}O_2$ should increase between consecutive stages (the expected $\Delta\dot{V}O_2$), Taylor et al. (1955, p.75) determined $\dot{V}O_2$ "in 13 subjects at two or more grades below the grades resulting in the oxygen intake plateau". They reported that the (mean ± SD) $\Delta\dot{V}O_2$ associated with a grade increase of 2.5% was 299 ± 87 $ml.min^{-1}$ (4.18 ± 1.07 $ml.kg^{-1}.min^{-1}$), with individual values ranging from 159 to 470 $ml.min^{-1}$ (2.2 to 5.9 $ml.kg^{-1}.min^{-1}$). On the basis of these data, they proposed that a $\dot{V}O_2$-plateau could be deemed to have occurred whenever a $\Delta\dot{V}O_2$ of less than 150 $ml.min^{-1}$ or 2.1 $ml.kg^{-1}.min^{-1}$ was observed between two consecutive stages. They then went on to show that using this definition allowed them to identify a plateau in 94% of subjects, whilst ensuring that "there is small chance of making an error in deciding that the maximal oxygen intake has been reached" (Taylor et al., 1955, p. 75). Since the cut-off value used (2.1 $ml.kg^{-1}.min^{-1}$ or 150 $ml.min^{-1}$) was apparently outside the 95% confidence interval for the sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$, the chance of making such an error would presumably have been <2.5%. However, it appears that the way in which Taylor et al. obtained the data from which they derived this value was such that this chance would in fact have been nearer 10%.

Taylor et al. (1955, p.75) claimed that "the mean oxygen intake increment for a 2.5% increase in grade on 30 occasions was found to be 299.3 with a standard deviation of 86.5 cc/min or 4.18 ± 1.07 cc/kg/min". However, they also claimed (p.75) that "the standard deviation of the differences between the first and second grade was 114 cc/min and 1.60 cc/kg/min". These two statements would appear to be incompatible, but it is likely that the two standard deviations actually refer to different data sets. It is unclear exactly how Taylor et al. obtained the data from which they concluded that the sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$ was 299 ± 87 $ml.min^{-1}$ (4.18 ± 1.07 $ml.kg^{-1}.min^{-1}$). They note that they determined $\dot{V}O_2$ in only 13 subjects, and yet they claim that these data were derived from 30 observations. Many of these observations must therefore have been repeat observations on a given subject. Furthermore, given that they determined $\dot{V}O_2$ at "two or more" sub-$\dot{V}O_{2peak}$ WRs in these 13 subjects and that the SD for these data is relatively small, it seems reasonable to propose that they pooled data from several WRs within a subject (i.e. used the slope of the $\dot{V}O_2$-treadmill grade relationship) to derive a single figure representing the expected $\Delta\dot{V}O_2$ for a 2.5% increase in grade.

All of this is speculation of course, but the picture that emerges is that the 30 observations from which Taylor et al. concluded that the $\Delta\dot{V}O_2$ was 299 ± 87 $ml.min^{-1}$ (4.18 ± 1.07 $ml.kg^{-1}.min^{-1}$) would not have represented 30 individual values for $\Delta\dot{V}O_2$ derived from 30 subjects. Using 30 observations on only 13 subjects would suppress the effect of inter-individual variability on the SD obtained, whilst using several WRs within a subject to derive a single figure for the $\Delta\dot{V}O_2$ would suppress the effect of intra-individual variability. The end result would be that the SD would be underestimated, and since Taylor et al. used the range of these 30 individual observations to derive their criterion $\Delta\dot{V}O_2$, this criterion would have been artificially large (i.e. the cut-off value they used to define a plateau would have been unjustifiably lenient).

The larger SD that Taylor et al. report (114 $ml.min^{-1}$; 1.60 $ml.kg^{-1}.min^{-1}$), which they refer to as the SD of "the differences between the first and second grade" (p. 75), would appear to be a more appropriate statistic to use, given that the aim was to establish confidence limits for the $\Delta\dot{V}O_2$ that might be observed in a typical individual. If Taylor et al.'s estimate for the mean $\Delta\dot{V}O_2$ (299 ml.min^{-1}; 4.18 ml.kg^{-1}.min^{-1}) is correct, a $\Delta\dot{V}O_2$ of 2.1 ml.kg^{-1}.min^{-1} (150 ml.min^{-1}) represents a deviation of 2.08 ml.kg^{-1}.min^{-1} (149 ml.min^{-1}) from the mean. This deviation represents 1.3 SDs, so for a linear $\dot{V}O_2$-running speed relationship, 9.7% of the observed values for $\Delta\dot{V}O_2$ should be less than 2.1 ml.kg^{-1}.min^{-1} (150 ml.min^{-1}). In other words, a final $\Delta\dot{V}O_2$ of less than 2.1 ml.kg^{-1}.min^{-1}, or 150 ml.min^{-1}, would be observed in 9.7% (11/115) of Taylor et al.'s subjects even if $\dot{V}O_2$ increased as a linear function of WR for the entire test. Hence, although Taylor et al. reported that a $\dot{V}O_2$-plateau was observed in 108 (94%) of 115 subjects, the real incidence was probably closer to 97/115, or 84%.

The Taylor paper is important because it was the first to emphasise the fact that the random variation present in a set of data may obscure the presence of a $\dot{V}O_2$-plateau. Implicit in Taylor et al.'s approach was the notion that an increase in $\dot{V}O_2$ might be observed between consecutive WRs even when the true $\Delta\dot{V}O_2$ is zero. This means that it is not appropriate to consider that a plateau has occurred only when $\dot{V}O_2$ shows no change or a decrease in response to an increase in WR. Indeed, doing so ignores one half of the distribution of values for $\Delta\dot{V}O_2$ that could potentially be observed given a true $\Delta\dot{V}O_2$ of zero. Taylor et al. did not actually focus on the distribution of the observed values for $\Delta\dot{V}O_2$ around a true $\Delta\dot{V}O_2$ of zero however. Instead they focused on the values for the observed $\Delta\dot{V}O_2$ around a given positive $\Delta\dot{V}O_2$ (the mean $\Delta\dot{V}O_2$ for a 2.5% increase in grade) in an attempt to define a cut-off value for the observed $\Delta\dot{V}O_2$. The thinking was presumably that the probability of observing a value smaller than this cut-off value given a linear relationship between true $\dot{V}O_2$ and WR would be so low that were such a value to be observed the logical conclusion would be that this relationship had departed from linearity.

In the years following the publication of the Taylor paper, several studies have been published in which a criterion $\Delta\dot{V}O_2$ has been used to define a $\dot{V}O_2$-plateau. The criterion that has been used most frequently is that of a $\Delta\dot{V}O_2$ less than the lower 95%

confidence limit for the sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$, determined either for the group as a whole (Mitchell et al., 1958; Niemelä et al., 1980; Sheehan et al., 1987) or for individual subjects (Rowland and Cunningham, 1992). Other criteria have also been used, such as a $\Delta\dot{V}O_2$ less than the mean sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$ (Freedson et al., 1986) or some fraction of this mean $\Delta\dot{V}O_2$ (Cumming and Friesen, 1967), but whilst there is a clear rationale for the use of the 95% confidence limits, there is no obvious rationale for the use of these other criteria.

Several studies have been published since 1955 in which a decision as to whether or not a $\dot{V}O_2$-plateau has occurred has been made on the basis of whether or not an "absolute plateau" (no increase or a decrease in $\dot{V}O_2$ despite an increase in WR) was observed (Clark and McConnell, 1986; Froelicher et al., 1974; Mayhew and Gross, 1975). In addition, many researchers (Armstrong et al., 1996; Boileau et al., 1977; Cunningham et al., 1977; Davies et al., 1984; Rivera-Brown et al., 1992; Rowland, 1993; Sidney and Shephard, 1977) have unthinkingly applied Taylor et al's criterion figure of 2.1 $ml.kg^{-1}.min^{-1}$ (or the equivalent absolute figure of 150 $ml.min^{-1}$) in situations where it is simply not applicable. It could be argued, therefore, that whilst many studies have presented data on the incidence of a $\dot{V}O_2$-plateau, few have presented data that allow an accurate assessment to be made of the real incidence of such a plateau.

There are two important points here. The first is that an absolute $\Delta\dot{V}O_2$ of 150 $ml.min^{-1}$ will only be equivalent to a relative $\Delta\dot{V}O_2$ of 2.1 $ml.kg^{-1}.min^{-1}$ in a subject whose body mass is ~72 kg, and the second is that Taylor et al.'s criterion is only applicable to a protocol for which the (mean ± SD) $\Delta\dot{V}O_2$ is 4.18 ± 1.07 $ml.kg^{-1}.min^{-1}$ or 299 ± 87 $ml.min^{-1}$. The figure of 72 kg was derived by dividing 299 $ml.min^{-1}$ by 4.18 $ml.kg^{-1}.min^{-1}$; it represents the average body mass for the subjects on whom Taylor et al. presented data for $\Delta\dot{V}O_2$. If a criterion figure of 150 $ml.min^{-1}$ is applied unthinkingly, the incidence of a $\dot{V}O_2$-plateau will be artificially high if the average mass of the subjects is <72 kg and artificially low if this mass is >72 kg. Similarly, if a figure of 2.1 $ml.kg^{-1}.min^{-1}$ (or 150 $ml.min^{-1}$) is applied, the incidence of a $\dot{V}O_2$-plateau will be artificially high if the $\Delta\dot{V}O_2$ for the protocol to which it is applied has a mean of less than 4.2 $ml.kg^{-1}.min^{-1}$ (or 299 $ml.min^{-1}$) or a SD in excess of 1.1 $ml.kg^{-1}.min^{-1}$ (or 87 $ml.min^{-1}$) and artificially low if the mean is higher or the SD is lower.

One important study for which such an assessment could potentially be made is that of Mitchell et al. (1958). These investigators adapted Taylor et al.'s discontinuous protocol by reducing the duration of each stage from 3 to 2.5 min and shortening the inter-stage rest periods from >24 hours to ~10 min. The treadmill speed was also reduced [from 7 mph (11.3 $km.h^{-1}$) to 6 mph (9.7 $km.h^{-1}$)], but Mitchell et al.'s was still a CSIG protocol in which treadmill grade was increased in increments of 2.5%. Like that of Taylor et al., the study of Mitchell et al. (1958) is often interpreted as providing evidence that the $\dot{V}O_2$-WR relationship plateaus in the majority of individuals. This is not surprising given their claim that in 72% of subjects a grade was reached beyond which $\dot{V}O_2$ remained unchanged or declined as the grade was further increased. Indeed they also presented data for 4 separate age groups which show that, in each group, the mean $\dot{V}O_2$ increased up to a point and then decreased slightly as the grade was further increased. However, Mitchell et al. also derived individual relationships between $\dot{V}O_2$ and treadmill grade for the 65 subjects they studied, and the implication of these data is that there was a problem with their data collection techniques.

Mitchell et al. report that the (mean ± SD) $\Delta\dot{V}O_2$ for a 2.5% increase in grade was 142 ± 44 $ml.min^{-1}$ (1.84 ± 0.57 $ml.kg^{-1}.min^{-1}$). This $\Delta\dot{V}O_2$ is very low in comparison to that which Taylor et al. reported for a similar protocol (4.18 $ml.kg^{-1}.min^{-1}$). Indeed, given that the speed at which Mitchell et al.'s subjects ran (9.7 $km.h^{-1}$) was only 1.6 $km.h^{-1}$ (14%) lower than that at which Taylor et al.'s subjects ran, it would be expected that the mean $\Delta\dot{V}O_2$ for Mitchell et al.'s subjects would be ~15% lower than that reported by Taylor et al., not 56% lower. Calculations of the delta efficiency for working against gravity yield a value of 54% for Taylor et al.'s data as compared with 105% for Mitchell et al.'s data, suggesting that the problem is not that Taylor et al.'s $\Delta\dot{V}O_2$ is too high, but rather that Mitchell et al.'s is too low. The only obvious difference between the two studies is that Mitchell et al.'s subjects were required to grip a supporting shelf with one hand while they ran whereas Taylor et al.'s were not. Although this is by no means certain, it is possible that the extent to which the subjects pulled on this shelf would have increased with increasing grade. As this is a possibility, it is difficult to draw any conclusions about the incidence of a $\dot{V}O_2$-plateau from Mitchell et al.'s study.

Wyndham et al. (1959) studied cycle ergometer exercise and modelled the $\dot{V}O_2$-power relationship. Over a period of ~4 months, each of 4 subjects completed a large number of exercise bouts at various WRs. Each subject completed at least 5 exercise bouts at each WR and between 8 and 11 WRs were studied in each individual. Heart rate (HR) and $\dot{V}O_2$ were determined during each exercise bout, and for each individual a separate two component model was used to relate each of these variables to WR. For both variables the model assumed a linear function for the lower and an exponential (asymptotic) function for the higher WRs. However, whilst this model appeared to provide an accurate description of the HR data, this was not the case for the $\dot{V}O_2$ data. The problem was that because $\dot{V}O_2$ tended to approach an asymptote very slowly the asymptotic $\dot{V}O_2$ predicted by the model was typically unrealistically high. Indeed the maximal (asymptotic) $\dot{V}O_2$ predicted from the model was consistently higher than the peak $\dot{V}O_2$ determined as the average $\dot{V}O_2$ for the three highest WRs.

Wyndham et al. (1959, pp. 932-933) criticised Taylor et al.'s approach to defining a maximal $\dot{V}O_2$, noting that the procedure employed by Taylor et al. "amounts to accepting as the maximum the level of O_2 intake just after the curve begins to depart from the linear." They also noted (p. 933) that "higher WRs were not studied by Taylor et al. ... and this probably accounts for the fact that they missed the slow approach of O_2 intake to the asymptote" (no further exercise bouts were performed by Taylor et al.'s subjects once a $\Delta\dot{V}O_2$ of <2.1 $ml.kg^{-1}.min^{-1}$ or <150 $ml.min^{-1}$ had been observed). Although it has been suggested (Åstrand, 1960) that Wyndham et al.'s results might have been influenced by the fact that their experiments were conducted at an altitude of ~1700 m (in Johannesburg, South Africa), findings have since been presented (Duncan et al., 1997; Glassford et al., 1965) which suggest that the points they made were valid.

Glassford et al. (1965) evaluated several discontinuous protocols including those that were used by Taylor et al. and Mitchell et al. Their paper is somewhat confusing as having first claimed that no further work bouts were completed once a $\Delta\dot{V}O_2$ of <2.1 ml.kg^{-1}.min^{-1} was observed (the implication being that such a $\Delta\dot{V}O_2$ was observed in all subjects) they then claim (p. 512) that some subjects "were continued on advanced workloads beyond the load on which the criterion value of maximal oxygen uptake was reached". Having defined a significant increase as an increase of >2.1 ml.kg^{-1}.min^{-1}, they note (p. 512) that "several subjects experienced a significant increase in oxygen uptake when subjected to the extra workloads", with one subject in fact experiencing "two such significant increases … and two plateaus beyond the initial criterion value". Glassford et al. offered no explanation for these findings, although they did suggest that further research was warranted to clarify the problem.

The Taylor protocol was evaluated again in a recent study by Duncan et al. (1997). These investigators stressed that the test was continued even if a $\Delta\dot{V}O_2$ of <2.1 ml.kg^{-1}.min^{-1} was observed, noting that "the endpoint of the .. test was an inability of the subject to complete 3 min at a given workload, and not the demonstration of an apparent plateau" (Duncan et al., 1997, p. 274). It is noteworthy that whereas Taylor et al. (1955) identified a plateau in 94% of subjects, Duncan et al. (1997) identified one in only 60% of subjects. Both groups studied males who were active but not specifically trained, and both used a protocol in which subjects ran at 7 mph (11.3 km.h^{-1}) and the treadmill grade was increased in 2.5% increments. The only difference was that Duncan et al.'s subjects continued the test for as long as they were able whilst Taylor et al.'s stopped as soon as a $\Delta\dot{V}O_2$ of <2.1 ml.kg^{-1}.min^{-1} was observed. Previously, Sheehan et al. (1987) had reported that the incidence of a plateau was 69% for a discontinuous test that was continued "until volitional exhaustion". However, given that Sheehan et al.'s subjects were children (10-12 years), this incidence is surprisingly high. There are no obvious problems with Sheehan et al.'s study. Rather, the suggestion is that the proposition (Cunningham et al., 1977; Rowland, 1989) that children often fail to demonstrate a plateau in $\dot{V}O_2$ because they have a small anaerobic capacity is unjustified.

Two studies by Krahenbuhl and co-workers are also relevant here (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979). The same test was used in both studies, and for this test, which was similar to the DCT of Taylor et al., the (mean ± SD) sub-$\dot{V}O_{2peak}$, $\Delta\dot{V}O_2$ was found to be 4.04 ± 1.49 $ml.kg^{-1}.min^{-1}$ (Krahenbuhl et al., 1979). Taylor et al.'s cut-off value of 2.1 $ml.kg^{-1}.min^{-1}$ was applied to define a plateau, and the test was stopped when a $\Delta\dot{V}O_2$ of <2.1 $ml.kg^{-1}.min^{-1}$ was observed. Since a $\Delta\dot{V}O_2$ of 2.1 $ml.kg^{-1}.min^{-1}$ represents a deviation of 1.3 SDs from the mean for this test, it can be concluded that, as was the case in Taylor et al.'s study, in each of these studies a final $\Delta\dot{V}O_2$ of <2.1 $ml.kg^{-1}.min^{-1}$ would have been observed in 9.7% of subjects even if $\dot{V}O_2$ continued to increase as a linear function of WR throughout the test. It is noteworthy that Taylor et al., Krahenbuhl et al., and Krahenbuhl and Pangrazi all identified a $\dot{V}O_2$-plateau in ~95% of subjects. This is particularly noteworthy given that the subjects in the Krahenbuhl studies were children (8-11 years).

3.2.2 *Continuous vs. discontinuous tests*

In each of the studies reviewed thus far, the protocol used for the assessment of $\dot{V}O_{2max}$ was discontinuous (i.e. comprised periods of exercise punctuated by periods of rest). The problem with discontinuous protocols is that they place excessive time demands on both subjects and experimenters. Taylor et al.'s protocol, for example, requires subjects to visit the laboratory on 4 or 5 separate occasions, as does Åstrand's. Mitchell et al.'s protocol is different in that the rest periods are short which means that the entire test can be completed in ~1.5 hours. However, even this test would not be suitable if there was a need to determine $\dot{V}O_{2max}$ in a large number of subjects and only limited time was available.

One way of reducing the duration of a discontinuous test would be to eliminate the rest periods completely (i.e., to turn it into a continuous test), and indeed there are many investigators who have done exactly this. These continuous tests have been compared with the more traditional discontinuous tests, either for cycle ergometer (McArdle et al., 1973; Shephard et al., 1968) or for treadmill (Duncan et al., 1997; McArdle et al., 1973; Rivera-Brown et al., 1994; Sheehan et al., 1987; Shephard et al., 1968; Stamford, 1976;

Wyndham et al., 1966) exercise, and it has been repeatedly demonstrated that, regardless of the exercise mode, the peak $\dot{V}O_2$ is the same for both types of protocol. Four of the above studies (Duncan et al., 1997; Rivera-Brown et al., 1994; Sheehan et al., 1987; Stamford, 1976) also commented on the incidence of a $\dot{V}O_2$-plateau, although it is not clear exactly how such a plateau was defined in the Stamford (1976) study. As for the remaining 3 studies, each used a confidence interval based approach similar to that of Taylor et al. to define a $\dot{V}O_2$-plateau (see section 3.2.1), and each found that the incidence of a $\dot{V}O_2$-plateau was higher for the discontinuous test (60-85 vs. 50-56%).

3.2.3 *Incremental vs. ramp tests*

All of the above studies focused on incremental protocols, but many cycle ergometer studies now use a ramp test to determine $\dot{V}O_{2peak}$ (Barstow et al., 1994; Belardinelli et al., 1995; Chicharro et al., 1996; Engelen et al., 1996; Lucia et al., 1998; Özyener et al., 1998; Passfield and Hale, 1995; Phillips et al., 1995). This type of test was first introduced almost 20 years ago (Whipp et al., 1981), and it was suggested at the time that the incidence of a $\dot{V}O_2$-plateau might be higher for a ramp test, in which the WR increases as a continuous linear function of time, than for an incremental test, in which the relationship between WR and time assumes a "step" pattern. Whipp et al. (1981) compared a ramp test with both a 1 min and a 5 min incremental test (on the cycle ergometer), and reported (p. 219) that "a plateau in $\dot{V}O_2$ was typically discerned from the ramp test, whereas this was often not the case with the ... incremental tests", although they presented no data in support of this statement.

Ramp tests have also been conducted on the motorised treadmill (Brubaker et al., 1997; Foley et al., 1997; Kaminsky and Whaley, 1998; Myers et al., 1989, 1990, 1991, 1994; Wiley and Rhodes, 1986). However, whereas ramp tests have been used for the determination of $\dot{V}O_{2peak}$ in competitive cyclists (Lucia et al., 1998; Palmer et al., 1997; Passfield and Hale, 1995), no study has yet been published in which a treadmill ramp test has been used for the determination of $\dot{V}O_{2peak}$ in competitive runners. The likely reason for this is that whilst there are many commercially available cycle ergometers for which various patterns of WR incrementation, including a ramp pattern, can be pre-programmed, computer controlled, pre-programmable treadmills are still relatively rare. Nevertheless, it should be acknowledged that, for treadmill running as well as for cycle ergometry, the incidence of a $\dot{V}O_2$-plateau might be higher for a ramp than for an incremental test.

3.2.4 *On-line vs. off-line data collection*

Whereas the classic studies of the 1950s (Mitchell et al., 1958; Taylor et al., 1955; Wyndham et al., 1959) all determined $\dot{V}O_2$ using the Douglas bag method (i.e. off-line), equipment is now available that allows $\dot{V}O_2$ to be determined on a breath-by-breath basis (i.e. on-line) (e.g. Davis et al., 1982; Whipp et al., 1981). When incremental protocols are used and $\dot{V}O_2$ is determined over certain discrete periods, it should not matter whether $\dot{V}O_2$ is determined by averaging breath-by-breath data or by collecting a sample of expirate over the relevant period. However, when a ramp test is used, either the peak $\dot{V}O_2$ or the incidence of a $\dot{V}O_2$-plateau could potentially be higher when $\dot{V}O_2$ is determined breath-by-breath than when the Douglas bag method is used.

When a distribution of values for $\Delta\dot{V}O_2$ obtained from WRs for which the $\dot{V}O_2$ is well below $\dot{V}O_{2peak}$ is used to derive a cut-off value to define a $\dot{V}O_2$-plateau (see section 3.2.1), it is assumed that the width of the confidence interval around a given mean $\Delta\dot{V}O_2$ does not change as the peak $\dot{V}O_2$ is approached. Given that the variability in $\dot{V}O_2$ increases as the period over which $\dot{V}O_2$ is determined (the sampling period) gets shorter (Myers et al., 1990), it is likely that this confidence interval will only be independent of WR if the sampling period that is used for WRs approaching the peak WR is the same as that which was used when the distribution of values for $\Delta\dot{V}O_2$ was derived. This is particularly important for a ramp test because for such a test the mean $\Delta\dot{V}O_2$ will also be a function of the sampling period (the ΔWR that is associated with this $\Delta\dot{V}O_2$ will increase as the sampling period increases). This means that for a ramp test the sampling period must always be pre-determined, and this in turn means that when the Douglas bag method is used there may be a period at the end of the test over which $\dot{V}O_2$ is not determined. For example, if a sampling period of 30 s is used and the subject stops the test at a time when the Douglas bag has been open for only 20 s the data from these final 20 s will effectively be lost. In contrast, when breath-by-breath data are collected it is possible to start from the end of the test and work backwards. This means that $\dot{V}O_2$ can be averaged over the pre-determined sampling period in such a way that the end of the final period will always coincide with the end of the test.

For a given sampling period, different conclusions may be drawn from a ramp test depending on whether $\dot{V}O_2$ is determined by the Douglas bag method or on a breath-by-breath basis. If a $\dot{V}O_2$-plateau is something that happens very late in such a test, the incidence of a $\dot{V}O_2$-plateau might be higher when $\dot{V}O_2$ is determined breath-by-breath than when the Douglas bag method is used. Alternatively, if $\dot{V}O_2$ does not plateau in such a test, the peak $\dot{V}O_2$ might be higher when $\dot{V}O_2$ is determined on a breath-by-breath basis.

Similarly, for a given method, different conclusions may be drawn depending on the length of the sampling period used. In the classic studies of Taylor et al., Mitchell et al., and Wyndham et al., a 60 s sampling period was used. However, if a $\dot{V}O_2$-plateau is something that happens very late in a ramp test, the incidence of a $\dot{V}O_2$-plateau might be higher when a relatively short sampling period such as 30 s is used. Alternatively, if $\dot{V}O_2$ does not plateau in such a test, the peak $\dot{V}O_2$ might be higher when such a short sampling period is used.

It is possible, however, that the increase in variability that would accompany a reduction in the sampling period (Myers et al., 1990) would be such that the presence of a $\dot{V}O_2$-plateau would be obscured. It is also possible that were $\dot{V}O_{2peak}$ to be defined as the highest single value of $\dot{V}O_2$ it would increase in response to a decrease in sampling period as a result of the increase in variability. Gomes et al. (1997) compared peak values for $\dot{V}O_2$ from raw breath-by-breath data with those determined by averaging over 5, 15, 20, 30, or 60 s. Although $\dot{V}O_{2peak}$ increased as the sampling period decreased (the peak $\dot{V}O_2$ was 5% higher for the 5 than for the 60 s averages), there were no significant differences in $\dot{V}O_{2peak}$ among the various sampling periods. No attempt was made to investigate the influence of sampling period on the incidence of a $\dot{V}O_2$-plateau in this study.

3.2.5 *Summary of published data*

The studies reviewed thus far provide some support for the notion that there is a limit to the $\dot{V}O_2$ an individual can attain, but the evidence is by no means conclusive. It is clear that the incidence of a $\dot{V}O_2$-plateau is low for continuous tests, and that such a plateau occurs more often when discontinuous tests are used. It is also clear that the peak $\dot{V}O_2$ is the same for the two types of test. It is reasonable to argue, therefore, that provided evidence is available to indicate that the highest $\dot{V}O_2$ attained in a DCT is in fact maximal, it is legitimate to treat the peak $\dot{V}O_2$ attained in a CT as a maximal $\dot{V}O_2$.

Further research is required to establish why the incidence of a $\dot{V}O_2$-plateau is higher for a DCT than for a CT and whether the highest $\dot{V}O_2$ attained in a DCT is in fact a maximal $\dot{V}O_2$. There is also a need, however, to address the theoretical question of whether a maximal $\dot{V}O_2$ might reasonably be expected to exist. Judging from the frequency with which a "$\dot{V}O_{2max}$" test is performed in a typical exercise physiology laboratory, it would appear that there is a common belief among physiologists that such a maximal $\dot{V}O_2$ either does or should exist. This may be a reflection of the fact that at about the same time as techniques for the assessment of "$\dot{V}O_{2max}$" were being refined, a strong theoretical argument for the existence of a maximal $\dot{V}O_2$ was developing.

3.3 Theoretical argument for the existence of a maximal $\dot{V}O_2$

3.3.1 *Background*

Hill's group may not have demonstrated that a maximal $\dot{V}O_2$ exists (see section 2.3), but they did present a theoretical argument to suggest that there should be a limit to the

$\dot{V}O_2$ an individual can attain. Hill and Lupton (1923, p. 155) wrote: "It is open to question whether the oxygen intake is limited by the heart or by the lungs. It is possible that, at the higher speeds of blood-flow, the blood is only imperfectly oxygenated in its rapid passage through the lung; on the other hand, the limit may be placed simply by the sheer capacity of the heart." They did not determine arterial oxyhaemoglobin saturation or cardiac output ($\dot{Q}_c$) in any of their studies, but they did perform some calculations which indicated that a $\dot{Q}_c$ of between 28 and 38 $L.min^{-1}$ would be required to support a $\dot{V}O_2$ of 4.175 $L.min^{-1}$ (the highest $\dot{V}O_2$ they observed in the course of their studies), and on the basis that this $\dot{Q}_c$ was much higher than anything that had been reported previously, they concluded (p. 154) that it is "impossible to be a good runner without possessing a powerful heart." Later, Hill et al. (1924b) investigated the effect of breathing a hyperoxic (~50% O_2) gas mixture on the $\dot{V}O_2$ that could be attained during standing running. Having found that $\dot{V}O_2$ was much higher in the hyperoxic condition, they concluded that some degree of desaturation must have occurred during the normoxic exercise.

Implicit in Hill and Lupton's argument is the idea that the $\dot{V}O_2$ that can be attained during running is limited not by the rate at which the muscles can use O_2 but by the rate at which the cardiovascular/respiratory system can supply it. Indirect support for this idea came from some classic studies, conducted in the 1960s, which showed that $\dot{Q}_c$ varied linearly with $\dot{V}O_2$ for both peak and sub-peak values of $\dot{V}O_2$. Åstrand et al. (1964) found that $\dot{V}O_2$ and $\dot{Q}_c$ were linearly related across a range of sub-$\dot{V}O_{2peak}$ WRs, whilst Saltin et al. (1968) showed that as $\dot{V}O_{2peak}$ varied with training and detraining so did the peak $\dot{Q}_c$. Furthermore, cross-sectional studies (Ekblom, 1969; Ekblom and Hermansen, 1968) revealed that among endurance athletes peak $\dot{Q}_c$ varies with $\dot{V}O_{2peak}$ and that these athletes attain peak values for both $\dot{Q}_c$ and $\dot{V}O_2$ that are much higher than those that sedentary individuals attain.

The above data were obtained during "whole body" exercise (running or cycling), and they were apparently interpreted as evidence that the $\dot{V}O_2$ which can be attained during such exercise is limited because $\dot{Q}_c$ is limited. The notion that the lungs might limit the $\dot{V}O_2$ that can be attained received little attention despite the fact that marked arterial desaturation was reported to occur during "maximal" exercise in some endurance athletes (Rowell et al., 1964). The reason for this was that other data were available which indicated that arterial O_2 saturation decreased little from rest to "maximal" exercise in both sedentary (Åstrand et al., 1964; Mitchell et al., 1958; Saltin et al., 1968) and highly trained (Ekblom and Hermansen, 1968) individuals. The result was that various studies were conducted in an attempt to demonstrate that the capacity of the skeletal muscle vasculature to dilate and receive blood flow is such that when at least two legs are involved in the exercise the heart is unable to supply the entire working muscle mass with a sufficient blood flow.

The argument, which has been presented in a series of publications by Saltin and associates (Saltin, 1986, 1988, 1990a, b; Saltin and Strange, 1992), is that for exercise involving a large muscle mass $\dot{V}O_2$ reaches a maximum because $\dot{Q}_c$ reaches a maximum and the a-v O_2 difference does not increase sufficiently to compensate. Evidence to support this argument comes from studies of one-legged vs. two-legged cycling (section 3.3.2), from studies of one-legged dynamic knee extensor exercise (section 3.3.4), and from studies which have demonstrated that there is competition for blood flow between different muscle groups during whole body exercise (section 3.3.5). The crucial assumptions are that $\dot{Q}_c$ is the primary determinant of muscle blood flow, at least for "whole body" exercise involving a given muscle mass (section 3.3.6), and that a maximal $\dot{Q}_c$ is reached during a progressive exercise test (section 3.3.8).

3.3.2 *One-legged vs. two-legged cycling*

In the 1970s, several studies were published that compared one- and two-legged cycling. The major finding was that peak values of $\dot{V}O_2$ (Davies and Sargeant, 1974; Gleser, 1973; Saltin et al., 1976; Stamford et al., 1978) and $\dot{Q}_c$ (Gleser, 1973; Stamford et al., 1978) for two-legged cycling were only 125-145 and ~115% of those for one-legged cycling. However a further important observation was that breathing a hyperoxic gas mixture ($F_IO_2 = 0.45$) increased two-legged $\dot{V}O_{2peak}$ by ~10% but had no effect on one-legged $\dot{V}O_{2peak}$ (Davies and Sargeant, 1974). Collectively these findings suggest that when exercise is performed in normoxia the peak $\dot{V}O_2$ is limited by the rate at which O_2 can be delivered to the working muscles for two- but not for one-legged cycling. Moreover, the observation that $\dot{V}O_{2peak}$ for two-legged cycling is <145% of that for one-legged cycling might suggest that the extent to which $\dot{V}O_2$ is limited during two-legged cycling is substantial. However, it should be recognised that it is not actually reasonable to expect the $\dot{V}O_{2peak}$ for two-legged cycling to reach 200% of that for one-legged cycling. This is partly because the active muscle mass for two-legged cycling will be <200% of that for one-legged cycling and partly because "resting $\dot{V}O_2$" will represent a relatively larger proportion of the total $\dot{V}O_2$ for one-legged exercise. In addition to the legs, the respiratory muscles, the myocardium, the muscles involved in supporting and stabilising the trunk, and other relatively inactive organs such as the liver and the brain, all use O_2 during cycling. For a given total $\dot{V}O_2$ ($\dot{V}O_{2total}$), the $\dot{V}O_2$ of the legs ($\dot{V}O_{2legs}$) will depend on the magnitude of this "extra" $\dot{V}O_2$. Theoretically, $\dot{V}O_{2peak}$ for two legged cycling should exceed that for one-legged cycling by an amount equivalent to the $\dot{V}O_{2legs}$ attained in this one-legged cycling. But if the size of the "extra" $\dot{V}O_2$ is not known for one-legged exercise, $\dot{V}O_{2legs}$ cannot be determined and nor, therefore, can the amount by which $\dot{V}O_{2peak}$ should increase when the second leg is added.

Klausen et al. (1982) determined leg blood flow ($\dot{Q}_{legs}$) and (femoral) a-v O_2 difference during one- and two-legged cycling, before and after a training programme in which each leg was trained separately. Prior to training, $\dot{Q}_{legs}$ was 8% higher, a-v O_2 difference was 4% lower, and "$\dot{V}O_{2legs}$" (a-v O_2 difference × $\dot{Q}_{legs}$) (per leg) was 4% higher for one- as opposed to two-legged cycling. However, post training, $\dot{Q}_{legs}$ was 23% higher, a-v O_2 difference was 6% higher, and $\dot{V}O_2$ was 16% higher for one-legged cycling. This effect was also reflected in the "whole body" data. For instance, whilst the peak values for $\dot{V}O_2$ and $\dot{Q}_c$ observed during two-legged cycling were 127 and 118% of those for one-legged exercise prior to training, after the training period the corresponding figures were 118 and 112%, respectively.

According to Klausen et al., their data indicate that blood flow to (and therefore O_2 uptake by) an exercising limb is compromised during two-legged exercise, particularly when trained legs are used in the exercise. However, when their leg data ($\dot{V}O_{2legs}$ = $\dot{Q}_{legs}$ × a-v O_2 difference) and their whole body data ($\dot{V}O_{2total}$ and $\dot{Q}_c$) are compared, inconsistencies emerge. For example, the (pre training) leg data suggest that the total $\dot{V}O_2$ for both legs (2 × $\dot{V}O_{2legs}$) should have been at least 1.18 $L.min^{-1}$ higher for the two-legged exercise, and yet $\dot{V}O_{2total}$ was in fact only 0.73 $L.min^{-1}$ higher. Assuming the leg data are accurate, the only possible explanation is that the $\dot{V}O_2$ of tissues other than those accounted for in the estimate of $\dot{V}O_{2legs}$ is relatively greater for one- than for two-legged cycling. Klausen et al. placed catheters in the iliac vessels, so it is likely that the venous blood they sampled would have drained most of the leg muscles involved in cycling. However, it may be that there are muscle groups which are particularly active during one-legged cycling, not directly in the development of power output but indirectly in a support/stabilisation role. The implication is that comparative data on $\dot{V}O_{2total}$ and $\dot{Q}_c$ for one- and two-legged cycling will always be difficult to interpret because the active muscle mass does not increase in a predictable fashion when the second leg is added. Nevertheless, Klausen et al.'s data (particularly the post training data) do indicate that $\dot{Q}_{legs}$ and $\dot{V}O_{2legs}$ are lower during two-legged exercise. Leg vascular resistance was higher during two-legged exercise, and it was suggested (Klausen et al., 1982, p. 983) that an "active local vascular constriction mediated via the sympathetic nervous system" was the most likely explanation.

3.3.3 *One-legged dynamic knee extensor exercise*

It is possible that during "maximal" two-legged cycling, $\dot{Q}_c$ does not increase sufficiently for blood pressure to be maintained in the face of a continuing drive for vasodilation in the active muscles. Were this the case, vasoconstriction would have to occur to prevent blood pressure from dropping. Moreover, it would have to occur in the active muscles because any other vascular bed that is able to constrict would already be maximally constricted during such exercise (Rowell, 1986). This would explain Klausen et al.'s findings, but the crucial assumption is that the capacity of the skeletal muscle vasculature to dilate and receive blood flow is such that the heart is unable to pump blood at a rate sufficient to meet the muscles' demands for blood flow when "maximal" two-legged cycling is performed.

In an attempt to determine the capacity of human skeletal muscle to receive a large blood flow, Andersen and Saltin (1985) determined femoral blood flow during one-legged dynamic knee extensor exercise. At the time, this was a novel exercise model, although it has since been used by various researchers (Bangsbo et al., 1990; Richardson et al., 1993, 1995b; Rowell et al., 1986). For Andersen and Saltin, the appeal of this model was that the exercise could be isolated to a well defined (and therefore quantifiable) muscle mass, for which cannularisation of the major artery and vein was possible. Furthermore, the assumption was that since the quadriceps is a small muscle group (average estimated mass of 2.3 kg for Andersen and Saltin's subjects) its blood flow would not be limited by $\dot{Q}_c$.

By 1985, many data had been published on $\dot{Q}_c$ during "maximal exercise", including data on elite endurance athletes (Ekblom, 1969; Ekblom and Hermansen, 1968). Data on muscle blood flow during exercise were, however, relatively scarce, and of those that were available many were obtained with the xenon clearance method, a method which dramatically underestimates flow (Cerretelli et al., 1984). Andersen and Saltin found that the peak blood flow attained during "maximal" exercise averaged 2.5 $L.min^{-1}$ per kg of muscle mass (2.5 $L.kg^{-1}.min^{-1}$) (muscle mass was estimated from anthropometric data). This flow rate was much higher than anything that had been reported previously for humans (c.f. Mellander and Johansson, 1968), and on the basis of these data they concluded (pp. 247-248) that "the capacity of the skeletal muscles by far exceeds that of the central circulation for supplying it with blood and oxygen, when a large fraction of the muscle mass is actively engaged in the exercise." Indeed they went on to claim that "in sedentary man ... only one-third of the muscle mass needs to be involved in intense exercise for the heart to reach its upper limit of cardiac output." This claim was apparently based on the assumption that a 70 kg man has a muscle mass of 30-35 kg and the observation (Hartley et al., 1969; Saltin et al., 1968) that peak $\dot{Q}_c$ is 18-22 L.min^{-1} in sedentary middle-aged men (see Saltin, 1990b). If one third of this muscle (10-12 kg) was active during exercise, the theoretical demand for blood flow (25-30 L.min^{-1} for a flow of 2.5 L.kg^{-1}.min^{-1}) would be considerably greater than the expected peak $\dot{Q}_c$ (18-22 L.min^{-1}).

Rowell et al. (1986) found that when progressive knee extensor exercise was performed in hypoxia (F_IO_2 = 0.10-0.11) leg blood flow increased from 2.73 (normoxia) to 3.09 L.kg^{-1}.min^{-1}. More recently, Richardson et al. (1993) found that when trained cyclists performed progressive knee extensor exercise following a protocol in which exhaustion was reached in 10-15 min peak quadriceps blood flow averaged 3.85 L.kg^{-1}.min^{-1} [c.f. earlier studies (Andersen and Saltin, 1985; Rowell et al., 1986) in which exhaustion was reached in 40-60 min]. Cardiac output during "maximal" running has been reported (Ekblom, 1969; Ekblom and Hermansen, 1968) to average 36 L.min^{-1} in a group of elite athletes (average body mass = 75 kg). Such a $\dot{Q}_c$ would be associated with a coronary blood flow of ~2 L.min^{-1} (Åstrand and Rodahl, 1986), and a further 2 L.min^{-1} would probably be "lost" in perfusing relatively inactive organs such as brain, liver, and skin, leaving 32 L.min^{-1} available to perfuse skeletal muscle. This means that 8.3 kg of muscle could potentially be perfused at a rate of 3.85 L.kg^{-1}.min^{-1}, which in turn means that to establish whether blood flow to the active muscles is likely to be limited by $\dot{Q}_c$ during "maximal" running, it is necessary to establish the extent to which the total active muscle mass is likely to exceed 8.3 kg when such an athlete performs a "maximal" run.

3.3.4 *Estimating the active muscle mass for "whole body" exercise*

Sloniger et al. (1997b) used exercise-induced contrast shifts in magnetic resonance images to estimate the active muscle mass for supra-$\dot{V}O_{2peak}$ treadmill running. They found that their active female subjects recruited 5.6 and 6.1 kg (67 and 73%) of their total lower extremity muscle mass during level and uphill running respectively. These masses represent 12 and 13% of the lean body mass (LBM) for these subjects, so the equivalent muscle mass for a 75 kg male athlete (assuming a body fat percentage of 10%) would be 8.1 or 8.8 kg. These figures represent just lower extremity muscle, but the arms, the respiratory muscles, and the stabilising muscles of the trunk would also be active to some extent during a "maximal" run. Indeed, for a 75 kg man, the mass of the respiratory muscles alone would be ~2.2 kg (Rochester, 1992), and these muscles would be very active during "maximal" exercise. It therefore seems reasonable to conclude that the total active muscle mass for either level or uphill running would exceed 8.3 kg in this athlete, and that vasoconstriction would have to occur in his active muscles during such running if his $\dot{Q}_c$ was limited to 36 L.min^{-1}.

Bonde-Petersen et al. (1975) estimated muscle mass from measurements of total body potassium in a group of healthy males (n = 16). The mean body mass was 71.7 kg, and the estimated muscle mass averaged 27.4 kg. However, it was suggested that no more than 70% of this muscle mass would be active during cycling, and that the active muscle mass for these subjects would therefore average 19.2 kg, or 27% of body mass. Medbø and colleagues (Medbø and Tabata, 1989, 1993; Medbø et al., 1988) have repeatedly stated that the active muscle mass should represent ~25% body mass for cycle ergometer exercise, although it is unclear whether they consider the respiratory muscles to be included in this 25%. Sloniger et al.'s data suggest, however, that a 75 kg male athlete would recruit 8-9 kg of leg muscle during running (see above).

For his active muscle mass to equal 25% of his body mass this athlete would have to recruit either 8-9 or 10-11 kg of muscle from the arms and the trunk, depending on whether this 19 kg does or does not include the respiratory muscles. It is unlikely that such a large amount of upper body muscle would be recruited, and hence it is reasonable to suggest that either the previous estimates of active muscle mass are too high or those derived from Sloniger et al.'s data are too low. Sloniger et al. (1997b) acknowledged that they used relatively new technology and that they may have underestimated the active muscle mass slightly. However, it should also be acknowledged that when the one-legged knee extensor exercise model has been used, it has been assumed that the entire muscle mass is active. Whether this is a reasonable assumption is uncertain, given Sloniger et al.'s data, and if the active muscle mass has been overestimated in these studies, the true peak blood flow (per kg muscle mass) will have been underestimated. As yet, Sloniger et al.'s is the only study in which a serious attempt has been made to estimate the active muscle mass for supra- $\dot{V}O_{2peak}$ running. Their approach appears to have potential, but further research is required.

3.3.5 *Competition for blood flow among different muscle groups*

Secher et al. (1977) were the first to present evidence that different muscle groups compete for blood flow during whole body exercise. They found that when (sub- $\dot{V}O_{2peak}$) arm exercise was added to ongoing (sub- $\dot{V}O_{2peak}$) leg exercise, vasoconstriction occurred in the legs and thus leg blood flow decreased. Although cardiac output increased slightly (from 21 to 23 $L.min^{-1}$) when the arm exercise was added, this increase was not sufficient to meet the demands of the arm muscles. It would appear that the arms were supplied with blood flow at the expense of the legs, and that the purpose of this redistribution of blood flow was to prevent a drop in blood pressure.

Strange et al. (1990) conducted a very similar experiment, but they failed to detect a decrease in $\dot{Q}_{legs}$. Adding (sub- $\dot{V}O_{2peak}$) arm exercise had no effect on $\dot{Q}_{legs}$, regardless of the intensity of the ongoing leg exercise (equivalent to ~50 or ~90% $\dot{V}O_{2peak}$). For the lower intensity, leg vascular resistance increased when arm exercise was added, but for the higher intensity no change in resistance was observed. Strange et al.'s findings are consistent with those of several similar studies (Richardson et al., 1995a; Richter et al., 1992; Savard et al., 1989), all of which found that $\dot{Q}_{legs}$ remained unchanged when arm exercise was added. In these studies, evidence of increased sympathetic excitation of leg vasculature (increased noradrenaline spillover) was obtained, but no increase in vascular resistance was observed.

Harms et al. (1997) manipulated the work of breathing in an attempt to establish whether it is possible for the respiratory muscles to "steal" blood flow from the leg muscles during "maximal" exercise. Subjects were studied during cycling at power outputs calculated to elicit 95-100% of $\dot{V}O_{2peak}$, whilst the work of breathing (Wb) was either increased (by applying an inspiratory resistive load) or decreased (by means of a proportional-assist ventilator) relative to the control condition (standard respiratory apparatus). When Wb was increased, $\dot{Q}_{legs}$ decreased relative to control values. Furthermore, because O_2 extraction across the legs remained constant (~90% of the O_2 delivered to the legs was extracted in each condition), $\dot{V}O_{2legs}$ also decreased. When Wb was decreased, $\dot{Q}_{legs}$ increased (relative to control), as did $\dot{V}O_{2legs}$, but the increase in $\dot{V}O_{2legs}$ was small (relative to the decrease observed when Wb was increased), possibly because the power output was such that the O_2 requirement of the legs could virtually be satisfied in the control condition. Leg vascular resistance changed in parallel with Wb, as did noradrenaline spillover, but no changes in mean arterial pressure (MAP) were observed.

Harms et al. suggested that when the Wb was increased blood flow was made available to the respiratory muscles at the expense of the legs. In an attempt to explain why they were successful in detecting a reduction in $\dot{Q}_{legs}$ when others (Savard et al., 1989; Richardson et al., 1995a; Richter et al., 1992) had been unsuccessful, they suggested that, in comparison to the muscles of the arms, the respiratory muscles might compete very effectively for their "share" of a limited $\dot{Q}_c$. Unfortunately, however, Harms et al. did not determine $\dot{Q}_c$ in any condition. It is impossible therefore to exclude the possibility that the changes observed in $\dot{Q}_{legs}$ simply reflect changes in $\dot{Q}_c$. They do discuss the likely impact that applying an inspiratory resistive load would have on $\dot{Q}_c$, but although each of the factors they mention would be likely to have an enhancing effect on $\dot{Q}_c$, they conclude that it is hard to predict exactly what the effect would be. They suggest that had $\dot{Q}_c$ increased when Wb was increased (relative to control), $\dot{V}O_{2total}$ (which was unchanged) would also have increased. However, $\dot{V}O_{2total}$ did decrease when Wb was decreased (relative to control), and they do concede that $\dot{Q}_c$ might have decreased in this situation.

3.3.6 *Cardiac output as a determinant of muscle blood flow*

Evidence that, for a given active muscle mass, $\dot{Q}_{legs}$ is determined by $\dot{Q}_c$ comes from studies in which $\dot{Q}_c$ has been manipulated pharmacologically. Pawelczyk et al. (1992) found that in response to acute adrenergic β_1-blockade, which reduced heart rate and thus $\dot{Q}_c$ during cycling, both $\dot{Q}_{legs}$ and leg vascular conductance decreased. Mean arterial pressure was unchanged, but leg noradrenaline spillover increased, suggesting that sympathetically mediated vasoconstriction occurred in the legs to prevent a drop in blood pressure. Conversely, Schmidt et al. (1995) found that when the ability to increase $\dot{Q}_c$ during exercise was enhanced (by digoxin) in a group of patients with heart failure, $\dot{Q}_{legs}$ and $\dot{Q}_c$ increased in concert.

3.3.7 *The potential impact of arterial desaturation*

Recent studies (Dempsey et al., 1984; Martin et al., 1992; Powers et al., 1988, 1992) have demonstrated that marked desaturation [decrease of >18 mm Hg in PaO_2 or >4% in arterial saturation (relative to resting levels) (Powers et al., 1993)] occurs in 40-50% of highly trained endurance athletes during "maximal" exercise. Such desaturation would alter the relationship between $\dot{Q}_c$ and the rate at which O_2 is delivered to the working muscles. That is, as arterial saturation decreases (for a given haemoglobin (Hb) concentration) so does the rate of O_2 delivery associated with a particular $\dot{Q}_c$.

It is conceivable that a plateau in the O_2 delivery rate (a function, primarily, of the arterial O_2 content and the $\dot{Q}_c$) could occur in the absence of a plateau in $\dot{Q}_c$, although this would only be the case if, for a given increase in WR, the decrease in arterial O_2 content (a function of [Hb] and % saturation) was sufficient to offset the increase in $\dot{Q}_c$. Limited data are available (Powers et al., 1988) to indicate that such a situation might occur in some individuals. However, whilst the reason why the O_2 delivery rate plateaus might differ between these individuals and those (the majority) in whom arterial saturation does not decrease appreciably, the response to this plateau should still be the same. That is, $\dot{V}O_2$ should plateau provided the a-v O_2 difference also plateaus.

3.3.8 *Evidence that cardiac output reaches a maximum in progressive exercise*

Typically, $\dot{Q}_c$ increases as a linear function of WR (Åstrand et al., 1964; Gledhill et al., 1994; Krip et al., 1997). However, for the $\dot{V}O_2$ that can be attained during "whole body" exercise to be limited by $\dot{Q}_c$, there must be a maximal $\dot{Q}_c$. The studies that have found that $\dot{Q}_{legs}$ is decreased when arm (Secher et al., 1977) or respiratory (Harms et al., 1997) muscle work is increased provide indirect evidence that such a maximal $\dot{Q}_c$ does in fact exist, but more direct evidence is also available. For instance, Mitchell et al. (1958) reported that in 6 subjects who demonstrated a clear plateau in $\dot{V}O_2$ with increasing WR, $\dot{Q}_c$ actually decreased when the WR was increased beyond that at which the maximal $\dot{V}O_2$ was attained. In these subjects, a-v O_2 difference increased when the WR was increased, but this increase was balanced by the decrease in $\dot{Q}_c$ to the extent that $\dot{V}O_2$ actually decreased slightly. These data are of interest, particularly as they apply to treadmill running, but it should be emphasised that there are problems associated with this study (see section 3.2.1). No other data are available for running, but in a recent study of cycle ergometer exercise Stringer et al. (1997) found that $\dot{Q}_c$ plateaued in the closing stages of a progressive (ramp) test. Oxygen uptake did not plateau along with $\dot{Q}_c$ in this study because a large increase in the a-v O_2 difference occurred after $\dot{Q}_c$ had plateaued. Nevertheless, this study does show that $\dot{Q}_c$ can plateau during progressive exercise.

3.3.9 *Hypothetical sequence of events that might explain the attainment of a maximal $\dot{V}O_2$ during "whole body" exercise*

When a progressive test is performed, $\dot{Q}_c$ and $\dot{V}O_2$ initially increase with WR in an essentially linear fashion. However, if the exercise involves a large fraction of the individual's total muscle mass, there should come a time when $\dot{Q}_c$ becomes limited and the $\dot{Q}_c$-WR relationship plateaus. From this point onwards, the blood flow that the working muscles demand will exceed that which the heart is able to supply, and hence vasoconstriction will have to occur in the active muscles so that blood pressure does not drop (Rowell, 1986). In theory, the extent of this vasoconstriction should increase in proportion to the active muscle mass, and indeed in practice plasma noradrenaline levels during "maximal" exercise increase as the active muscle mass increases, being highest in combined arm + leg exercise (Savard et al., 1989).

If $\dot{Q}_c$ plateaus and vasoconstriction occurs in the active muscles [it is presumed that other vascular beds are already maximally constricted (Rowell, 1986)], $\dot{Q}_{legs}$ should also plateau. That a plateau in $\dot{Q}_{legs}$ can occur in humans was demonstrated by Knight et al. (1992) who studied only subjects in whom a plateau in whole body $\dot{V}O_2$ was consistently observed and found that $\dot{V}O_{2legs}$ actually plateaued along with $\dot{V}O_{2total}$ because both $\dot{Q}_{legs}$ and leg a-v O_2 difference plateaued ($\dot{Q}_c$ was not measured in this study). It has previously been suggested that $\dot{V}O_{2max}$ is set by a peripheral (muscle) diffusion limitation, secondary to a limited O_2 delivery rate (Hogan et al., 1989; Roca et al., 1989; Wagner, 1992, 1995, 1996), and these results would certainly be consistent with this view. Given that $\dot{Q}_{legs}$ plateaus, whether the $\dot{V}O_2$-WR relationship plateaus in a progressive test will presumably depend on whether exercise is continued up to, and for a sufficient period beyond, the point at which such a diffusion limitation is reached. Whether exercise can be continued beyond this point (i.e. beyond the WR at which $\dot{V}O_2$ starts to plateau) will depend on whether energy can be derived from anaerobic metabolism at a rate sufficient to support the increase in WR. Hence both O_2 delivery and anaerobic energy production must be involved in determining the peak WR that can be reached on a progressive test.

3.3.10 *Alternative explanations*

It should be stressed that the above sequence of events represents just one possible explanation for a plateau in the $\dot{V}O_2$-WR relationship. Whilst some data are available to support the argument on which it is based, the evidence to indicate that this sequence can realistically be expected to occur in the majority of individuals is by no means conclusive. Evidence to indicate that each of the components in this sequence can occur in humans is available, but the complete sequence is, as yet, hypothetical.

It should also be stressed that a plateau in the $\dot{V}O_2$-WR relationship is not always observed in a progressive treadmill test (see section 3.2), and that there are several possible explanations for why such a plateau may not be observed. Some of these are considered in the following chapter (Chapter 4).

CHAPTER 4: PROBLEMS WITH THE NOTION THAT AN UPPER LIMIT FOR $\dot{V}O_2$ IS, OR SHOULD BE, REACHED DURING PROGRESSIVE EXERCISE

4.1 Introduction

The problems with Hill's group's work have already been outlined (see Chapter 2). There are, however, other problems with the notion that a maximal $\dot{V}O_2$ is typically reached during progressive exercise. Although there have been others (Myers et al., 1989, 1990; Rowland, 1995), the main critic of the $\dot{V}O_{2max}$ concept has been the South African physiologist Tim Noakes. Over the last 10 years, Noakes (1988, 1997, 1998) has authored a series of papers in which he has highlighted some of the problems with Hill's group's original work and developed the argument that factors unrelated to O_2 supply might be important in determining the peak WR that can be reached in a progressive exercise test, and thus $\dot{V}O_{2peak}$. Some of this work will be reviewed in this chapter. However, the aim is to provide a comprehensive commentary on the problems associated with the $\dot{V}O_{2max}$ concept and the literature relevant to these problems. It is not sufficient, therefore, merely to review Noakes' work. Rather it is necessary to review studies other than those that he has mentioned and to develop arguments other than those that he has presented. In particular, it is necessary to outline the assumptions that underpin current approaches to the assessment of $\dot{V}O_{2max}$, many of which will be tested in Study 1 (Chapter 7).

4.2 Terminology

It has been suggested (Armstrong and Welsman, 1994; Davis, 1995) that the term maximal $\dot{V}O_2$ ($\dot{V}O_{2max}$) should be reserved for situations in which a $\dot{V}O_2$-plateau occurs, and that in situations where no plateau occurs the term peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) should be used. The term $\dot{V}O_{2peak}$ is currently used by some authors (Barnett et al., 1996; Barstow et al., 1996; Gastin and Lawson, 1994a, b; Green et al., 1996; Londeree et al., 1997), particularly those who work with children (Armstrong et al., 1996, 1998; Cureton et al., 1997; Fredriksen et al., 1998; Hebestreit et al., 1998; Pianosi et al., 1995;

Sloniger et al., 1997a; Welsman et al., 1996), but more often than not the term $\dot{V}O_{2max}$ is used to describe the highest $\dot{V}O_2$ attained in a continuous test, regardless of whether a $\dot{V}O_2$-plateau is observed. Whether this use of the term $\dot{V}O_{2max}$ reflects a conscious belief among those who use it that the peak $\dot{V}O_2$ attained in a progressive test is a maximal $\dot{V}O_2$ is unknown. However, given that one of the aims of this thesis is to investigate whether the peak $\dot{V}O_2$ attained in such a test is in fact maximal, it is essential that a distinction is made between a maximal and a peak $\dot{V}O_2$. Throughout this thesis, care has been taken to ensure that the term $\dot{V}O_{2max}$ is reserved for those situations in which there is good reason to believe that the peak $\dot{V}O_2$ is indeed a maximal one. For those situations in which this is not the case the term $\dot{V}O_{2peak}$ (or the phrase "the peak $\dot{V}O_2$") has been used, and as a result some relatively unfamiliar terms have been used. For example, exercise intensity has been classified as sub-$\dot{V}O_{2peak}$ or supra-$\dot{V}O_{2peak}$. The corresponding terms that would typically be found in the literature, i.e. sub-maximal and supra-maximal, will almost certainly be more familiar. However, using these terms assumes that the peak $\dot{V}O_2$ attained is a maximal one, and hence they should not be used when evidence that this is indeed the case (i.e. a plateau-in $\dot{V}O_2$ that is not an artefact of the test protocol) is lacking.

There is a further problem concerning terminology that is particularly relevant to a thesis on the assessment of $\dot{V}O_{2max}$ in runners, namely that it is difficult to quantify the external mechanical work done in running (Cavanagh and Kram, 1985). The term work rate (WR) has been used in the present thesis to refer to an increase in grade or speed for running or an increase in power output for cycling. It will continue to be used in this way throughout the thesis. However, the term WR will not be used when it is clear which of these 3 variables is the relevant one. For example, when a progressive test is mentioned, the $\dot{V}O_2$-running speed relationship will be referred to if the test is a CGIS test and the $\dot{V}O_2$-treadmill grade relationship will be referred to if it is a CSIG test; the $\dot{V}O_2$-WR relationship will only be referred to when it is necessary or desirable to refer to a progressive test without specifying the test type. Whilst it is acknowledged that it is not really appropriate to use the term WR in the context of running, it was felt to be necessary to adopt such a term because there are several themes related to the $\dot{V}O_{2max}$ concept that could usefully be discussed in a general context were appropriate terminology available.

4.3 Problems with the use of grade incremented tests for the assessment of $\dot{V}O_{2max}$

4.3.1 *Grade incremented vs. speed incremented tests*

Following Taylor et al.'s 1955 paper, the majority of studies have used CSIG protocols. Since this approach deals with responses to increases in gradient it is of limited value when the aim is to identify the physiological determinants of track (i.e. level) running performance. Current models assume that $\dot{V}O_2$ increases with running ***speed*** until a critical speed is reached beyond which no further increase occurs. The validity of these models can only be assessed by using CGIS protocols.

4.3.2 *Effect of treadmill inclination on the incidence of a $\dot{V}O_2$-plateau*

The finding of Taylor et al. (1955) that the incidence of a $\dot{V}O_2$-plateau is higher for a CSIG than for a CGIS test performed on a level treadmill is important. However, since 1955, only 3 studies (Davies et al., 1984; Jones and Doust, 1996; Mayhew and Gross, 1975) have been published which have compared a CSIG with a CGIS protocol and commented on the incidence of a $\dot{V}O_2$-plateau for the two protocols. Moreover, of these 3 studies, one (Jones and Doust, 1996) gave no information on how a $\dot{V}O_2$-plateau was defined and another (Davies et al., 1984) applied Taylor et al.'s cut-off value in situations where it was not applicable. The remaining study (Mayhew and Gross, 1975) focused on 10 well-trained runners and compared a CSIG and a CGIS (0% grade) protocol. Having presented plots of $\dot{V}O_2$ vs. time for each runner and for each protocol, Mayhew and Gross concluded that 50% of subjects demonstrated a plateau, regardless of the way in which the WR was incremented.

4.3.3 *Effect of treadmill inclination on peak physiological responses*

Liefeldt et al. (1992) studied well-trained runners and compared the physiological responses to 2 CGIS tests, one where the treadmill grade was maintained at 0% and another where it was maintained at -5.25%. As expected, they found that subjects reached a higher peak speed in the downhill test. However, the increase in peak speed was small relative to the decrease in the $\dot{V}O_2$ required to run at a given speed, and as a result the peak values attained for $\dot{V}O_2$ (67.8 vs. 57.8 $ml.kg^{-1}.min^{-1}$; $\Delta = 17\%$), minute ventilation ($\dot{V}_E$) (125.4 vs. 104.1 $L.min^{-1}$; $\Delta = 20\%$), respiratory exchange ratio (RER) (1.08 vs. 0.97; $\Delta = 11\%$), and blood lactate concentration ([Bla]) (7.4 vs. 4.1 $mmol.L^{-1}$; $\Delta = 80\%$) were much lower for the downhill test. No data were presented on the incidence of a $\dot{V}O_2$-plateau. However even without these data there is evidence to suggest that, at least during downhill running, the subjects were unable to run sufficiently fast to reach $\dot{V}O_{2max}$. Having noted that the peak stride frequency was the same for the two tests, Liefeldt suggested (p. 495) that "stride frequency or the rate of limb recovery or both" may have limited the peak speed for the downhill test.

These findings are important because they show that there are situations in which factors other than an inadequate supply of oxygen and the associated demand for anaerobic metabolism can limit the speed a runner can reach on a progressive test. Whilst it is unclear exactly what prevented the subjects from reaching a higher speed in the downhill test, it is clear that the reason they terminated this test was not that they reached a limiting $\dot{V}O_2$ and were unable to supply energy anaerobically at a rate sufficient to allow an increase in running speed. In other words, it is clear that the peak speed for the downhill test was limited by non-metabolic factors.

Although Liefeldt et al. went on to suggest that the peak speed was probably limited in a similar way for the horizontal test, no data were presented in support of this suggestion. It is possible that the peak speed is limited by non-metabolic factors when a CGIS test is performed on a level treadmill but that this is not the case when such a test is performed on an uphill treadmill. Were this the case, it would be expected that the peak values for $\dot{V}O_2$, RER, and [Bla] would be higher for the uphill test. However, were similar peak values for these variables to be attained in both tests, it could reasonably be concluded that the factors which determine the peak WR that can be reached are similar for both level and uphill running.

Very few investigators have used a speed incremented protocol with the treadmill grade set at anything other than 0%, but it is possible to get an indication of whether the peak WR reached in a progressive test is limited by similar factors for both level and uphill running by comparing the peak values of $\dot{V}O_2$, RER, and [Bla] for a CSIG and a (0% grade) CGIS test. A few of the studies (Molnar et al., 1974; Weltman, 1982; Weltman et al., 1990) that have compared a horizontal protocol with an inclined protocol have been designed in such a way that not only the inclination of the treadmill but also the rate of WR increase or the test duration has differed markedly between the two types of protocol. In addition, one study (Sucec, 1981) gave no information on either of these factors. All of these studies have been excluded from analysis because it has been demonstrated (Buchfuhrer et al., 1983) that both factors can influence the peak physiological responses for a progressive test. (It is difficult to say which factor is the more important because in the study cited both factors were manipulated simultaneously.)

Excluding these 3 studies leaves 9 studies, of which 6 (Åstrand and Saltin, 1961a; Hermansen and Saltin, 1969; Jones and Doust, 1996; Mayhew and Gross, 1975; Sloniger et al., 1997b; Taylor et al., 1955) found that a higher $\dot{V}O_2$ could be attained on an inclined protocol, 2 found no effect of treadmill inclination on the peak $\dot{V}O_2$ attained (Davies et al., 1984; Kasch et al., 1976;), and 1 found a higher $\dot{V}O_2$ could be attained on a horizontal protocol (Wilson et al., 1979). In this last study, the belt speed was held constant while the WR was increased either by increasing the treadmill grade or by adding weight to a pulley system that applied a retarding force to the runner. A higher speed was maintained in the weight incremented protocol (18.0 vs. 11.3 $km.h^{-1}$), but the well trained runners who served as subjects would still have reached much higher speeds had they completed a CGIS protocol on a level treadmill with no added weight. It can be concluded, therefore, that this study is of no relevance to the question of whether peak speed is likely to be limited by non-metabolic factors during (unweighted) level running.

One of the studies that reported a higher peak $\dot{V}O_2$ for the inclined protocol (Mayhew and Gross, 1975) and one of the studies that reported no difference in peak $\dot{V}O_2$ between the protocols (Kasch et al., 1976) also reported peak values for RER, but both of these studies reported no effect of treadmill inclination on the peak RER attained. Similarly, one of the studies that reported a higher peak $\dot{V}O_2$ for the inclined protocol (Hermansen and Saltin, 1969) and one of the studies that reported no difference in peak $\dot{V}O_2$ between the protocols (Davies et al., 1984) also reported peak values for [Bla]. Again, both these studies reported no effect of treadmill inclination on the peak [Bla], although in the study of Hermansen and Saltin (1969) the mean peak [Bla] was 2.2 mmol.L^{-1} higher (14.3 vs. 12.1 mmol.L^{-1}) on the inclined protocol (this difference did not reach statistical significance for the 6 subjects studied). It is important to recognise that the differences in $\dot{V}O_{2peak}$ which have been reported for uphill vs. level running are small relative to that which was reported by Liefeldt et al. (1992) for level vs. downhill running. Indeed, whereas Liefeldt et al. reported a difference of 10 ml.kg^{-1}.min^{-1} (17%) in peak $\dot{V}O_2$ between downhill (-5.25%) and level running, the reported differences in peak $\dot{V}O_2$ between level and uphill running range from ~3 (Mayhew and Gross, 1975; Sloniger et al., 1997b) to ~6% (Jones and Doust, 1996).

There are two possible explanations for this observation. The first assumes that the running speed a subject can reach on a horizontal or a downhill treadmill is limited by non-metabolic factors but that this limitation is no longer present when the subject runs at even a very moderate uphill grade. The second assumes that non-metabolic factors limit the running speed a subject can reach during downhill running only and that the small increase in peak $\dot{V}O_2$ that is observed when the treadmill is inclined is simply a reflection of the fact that the active muscle mass is higher for uphill than for level running. If the first of these explanations is correct, the incidence of a $\dot{V}O_2$-plateau and the peak values for $\dot{V}O_2$, RER, and [Bla] should all be higher for a CSIG test or a CGIS test performed at a moderate uphill grade than for a CGIS test performed on a horizontal treadmill, even if the grade which is maintained throughout the uphill CGIS test or reached in the CSIG test is very moderate. However, if the second is correct, no differences in RER or [Bla] should be observed when a CSIG test or a CGIS test performed at a moderate uphill grade is compared with a similar test performed on a horizontal treadmill.

Those studies that have reported peak values for RER (Kasch et al., 1976; Mayhew and Gross, 1975) and [Bla] (Davies et al., 1984) to be no higher for a CSIG test in which a substantial (~10%) grade is reached than for a CGIS (0% grade) test would appear to provide support for the second explanation. So too would the finding (Taylor et al., 1955) that for those subjects in whom a plateau in the $\dot{V}O_2$-WR relationship was observed for both a CSIG and a CGIS (0% grade) test, the peak $\dot{V}O_2$ was ~5% higher for the CSIG test. Taylor et al.'s explanation was that a greater muscle mass was recruited during the uphill running. A similar explanation was favoured by Åstrand and Saltin (1961a), who found that the peak $\dot{V}O_2$ for uphill was 4.5 % higher than for uphill than for level running.

Hermansen (1973) compared uphill running with cycle ergometer exercise. He showed that the higher peak $\dot{V}O_2$ attained during uphill running was consequent to a higher cardiac output (the a-v O_2 difference was the same for the two types of exercise), and that both mean arterial pressure and total peripheral resistance were lower during "maximal" (uphill) running than during "maximal" cycling. The lower total peripheral resistance observed during uphill running can be seen as consistent with the recruitment of a greater muscle mass as long as it is assumed that the available capillary volume increases in concert with the active muscle mass. This lowering of total peripheral resistance would, in turn, facilitate an increase in cardiac output through a reduction in afterload, particularly as increasing the active muscle mass should increase the effectiveness of the muscle pump and thus facilitate an enhanced venous return. Data indicating that the muscle mass is higher for uphill than for level running have recently been published (Sloniger et al., 1997b) (see section 3.3.4).

4.4 $\dot{V}O_2$ kinetics during treadmill running: implications for the assessment of $\dot{V}O_{2max}$

4.4.1 *Potential impact of $\dot{V}O_2$ kinetics*

The finding that the incidence of a $\dot{V}O_2$-plateau is higher for a DCT than for a CT (Duncan et al., 1997; Rivera-Brown et al., 1994; Sheehan et al., 1987) can be explained if it is assumed that the effect of the rest periods is to ensure that anaerobic metabolism can be sustained at a relatively high rate throughout each of the heaviest WRs. This would appear to be a reasonable assumption, given that the ability to generate energy anaerobically should be at least partially restored while the subject rests between stages. However, an alternative explanation has been proposed by Noakes (1997), who argues that a $\dot{V}O_2$-plateau observed in the type of DCT that is typically used may be an artefact of the testing protocol.

Noakes' criticism was directed at the DCT used by Mitchell et al. (1958), but since a similar test has been used in various other studies (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979; Sheehan et al., 1987; Taylor et al., 1955) it also has a wider application. Noakes (1997, p. 578) points out that "the only physiological model which allows conclusions to be drawn from the testing protocol of Mitchell et al.", in which $\dot{V}O_2$ was determined over the final minute of each 2.5 min stage, "is one in which $\dot{V}O_2$ rises very rapidly at the onset of exercise, reaching its maximum within 90 s". After suggesting that this model might be incorrect, he notes that "an apparent 'plateau phenomenon' would occur ... if the initial rate of increase in $\dot{V}O_2$ were the same for all the high work rates that they studied." The point here is that if >90 s is required for $\dot{V}O_2$ to reach its final value and the initial rate of increase in $\dot{V}O_2$ is the same (in absolute terms) for all of these work rates, the time taken for $\dot{V}O_2$ to reach its final value will increase as this final $\dot{V}O_2$ increases with increasing WR. An artificial "plateau" might therefore be observed, not because the final $\dot{V}O_2$ ceases to increase linearly with WR but because the difference between the final $\dot{V}O_2$ and the average $\dot{V}O_2$ determined from 1.5 to 2.5 min after the onset of exercise starts to increase.

4.4.2 *Early studies of $\dot{V}O_2$ kinetics during exercise*

Hill and Lupton (1923) presented $\dot{V}O_2$ data on Hill himself for running speeds of 10.9, 12.2, and 16.0 km.h^{-1}, from which they concluded (p.150) that $\dot{V}O_2$ rises rapidly at the start of exercise, "reaching its final ... value in 100 to 150 secs." Interestingly they also reported that a gradual rise in Hill's $\dot{V}O_2$ occurred from the 3rd to the 18th minute of a prolonged run at 14.4 km.h^{-1}. This they attributed to "a painful blister causing inefficient movement" (p. 155).

Mitchell et al. cite three studies (Donald et al., 1955; Robinson, 1938; Taylor et al., 1955) as justification for their decision to determine $\dot{V}O_2$ from 1.5 min to 2.5 min of exercise. Both Robinson (1938) and Taylor et al. (1955) studied treadmill running, whilst Donald et al. (1955) studied cycle ergometer exercise. Robinson presented a graph showing mean $\dot{V}O_2$ as a function of time for an exhaustive run. Although the time to exhaustion for individual subjects ranged from 2 to 5 min, mean data were presented for each of 10 different age groups over the entire 5 minute period. The graphs suggest that in all but the oldest subjects $\dot{V}O_2$ increased rapidly during the first 1.5 min of the run. Thereafter, $\dot{V}O_2$ increased slightly from 1.5 to 3 min, at which point an apparent steady state was reached. It is unclear, however, whether the mean data presented apply to all subjects or just to those who completed the full 5 min. It has since been shown (Åstrand and Saltin, 1961b; see also section 4.4.5.1) that the rate at which $\dot{V}O_2$ increases at the start of exercise is faster for exercise that can be sustained for ~2 min than for that which can be sustained for ~6 min. It is possible, therefore, that were a 5 min exhaustive treadmill run to be performed the actual rate of increase in $\dot{V}O_2$ would be slower than that which would be predicted on the basis of Robinson's graph. On the other hand, Taylor et al. (1955, p. 74) justified their use of a DCT in which $\dot{V}O_2$ was determined from 1.75 to 2.75 min of each stage with the observation that, "under conditions which would elicit a maximal oxygen intake", the mean $\dot{V}O_2$ was the same, regardless of whether expirate was collected from 1.75-2.75 or from 2.75-3.75 min after the onset of exercise.

Donald et al. (1955) determined $\dot{V}O_2$ during 5 min of exercise for which the mean $\dot{V}O_2$ averaged over the last 3 min varied from ~8 to ~30 $ml.kg^{-1}.min^{-1}$. Their conclusion was that $\dot{V}O_2$ attained a steady state after the first minute of exercise. However, their data show not only that $\dot{V}O_2$ typically increased between the 2nd and the 3rd minute but also that this increase was most pronounced for the highest exercise intensity.

Several studies investigating the kinetics of the $\dot{V}O_2$ response ($\dot{V}O_2$ kinetics) for cycle ergometer exercise were conducted during the 1960s. Some of these found that $\dot{V}O_2$ kinetics were affected by exercise intensity (Gilbert et al., 1967; Wasserman et al., 1967), but others found that these kinetics were independent of exercise intensity (Cerretelli et al., 1966; Whipp, 1971). Whipp and Wasserman (1972) went some way towards clarifying the situation. They showed that whilst the time taken for $\dot{V}O_2$ to reach a steady state was independent of WR for moderate exercise intensities it increased with WR for WRs above that at which lactate started to accumulate in the blood [i.e. WRs above that at which the lactate threshold (LT) occurred].

4.4.3 *Current conceptions of $\dot{V}O_2$ kinetics during exercise*

Many data have now been published which agree with those of Whipp and Wasserman (1972). Indeed, it is now reasonably well established (Barstow, 1994; Barstow and Molé, 1991; Barstow et al., 1993; Paterson and Whipp, 1991; Whipp, 1994) that whereas for sub-LT WRs $\dot{V}O_2$ typically reaches a steady state within 3 min of the onset of exercise, for supra-LT WRs it may take longer than 3 min for $\dot{V}O_2$ to reach a steady state, or indeed a steady state may not be attained at all before the subject becomes exhausted and terminates the exercise. It should be recognised, however, that current conceptions about $\dot{V}O_2$ kinetics are based on data that were obtained during cycle ergometer exercise, and that, to date, only a few studies have compared $\dot{V}O_2$ kinetics for running and cycling (see section 4.4.4).

For cycle ergometer exercise, it has been shown that the $\dot{V}O_2$ response to a constant WR, "square wave" exercise bout can be well described by a two component model (Barstow and Molé, 1991; Barstow et al., 1993). The two components are a primary (fast) component and a secondary (slow) component (the $\dot{V}O_2$ slow component). Both are exponential functions of time, and both are delayed in onset, but the time delay is much longer for the secondary component (~100 vs. ~ 10 s), as is the time constant (>100 vs. ~25 s) (Barstow and Molé, 1991; Barstow et al., 1993). The time delay for the primary component is thought to reflect the transit delay from the working muscles to the lungs (Whipp, 1994), but a convincing explanation for the delayed onset of the slow component has not been presented. [Oxygen uptake, as measured at the mouth, actually increases slightly during the initial "delay" period because pulmonary blood flow increases (Whipp, 1994). This is a small effect, however, and in the discussion that follows it has been ignored.]

The primary component is present for all exercise intensities and the asymptotic $\dot{V}O_2$ for this component increases as a linear function of WR. The slow component, on the other hand, is present only for supra-LT WRs and the asymptotic $\dot{V}O_2$ for this component increases as a positive non-linear function of WR. There is some debate over whether the time constant for the primary component does (Paterson and Whipp, 1991) or does not (Barstow and Molé, 1991; Bartsow et al., 1993) increase slightly with increasing exercise intensity, but it is clear that it is relatively independent of exercise intensity. In normal healthy individuals it averages 25 to 30 s (Bartsow and Molé, 1991; Barstow et al., 1993; Paterson and Whipp, 1991), so for this component $\dot{V}O_2$ will have reached 99% of the asymptotic value within 2.5 min of the onset of exercise (assuming a time delay of 10 s).

The implication is that for sub-LT WRs $\dot{V}O_2$ typically reaches a steady state within 3 min and the $\dot{V}O_2$-WR relationship is linear, whilst for supra-LT WRs more than 3 min are required for a steady state $\dot{V}O_2$ to be attained and the $\dot{V}O_2$-WR relationship is non-linear. Studies of cycle ergometer exercise have shown that the increase in $\dot{V}O_2$ between the 3rd and the 6th minute of exercise, which is zero for sub-LT WRs, increases with WR for supra-LT WRs (Henson et al., 1989; Paterson and Whipp, 1991; Roston et al., 1987; Whipp and Wasserman, 1972, 1986). Additionally, Zoladz et al. (1995) have recently reported that the $\dot{V}O_2$-power relationship for a continuous incremental cycle ergometer test is linear for sub-LT WRs and curvilinear for supra-LT WRs. These investigators found that for supra-LT WRs the slope of the $\dot{V}O_2$-power relationship increased with increasing WR. Green and Dawson (1995) have also shown that, across a wide range of WRs, the $\dot{V}O_2$-power relationship is non-linear, with the slope of this relationship being higher for supra- than for sub-LT WRs.

4.4.4 *$\dot{V}O_2$ kinetics for running vs. those for cycling*

Data are rapidly becoming available to suggest that most of what has been established about $\dot{V}O_2$ kinetics from studies of cycle ergometry is also applicable to treadmill running. Sloniger et al. (1996) studied well-trained runners and found that $\dot{V}O_2$ continued to increase beyond the 3rd minute of a constant speed, exhaustive treadmill run. The time to exhaustion for this run ranged from ~7 to ~14 min, and for most of the subjects $\dot{V}O_2$ continued to increase throughout the run. More recently, Carter et al. (1997) have shown that the increase in $\dot{V}O_2$ between the 3rd and the 6th minute of exercise, which is zero for sub-LT running speeds, increases with running speed for supra-LT speeds. Also, Wood et al. (1997) have shown that the $\dot{V}O_2$-running speed relationship is non-linear, with the slope of this relationship being higher for supra- than for sub-LT speeds [c.f. Green and Dawson's (1995) study of cycle ergometer exercise].

In contrast to the above studies, a recent study by Billat et al. (1998a) found that no increase in $\dot{V}O_2$ occurred beyond the 3rd minute of a supra-LT treadmill run. However, Billat et al. studied elite middle-long distance runners who have been shown to possess a higher than average percentage of type I muscle fibres (Costill et al., 1976). The subjects in the studies of Sloniger et al., Carter et al., and Wood et al. were simply individuals who were engaged in regular training for running, and whilst many of these were specialist runners, few were elite athletes. Barstow et al. (1996) studied cycle ergometer exercise and found that for a given exercise intensity the relative contribution of the slow component to the total increase in $\dot{V}O_2$ was lowest in those subjects who had the highest percentage of type I fibres in their vastus lateralis. It might be expected, therefore, that a relatively small $\dot{V}O_2$ slow component would be observed in Billat et al.'s subjects even for cycle ergometer exercise.

It should also be mentioned at this point that it is uncertain whether the supra-LT run performed by these subjects represented a genuine "square wave" exercise bout. Billat et al. (1998a, p. 39) note that after a warm up period at 60% $v\dot{V}O_{2max}$, "the runner's speed was quickly increased to 90% $v\dot{V}O_{2max}$". The implication here is that the subject continued running while the belt speed was increased. Were this the case, it would have taken at least 10-15 s to reach the target speed, whereas when square wave exercise bouts are performed on a cycle ergometer the target WR is usually reached within 1-2 s. This would suggest that perhaps Billat et al.'s data should not be expected to agree with those that have been obtained during cycle ergometry. However, a very recent study (Bernard et al., 1998), in which the belt speed was increased from zero to the desired speed in 20-30 s at the start of exercise, suggests that $\dot{V}O_2$ kinetics during running conform well to the model that has been presented previously (Barstow and Molé, 1991; Barstow et al., 1993), even though this model was developed from studies of cycle ergometer exercise (see section 4.4.3). Bernard et al. studied various intensities of treadmill running in 13 trained subjects, of whom some, but not all, were competitive runners. They found that for supra-LT speeds the $\dot{V}O_2$ response could be well described by a two component model in the majority of subjects, and that the time constant was ~25 s for the fast and >100 s for the slow component. These time constants are similar to those that have been reported previously for cycling (see section 4.4.3), but the time delay reported by Bernard et al. was longer than that which has been reported previously for both the fast and the slow component. It is likely, however, that this difference can be explained, at least in part, by the fact that the speed was increased over 20-30 s at the start of each run (i.e. time 0 was the time at which the subject started running not the time at which the desired speed was attained).

Billat et al. (1998b) compared the $\dot{V}O_2$ response for exhaustive supra-LT bouts of running and cycling. They studied triathletes and found that the increase in $\dot{V}O_2$

between the 3rd and the last minute of exercise was much greater for cycling (269 vs. 21 ml.min^{-1}). In contrast, Jones and McConnell (1999), who studied healthy individuals who were not specifically trained for cycling or running, found that the increase in $\dot{V}O_2$ between the 3rd and the 6th minute of a supra-LT exercise bout was only slightly higher for cycling than for running (290 vs. 200 ml.min^{-1}). Jones and McConnell set the exercise intensity for both exercise bouts relative to the LT and to $\dot{V}O_{2peak}$ (equivalent to ~55%Δ, where Δ is the difference between the $\dot{V}O_2$ at the LT and $\dot{V}O_{2peak}$), whilst Billat et al. set it relative to $\dot{V}O_{2peak}$ only (equivalent to 90% $\dot{V}O_{2peak}$). However, the fact that both the end exercise [Bla] and the time to exhaustion were similar for the running and cycling bouts in Billat et al.'s study suggests that these authors were successful in controlling for the relative intensity of the bout, as were Jones and McConnell. There is no obvious explanation for the discrepancy between the findings of these two studies, but it should be recognised that the majority of the available evidence suggests that $\dot{V}O_2$ kinetics for running are similar to those for cycling. In the following section, it is assumed (unless otherwise stated) that for both sub- and supra-LT WRs $\dot{V}O_2$ kinetics can be characterised in a similar way for both running and cycling.

4.4.5 *Implications for the assessment of $\dot{V}O_{2max}$*

4.4.5.1 Discontinuous tests

It has been demonstrated that as exercise intensity increases beyond that at which the LT occurs the contribution that the slow component makes to the total $\dot{V}O_2$ response increases, and therefore, effectively at least, $\dot{V}O_2$ kinetics get slower (the time taken for $\dot{V}O_2$ to reach its final value increases). The $\dot{V}O_2$ slow component will have a very small effect on the "early $\dot{V}O_2$" (e.g. the $\dot{V}O_2$ determined from 1.5 to 2.5 min after the onset of exercise) because its onset is delayed [it typically becomes manifest after a delay of ~100 s (see section 4.4.3)]. Therefore the slope of the relationship between the early $\dot{V}O_2$ and WR will decrease as WR increases, provided the final $\dot{V}O_2$ increases as a linear function of WR. However, in practice this is unlikely to happen because the influence of the $\dot{V}O_2$ slow component on the final $\dot{V}O_2$ is such that this final $\dot{V}O_2$

increases as a non-linear function of WR (the slope of the $\dot{V}O_2$-WR relationship for this final $\dot{V}O_2$ increases as WR increases). In fact, since the early $\dot{V}O_2$ is influenced mainly by the primary (fast) component, for which the time constant is essentially independent of WR and the asymptotic $\dot{V}O_2$ varies linearly with WR, this early $\dot{V}O_2$ should increase as an essentially linear function of WR. This means that a spurious plateau is unlikely to observed even though the difference between the early $\dot{V}O_2$ and the final $\dot{V}O_2$ is likely to increase over the final stages of a DCT.

If the time constant and delay for this component are 30 and 10 s respectively (see section 4.4.3), the net $\dot{V}O_2$ (exercise $\dot{V}O_2$ - baseline $\dot{V}O_2$) will reach 93.1 and 99.1% of this component's asymptotic $\dot{V}O_2$ after 1.5 and 2.5 min of exercise. The fact that $\dot{V}O_2$ increases exponentially as opposed to linearly with time means that the average (net) $\dot{V}O_2$ determined from 1.5 to 2.5 min after the onset of exercise will be closer to 99.1 than to 93.1% of the asymptotic value, but nevertheless this average $\dot{V}O_2$ will represent only ~97% of the asymptotic value, or ~98% of the 2.5 min value. This suggests that when a DCT is performed and $\dot{V}O_2$ is determined from 1.5 to 2.5 min of each stage the true peak $\dot{V}O_2$ might be underestimated slightly. The extent of this underestimation would potentially be less were a later sampling period used (the 2 min $\dot{V}O_2$, for instance, represents >99% of the 3 min $\dot{V}O_2$). However, it should be recognised that the increase in $\dot{V}O_2$ that occurs over the course of a later period might be greater than expected due to the influence of the $\dot{V}O_2$ slow component.

The idea that even if a $\dot{V}O_2$-plateau occurs during a DCT the peak $\dot{V}O_2$ attained may be an underestimation of the true $\dot{V}O_{2max}$ is of interest given that the incidence of a $\dot{V}O_2$-plateau is higher for a DCT than for a CT but the peak $\dot{V}O_2$ is not. Whipp (1994) has suggested that the time constant for the fast component of $\dot{V}O_2$ kinetics, which is ~30 s for WRs where the $\dot{V}O_2$ required is $< \dot{V}O_{2peak}$ (see section 4.4.3), is also ~30 s for WRs where the $\dot{V}O_2$ required is $> \dot{V}O_{2peak}$. The difference, he suggests, is that in the latter case this time constant applies to an exponential function which has as its asymptotic value not $\dot{V}O_{2peak}$ but rather the required (predicted) $\dot{V}O_2$. The implication is that the time taken to reach $\dot{V}O_{2peak}$ should decrease as the extent to which the predicted $\dot{V}O_2$ exceeds $\dot{V}O_{2peak}$ increases. That is, for supra-$\dot{V}O_{2peak}$ exercise, the rate at which $\dot{V}O_2$ increases should increase in proportion to the relative intensity (relative to $\dot{V}O_{2peak}$) of the exercise.

There is some indication that the rate at which $\dot{V}O_2$ increases at the onset of exercise does indeed increase with relative intensity for supra-$\dot{V}O_{2peak}$ running (Margaria et al., 1965; Spencer et al., 1996; Williams et al., 1998) and cycling (Åstrand and Saltin, 1961b). However, whilst it is clear that $\dot{V}O_2$ increases very quickly at the onset of exercise which can only be maintained for 2-3 min, it is unclear whether the final $\dot{V}O_2$ attained in such exercise is equal to (Williams et al., 1998) or lower than (Åstrand and Saltin, 1961b; Spencer et al., 1996) that which is attained in a progressive CT.

Williams et al. (1998) determined $\dot{V}O_2$ breath-by-breath throughout 4 exhaustive bouts of high intensity treadmill running. The (mean ± SD) time to exhaustion ranged from 126 ± 42 s for the highest to 301 ± 148 s for the slowest speed, and Williams et al. claimed that for each of the runs the $\dot{V}O_2$ at fatigue was "not different from $\dot{V}O_{2max}$" (as determined from a progressive test). Although they presented no data in support of this claim (the study has so far only been reported as an abstract), they did present data on the kinetics of the $\dot{V}O_2$ response for each of the runs. These data show that the rate at which $\dot{V}O_2$ increased at the onset of exercise increased as the intensity of the run increased.

Åstrand and Saltin (1961b) used the Douglas bag method to determine $\dot{V}O_2$ throughout various exhaustive bouts of cycle ergometer exercise. Each subject completed 3-5 exercise bouts, for which the time to exhaustion ranged from ~2 to ~6.5 min, and the data show that, within each individual, the rate at which $\dot{V}O_2$ increased at the onset of exercise increased in proportion to the intensity of the exercise. However, the data also show that the peak $\dot{V}O_2$ attained was typically higher for the 6.5 min than for the 2 min bout.

A similar phenomenon was described by Spencer et al. (1996), who studied trained middle-distance runners. They determined $\dot{V}O_2$ breath-by-breath throughout two constant speed (square wave) runs, one for which the time to exhaustion averaged ~2 min and another for which this time averaged ~4 min. They found that the peak $\dot{V}O_2$ attained was higher for the longer run, but that the peak $\dot{V}O_2$ attained in a progressive CT was higher still (this $\dot{V}O_2$ was 11% higher than that which was attained in the 2 min run and 6% higher than that which was attained in the 4 min run). Sloniger et al. (1996) also studied trained runners, and these authors reported that the peak $\dot{V}O_2$ attained in a progressive CT was 3.6% higher than that which was attained in a constant speed (square wave) run for which the time to exhaustion averaged ~7 to ~14 min.

Taken together these studies suggest that the peak $\dot{V}O_2$ will always be higher for a progressive CT than for a constant speed (square wave) run, but that the difference between the two values should decrease as the duration of the constant speed run increases. However, it should be stressed that in both of these studies the progressive test was a CSIG test whereas the square wave runs were completed on a level treadmill. On the basis that $\dot{V}O_{2peak}$ is typically 3-6% higher for uphill than for level running (see section 4.3.3), it can be argued that the correct interpretation of these studies is that the peak $\dot{V}O_2$ for a square wave run will be lower than that for a progressive CT if the duration of the square wave is ~2 min but not if it is >7 min. It is possible that the peak $\dot{V}O_2$ will be slightly lower for a 4 min square wave than for a progressive CT, but presumably a duration will be reached somewhere between 2 and 7 min for which the peak $\dot{V}O_2$ attained in a square wave is equal to that which can be attained in a CT. It is noteworthy that in the shortest of the exercise bouts studied by Åstrand and Saltin (1961b) and Spencer et al. (1996), $\dot{V}O_2$ appeared to reach a steady state before the exercise was terminated (at a level that was clearly sub maximal). This is especially apparent in the Spencer paper where the breath-by-breath data are presented as 10 s averages [mean data (n = 5)]. These data show that no increase in $\dot{V}O_2$ occurred over the final 40 s of the 2 min run.

The above findings raise the possibility that the peak $\dot{V}O_2$ will be lower for a bout of "maximal" running that lasts 2.5 or 3 min than for either a progressive CT or a relatively long (i.e. ≥7 min), exhaustive square wave. If this possibility is accepted, it must also be accepted that even when a plateau in the $\dot{V}O_2$-WR relationship is observed in a DCT, the peak $\dot{V}O_2$ for this test might be below $\dot{V}O_{2max}$, particularly if the duration of each stage is short (i.e. 2.5 to 3 min).

4.4.5.2 Continuous tests

When a criterion $\Delta\dot{V}O_2$ which is derived from the distribution of the sub-$\dot{V}O_{2peak}$ values for $\Delta\dot{V}O_2$ is used to define a $\dot{V}O_2$-plateau, it is assumed that the $\dot{V}O_2$-WR relationship is linear up to the point at which $\dot{V}O_2$ plateaus (i.e. it is assumed that, for a given ΔWR, the $\Delta\dot{V}O_2$ is independent of WR until the $\dot{V}O_2$-WR relationship starts to plateau). If the slope of this relationship actually increases as WR increases, the criterion $\Delta\dot{V}O_2$ will be too stringent and the incidence of a $\dot{V}O_2$-plateau will be artificially low. Conversely, if the slope of this relationship decreases with increasing WR, the criterion $\Delta\dot{V}O_2$ will be too lenient and the incidence of a $\dot{V}O_2$-plateau will be artificially high.

For a DCT, the $\dot{V}O_2$-WR relationship should be linear provided $\dot{V}O_2$ is determined relatively soon (e.g. 2-3 min) after the start of each stage because the asymptotic $\dot{V}O_2$ for the primary component of the $\dot{V}O_2$ response should increase as a linear function of WR. It has been shown (Barstow and Molé, 1991; Barstow et al., 1993; Paterson and Whipp, 1991) that when only the primary component is considered the $\dot{V}O_2$-WR relationship for cycle ergometer exercise is linear, with a slope of ~10 $ml.min^{-1}.W^{-1}$. The observation that the $\dot{V}O_2$-WR relationship for a ramp test is similar (i.e. linear with a slope of ~10 $ml.min^{-1}.W^{-1}$) (Davis et al., 1982; Whipp et al., 1981) might be taken as evidence that the $\dot{V}O_2$ response for such a test is dominated by the primary component.

However, Hansen et al. (1988) have shown that the $\dot{V}O_2$-WR relationship for a cycle ergometer ramp test is different for different ramp rates. In this study, subjects performed tests in which the WR was increased at a rate of 15, 30, or 60 W.min^{-1}. Having determined $\dot{V}O_2$ throughout each test, Hansen et al. (1988, p. 141) noted that the $\dot{V}O_2$-WR relationship for each subject "was not strictly linear by inspection". To investigate this non-linearity they derived two linear $\dot{V}O_2$-WR relationships for each test, one for intensities below, and one for those above, 50% $\dot{V}O_{2peak}$. For both the 15 and the 30 W.min^{-1} tests, the slope of the $\dot{V}O_2$-WR relationship averaged 9.9 ml.min^{-1}.W^{-1} for intensities below 50% $\dot{V}O_{2peak}$. However, whilst the slope of this relationship was only slightly higher (10.5 ml.min^{-1}.W^{-1}) for intensities above 50% in the 30 W.min^{-1} test, it was much higher (12.5 ml.min^{-1}.W^{-1}) in the 15 W.min^{-1} test. For the 60 W.min^{-1} test, the slope of the $\dot{V}O_2$-WR relationship was similar for intensities below (8.4 ml.min^{-1}.W^{-1}) and above (8.7 ml.min^{-1}.W^{-1}) 50% $\dot{V}O_{2peak}$, although even below 50% it was lower than that for the 15 or the 30 W.min^{-1} test (8.4 vs. 9.9 ml.min^{-1}.W^{-1}).

The presence of a $\dot{V}O_2$ slow component at supra-LT WRs would cause the slope of the $\dot{V}O_2$-WR relationship to increase with increasing WR (see section 4.4.3). The LT typically occurs at 50-60% $\dot{V}O_{2peak}$ in untrained subjects similar to those studied by Hansen et al. (Davis et al., 1976, 1979, 1982; Whipp et al., 1981). It is reasonable to suggest, therefore, that the steep slope of the $\dot{V}O_2$-WR relationship observed for intensities >50% $\dot{V}O_{2peak}$ in the 15 W.min^{-1} test reflects the influence of the $\dot{V}O_2$ slow component (i.e., it is the result of fitting a linear function to a non-linear $\dot{V}O_2$-WR relationship for which the slope increases with increasing WR). All tests started with unloaded pedalling, and the test duration averaged ~16 and ~9 min, respectively, for the 15 and the 30 W.min^{-1} tests. If the LT occurred at 50% $\dot{V}O_{2peak}$ in both tests and this $\dot{V}O_2$ occurred half-way through each test, the total time spent at supra-LT WRs would be ~8 and ~4.5 min, respectively, for the 15 and the 30 W.min^{-1} tests. It is noteworthy that the other studies which have found the $\dot{V}O_2$-WR relationship to be non-linear for a CT have used tests with a stage duration of 3 (Zoladz et al., 1995) or 4 (Green and Dawson, 1995) min. The data presented in these papers suggest that the total time spent at supra-LT WRs would have been 9-18 (Zoladz et al., 1995) or ~8 (Green and Dawson, 1995) min. It would seem then that, for cycle ergometry at least, the $\dot{V}O_2$-WR relationship for a CT will only be linear when the time spent at WRs above the LT is insufficient for a substantial $\dot{V}O_2$ slow component to develop (i.e. when the dominant component in the $\dot{V}O_2$ response is the primary component).

Wood et al. (1997) found that the $\dot{V}O_2$-running speed relationship was non-linear for a CT in which each stage lasted 4 min. The speed at which the LT occurred was also determined for each subject, and from these (unpublished) data it can be calculated that the time spent at supra-LT speeds would have ranged from 8-20 min (mean ± SD: 13.3 ± 3.3 min). If the non-linearity of the $\dot{V}O_2$-running speed relationship is due to the influence of the $\dot{V}O_2$ slow component, this relationship should be linear when a test is performed in which there is insufficient time for a substantial $\dot{V}O_2$ slow component to develop. Current knowledge of $\dot{V}O_2$ kinetics during running (see sections 4.4.3 and 4.4.4) suggests that there will be insufficient time for a substantial slow component to develop when a CGIS DCT is performed and $\dot{V}O_2$ is determined relatively early (i.e. before the 4th minute) in each stage. Moreover, the study of Hansen et al. (see above) suggests that there will also be insufficient time for a substantial slow component to develop when a CGIS CT is performed and the WR is increased at a relatively fast rate. To date, no studies have investigated whether the $\dot{V}O_2$-running speed relationship is linear in either of these situations. Nevertheless, it appears that if a CGIS CT is used for the determination of $\dot{V}O_{2max}$ during running it should be one for which the total time spent at supra-LT speeds is relatively short. Moreover, it appears that it should be possible to get an insight into whether the asymptotic $\dot{V}O_2$ for the primary component of the $\dot{V}O_2$ response does increase as a linear function of running speed by establishing whether the $\dot{V}O_2$-running speed relationship is linear for a CT in which speed is increased at a relatively fast rate.

4.5 Determinants of $\dot{V}O_{2peak}$ for a progressive test

Noakes (1988, 1997, 1998) has repeatedly stressed that when a plateau in the $\dot{V}O_2$-WR relationship is not observed in a progressive test it is impossible to be certain that the peak $\dot{V}O_2$ was limited by factors related to O_2 delivery to, or use by, skeletal muscle. In his 1988 paper he proposed that the peak WR that can be attained in such a test might instead be limited by factors related to muscle contractility. The implication here was that any intervention that increased muscle contractility would also increase the peak WR that could be attained, and thus the peak $\dot{V}O_2$ that could be reached, in a progressive test.

In 1997 Noakes presented a different model. He suggested that "skeletal muscle contractile function is regulated during exercise in both health and disease by a hierarchy of central and peripheral mechanisms, the goal of which is likely to prevent organ damage, including death" (Noakes, 1997, p. 581). As support for his argument, he cited studies which show that when the ability to produce ATP is markedly reduced, either as a result of muscle ischemia (Spriet et al., 1987) or as a result of a disease of skeletal muscle metabolism such as phosphorylase deficiency (Lewis and Haller, 1986), skeletal muscle contractile function (and its rate of ATP use) is also reduced so that the decrease in [AT.P] that occurs during exercise is not abnormally large. He went on to stress that progressive exercise at high altitude is terminated at a time when both [Bla] (Green et al., 1989) and the integrated electromyographic activity of the active muscles (Kayser et al., 1994) are low relative to similar exercise performed at sea level, and that progressive exercise in heart failure patients, both before and after transplant, is terminated at a time when WR, $\dot{V}O_2$, and [Bla] are greatly reduced relative to those at which such exercise is terminated in normal subjects. Finally he proposed that in healthy subjects (at sea level) skeletal muscle recruitment might be limited (i.e. the test might be terminated) once the maximal cardiac output has been reached in a progressive exercise test so that vasodilation is not induced to the point where a drop in blood pressure occurs.

This paper is important in that it shows that there are situations in which factors other than those related to a limited O_2 supply and the associated demand for anaerobic metabolism might limit progressive exercise to exhaustion. Nevertheless, the explanation he gives for what might limit the peak WR for a progressive test in which no plateau is observed is very similar to that which was presented in section 3.3.9 to explain the occurrence of a $\dot{V}O_2$-plateau. The similarity is that in both cases the maximal $\dot{Q}_c$ would be seen as the primary determinant of the peak $\dot{V}O_2$ for a progressive test. There are differences however. In section 3.3.9 it was assumed that $\dot{V}O_2$ would plateau and exercise would continue for as long as anaerobic metabolism was able to supply ATP at a sufficient rate, with excessive vasodilation being prevented by sympathetically mediated vasoconstriction in the active muscles. Noakes' argument, on the other hand, would suggest that $\dot{V}O_2$ would not plateau, and that exercise would be terminated shortly after the maximal $\dot{Q}_c$ was reached because blood pressure would start to drop.

In 1998 Noakes questioned the notion that there is a maximal $\dot{Q}_c$. Starting from the premise that a plateau in $\dot{Q}_c$ must be the result of a plateau in the O_2 supply to the myocardium, he went on to point out that whilst myocardial O_2 supply will only plateau if coronary blood flow plateaus, there is no logical reason to believe that coronary blood flow would plateau before $\dot{Q}_c$. He proposed that instead skeletal muscle function might be regulated to prevent myocardial ischemia in such a way that neither $\dot{V}O_2$ nor $\dot{Q}_c$ would plateau in a progressive test.

There are two obvious problems with this most recent of Noakes' theories. The first is that it is not consistent with those studies (Mitchell et al., 1958; Stringer et al., 1997) which have shown that $\dot{Q}_c$ does in fact plateau in the later stages of a progressive test. The second is that it fails to take account of the fact that $\dot{Q}_c$ might plateau even if myocardial O_2 supply is completely adequate. Concerning the second problem, the obvious point is that, since "the heart ... cannot pump out what it does not receive" (Rowell, 1986, p. 137), $\dot{Q}_c$ will plateau if venous return plateaus. It has been shown that whilst the left ventricular ejection fraction typically increases from rest to moderate intensity exercise, little or no increase is observed when exercise intensity increases beyond that at which the LT occurs (Boucher et al., 1985; Clausell et al., 1993; Foster et al., 1995, 1997). Furthermore, the ejection fraction typically reaches 70 or 80% (di Bello et al., 1996; Clausell et al., 1993; Foster et al., 1995; Goodman et al., 1991), or even slightly higher (Brandao et al., 1993), in young, normal subjects during exercise at intensities close to that at which $\dot{V}O_{2peak}$ is attained. It is unlikely, therefore, that the tendency for $\dot{Q}_c$ to plateau in response to a plateau in the rate of venous return would be offset by an increase in the ejection fraction.

4.6 Implications for current models of running performance

Of the various explanations that Noakes has put forward for what might limit the peak WR that can be attained in a progressive test, it is the one that considers this peak WR to be determined by factors related to muscle contractility (Noakes, 1988) that has the most profound implications for current models of running performance. Current models of endurance performance in general (Coyle, 1995), and distance running performance in particular (Bassett and Howley, 1997; di Prampero, 1986; Joyner, 1991; Péronnet and Thibault, 1989; Sparling, 1984), consider performance to be a function of the $\dot{V}O_2$ that can be sustained for the duration of the event (the sustainable $\dot{V}O_2$) and the economy of movement. Consistent with these models is the finding that distance running performance can be predicted from the derived variable, $v\dot{V}O_{2peak}$, a composite of running economy and $\dot{V}O_{2peak}$ that is derived by extrapolating the $\dot{V}O_2$-running speed relationship to $\dot{V}O_{2peak}$ (Morgan et al., 1989). The finding that the peak speed attained in a CGIS (0% grade) test is a good predictor of distance running performance (Noakes et al., 1990; Scott and Houmard, 1994; Scrimgeour et al., 1986) can also be seen as consistent with these models provided the assumption is made that this peak speed is determined primarily by $\dot{V}O_{2peak}$ and running economy. However, Noakes' perspective is that the peak speed is an important determinant of performance because it is determined by factors related to muscle contractility. According to Noakes (1988), the peak $\dot{V}O_2$ is simply a reflection of how high this peak speed is and how economical the runner is.

It is unclear exactly what Noakes means by "muscle contractility". He seems to use the term when he wants not only to refer to the ability of skeletal muscle to generate power output but also to separate this ability from the ability to produce ATP at a high rate. In his book, The Lore of Running, Noakes (1991, p.21) suggests that "the best athletes have muscles with superior contractility either on the basis of superior myosin ATPase activity or enhanced sensitivity to calcium". It is difficult to conceive that either myosin ATPase activity or calcium sensitivity per se is likely to limit the peak WR that can be reached in a progressive test, given that this WR is well below that which can be attained in a short duration, all out effort such as a 30 s sprint (Barnett et al., 1996). Nevertheless, it is important to recognise that whereas if the current models of performance are correct any factor that influences the rate at which an individual can take up and use O_2 should also influence running performance, if Noakes' (1988) theory is correct such factors will only affect performance if they also affect muscle contractility. Since very different training would be required, depending on whether the aim was to improve muscle contractility or to improve the rate at which O_2 can be delivered to the muscle, it is necessary to establish whether the peak $\dot{V}O_2$ that can be attained in a progressive test is indeed determined by muscle contractility. This cannot be the case in those instances in which the $\dot{V}O_2$-WR relationship plateaus, so a useful first step would be to establish whether such a plateau actually occurs in the majority of individuals.

This chapter has raised several issues related to the assessment of $\dot{V}O_{2max}$ in runners. There is a need to establish whether the incidence of a $\dot{V}O_2$-plateau is higher for a DCT than for a CT when both tests are CGIS tests, and whether the plateau that occurs in such a DCT is an artefact of the test protocol. In addition, there is a need to establish whether the peak speed is typically limited by non-metabolic factors for level running, and whether this limitation is still present for uphill running. However, Chapters 2 and 3 highlighted that the extent to which there is variability in the $\dot{V}O_2$ data and the way in which this variability is dealt with can influence whether or not a $\dot{V}O_2$-plateau is identified. The suggestion is that it will only be possible to establish the true incidence of a $\dot{V}O_2$-plateau if great care is taken to ensure that the variability in the $\dot{V}O_2$ data is minimised. Chapter 5 outlines the procedures that were adopted to determine $\dot{V}O_2$ in the studies reported in this thesis. It highlights the potential sources of error, and presents a rationale for the strategies that were adopted to maximise the accuracy and precision of the calculated values for $\dot{V}O_2$.

PART II

TECHNICAL CONSIDERATIONS

CHAPTER 5: GENERAL CONSIDERATIONS FOR THE DETERMINATION OF $\dot{V}O_2$ AND RER DURING EXERCISE

5.1 Introduction

The focus of this thesis is the question of whether the $\dot{V}O_2$-running speed relationship plateaus at high speeds. The key variable is therefore $\dot{V}O_2$, and the key requirement is to be able to determine $\dot{V}O_2$ with a high degree of accuracy and precision, where accuracy and precision are defined as the extent to which the measured values agree with the actual or expected value and the extent to which these measured values agree with one another, respectively (Challis, 1997; Topping, 1972). It is necessary to be able to do this across a wide range of speeds and metabolic rates. However, for intensities close to that at which $\dot{V}O_{2peak}$ is attained, it is also desirable to be able to determine RER with a high degree of accuracy and precision.

Liefeldt et al. (1992) found that the peak RER for a CGIS test was much lower when the test was conducted on a downhill treadmill than when it was conducted on a level treadmill. This finding was taken as evidence that the downhill test was terminated at a time when anaerobic metabolism was operating at a relatively low rate, and this in turn was taken as evidence that the peak speed was limited by non-metabolic factors for the downhill test (see section 4.3.3). Liefeldt et al. went on to suggest that the peak speed might have been limited in a similar way for the level test. However, there are only two studies (Kasch et al., 1976; Mayhew and Gross, 1975) that have compared the peak RER for level and uphill running, and both of these found that the treadmill inclination had no effect on the peak RER attained. It would seem, therefore, that further research is needed to establish whether the peak speed for level running is limited by non-metabolic factors. A potentially useful approach would be to compare the peak physiological responses (in particular the peak values for $\dot{V}O_2$ and RER) for a CGIS test conducted on a level treadmill with those for a similar test conducted at a moderate (uphill) grade. The RER is the ratio of carbon dioxide output ($\dot{V}CO_2$) to oxygen uptake

(RER = $\dot{V}CO_2 / \dot{V}O_2$), so for the higher exercise intensities it is necessary to be able to determine both $\dot{V}O_2$ and $\dot{V}CO_2$ with a high degree of accuracy and precision.

This chapter describes the procedures that were employed to determine $\dot{V}O_2$ and $\dot{V}CO_2$ in the studies reported in this thesis. The early sections focus on the calculations involved in determining $\dot{V}O_2$ and $\dot{V}CO_2$; the later ones focus on the associated procedures and equipment.

5.2 Calculations involved in the determination of $\dot{V}O_2$ and $\dot{V}CO_2$

5.2.1 *Determination of $\dot{V}O_2$*

As Howley et al. (1995) have pointed out, it is important to recognise that $\dot{V}O_2$ is a calculated variable. The basic calculation is

$$\dot{V}O_2 = \dot{V}_I \times F_IO_2 - \dot{V}_E \times F_EO_2 \quad \text{.. .. ..} \quad (1),$$

where $\dot{V}_I$ is the rate at which air is inspired, F_IO_2 is the fraction of oxygen in the inspired air, $\dot{V}_E$ is the rate at which air is expired, and F_EO_2 is the fraction of oxygen in the expired air.

When the Douglas bag method is used, $\dot{V}_I$ is not measured; instead it is calculated from $\dot{V}_E$ by means of what is commonly referred to as the "Haldane Transformation". The basis for this transformation is the assumption that the volume of nitrogen (N_2) expired and the volume of N_2 inspired are equal (i.e. it is assumed that N_2 is metabolically inert). This equality was first demonstrated in the late 18th century by Lavoisier (see Lamarra and Whipp, 1995), and the first description of how $\dot{V}_I$ can be calculated from $\dot{V}_E$ if this assumption is made appeared some 100 years later in a paper by Geppert and Zuntz (Geppert and Zuntz, 1888 - cited in Poole and Whipp, 1988). Since then this transformation has been widely adopted by physiologists, and, curiously, along the way it has become known as the Haldane Transformation. Exactly why this transformation has been credited to JS Haldane is unknown. However, whilst it should perhaps correctly be termed the "Geppert and Zuntz Transformation", it is now so familiar in its guise as the Haldane Transformation that there would appear to be little to be gained by referring to it correctly.

The transformation is as follows:

$$\dot{V}_I = \dot{V}_E \times \frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)},$$

where F_ICO_2 and F_ECO_2 are the inspired and expired fractions of CO_2. Substituting for $\dot{V}_I$ in equation (1) gives

$$\dot{V}O_2 = \dot{V}_E \times \frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)} \times F_IO_2 - \dot{V}_E \times F_EO_2,$$

and rearranging gives

$$\dot{V}O_2 = \dot{V}_E \times \left(\frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)} \times F_IO_2 - F_EO_2 \right) \quad .. \quad .. \quad .. \quad .. \quad (2).$$

It has been shown that when subjects are studied in the postabsorptive state (2 to 4 hours after their last meal), a small amount of nitrogen retention occurs, so that using the Haldane transformation to determine $\dot{V}_I$ leads to the true $\dot{V}O_2$ being overestimated (Wilmore and Costill, 1973). However, on the basis that the difference between the estimated and the actual $\dot{V}O_2$ was only ~30 ml.min^{-1}, Wilmore and Costill concluded that the use of the Haldane transformation in the calculation of oxygen uptake seems justified. Similar results were obtained by Musch and Brooks (1976), who found that using the Haldane transformation to determine $\dot{V}O_2$ resulted in a $\dot{V}O_2$ which was a slight underestimation of the actual $\dot{V}O_2$, regardless of whether exercise took place after an overnight fast, or 1 to 2 hours after either a normal mixed meal or a special high protein meal. It is noteworthy that the absolute difference between the estimated and the actual $\dot{V}O_2$ appeared to be independent of exercise intensity (Wilmore and Costill, 1973). This suggests that whilst errors associated with the use of the Haldane transformation might be significant in studies of resting metabolism, such errors are of negligible importance in studies where the focus is the determination of $\dot{V}O_2$ during high intensity exercise.

5.2.2 *Determination of $\dot{V}CO_2$*

Just as $\dot{V}O_2$ is a calculated variable, so is $\dot{V}CO_2$. The basic calculation is

$$\dot{V}CO_2 = \dot{V}_E \times F_ECO_2 - \dot{V}_I \times F_ICO_2,$$

and although the Haldane transformation could be used to derive $\dot{V}_I$ from $\dot{V}_E$, in the determination of $\dot{V}CO_2$ it is typically assumed (McArdle et al., 1991; Lamarra and Whipp, 1995) that $\dot{V}_E$ and $\dot{V}_I$ are equal. The error in $\dot{V}CO_2$ associated with this assumption, which is equal to $F_ICO_2 \times (\dot{V}_E - \dot{V}_I)$, is small provided F_ICO_2 is low. For example, for the situation in which $\dot{V}O_2$ is 4, $\dot{V}CO_2$ is 5.2, and $\dot{V}_E$ is 100 L.min^{-1}, the true $\dot{V}_I$ would be 98.8 L.min^{-1} ($\dot{V}_I = \dot{V}_E - \dot{V}CO_2 + \dot{V}O_2$), and the error introduced into the calculation of $\dot{V}CO_2$ would be $F_ICO_2 \times (100 - 98.8)$, or 0.00072 L.min^{-1} (0.014%) for an F_ICO_2 of 0.06% (see section 5.5.4). Hence $\dot{V}CO_2$ can be calculated as:

$$\dot{V}CO_2 = \dot{V}_E \times (F_ECO_2 - F_ICO_2) \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (3).$$

5.3 Standardisation of gas volumes

In order that comparisons can be made between data collected on different days or in different laboratories, gas volumes have to be standardised. This standardisation is necessary because the volume occupied by a given mass of gas is a function of its temperature (Charles' law) and the pressure it is under (Boyle's law), and because the water vapour contained in expirate occupies a volume. Gas volumes are typically reported as the volume that would have been obtained if the measurement had been made under standard conditions. By convention, these standard conditions are defined as a temperature of 0 °C (273 K), a pressure of 760 mmHg, and a water vapour content of zero [i.e., standard temperature and pressure, dry (STPD)]. Since the typical ambient temperature for a physiology laboratory (15-25 °C) is well below body temperature (37 °C), it is safe to assume that expirate will be saturated with water vapour at this ambient temperature. That is to say, the volume of a sample of expirate is measured at ambient temperature and pressure, saturated (ATPS), where ambient temperature and pressure are the temperature of the expirate and the pressure acting on it at the time its volume is measured.

$\dot{V}_{E\,(STPD)}$ can be calculated from $\dot{V}_{E\,(ATPS)}$ as follows:

$$\dot{V}_{E\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273}{T_{EXP}} \times \frac{(P_B - P_{H_2O})}{760} \quad .. \quad .. \quad .. \quad .. \qquad (4),$$

where T_{EXP} is the temperature of the expirate (in Kelvin) and P_B is the pressure acting on it (in mmHg) at the time its volume is measured. P_{H_2O} is the saturated vapour pressure of water associated with the particular value for T_{EXP}.

5.4 Factors affecting the accuracy and precision with which $\dot{V}O_2$ and $\dot{V}CO_2$ can be determined

Equations (2) and (4) can be combined to yield the following equation [equation (5)] for the determination of $\dot{V}O_{2\,(STPD)}$

$$\dot{V}O_{2\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \times \left(\frac{(1 - F_EO_2 - F_ECO_2)}{(1 - F_IO_2 - F_ICO_2)} \times F_IO_2 - F_EO_2 \right).$$

Similarly, equations (3) and (4) can be combined to yield the following equation [equation (6)] for the determination of $\dot{V}CO_{2\,(STPD)}$

$$\dot{V}CO_{2\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \times \left(F_ECO_2 - F_ICO_2\right).$$

From the above equations and the preceding discussion, it is apparent that the accuracy and precision with which both $\dot{V}O_2$ and $\dot{V}CO_2$ can be determined will be affected by the accuracy and precision with which:

1. $\dot{V}_{E\,(ATPS)}$ can be determined;
2. P_B can be measured;
3. T_{EXP} can be measured (P_{H_2O} is a function of T_{EXP});
4. F_IO_2 and F_ICO_2 can be measured or estimated;
5. F_EO_2 and F_ECO_2 can be determined.

5.5 Procedures adopted for the determination of $\dot{V}O_2$ and $\dot{V}CO_2$

5.5.1 *Determination of $\dot{V}_{E\,(ATPS)}$*

The Douglas bag method was used. Subjects wore a nose-clip and breathed through a low resistance valve-box (Jakeman and Davies, 1979), the expired side of which was connected to a 200 L plastic Douglas bag (Cranlea and Co., Birmingham, UK) via a 1.5 m length of Falconia tubing (3 cm internal diameter; Baxter, Woodhouse and Taylor Ltd, Macclesfield, UK). Each Douglas bag was fitted with a two-way valve, so that whilst the Falconia was connected to the bag, the subject's expirate could either be collected in the bag or vented into the laboratory. These bags were arranged in racks, each of which contained 4 bags (figure 5.1, below).

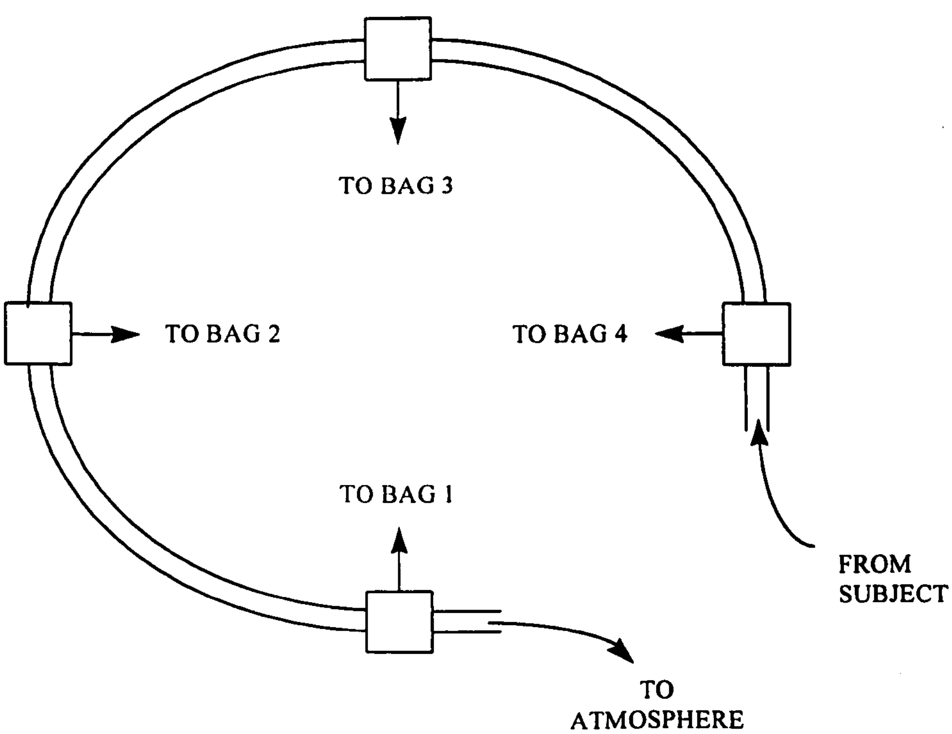

Figure 5.1. Schematic of the racking system which was used for all Douglas bags.

Within each rack, the 4 bags were arranged so that expirate could be collected continuously. However, when more than 4 collections were required it was necessary to switch between racks. In these situations, it was important that the tubing between the "subject" end of the rack and valve 1 (~1.5 m of tubing) was flushed with expirate before bag 1 was opened. This tubing had an internal diameter of ~2 cm (cross-sectional area = 0.000314 m^2), so the volume of tubing encountered before the subject's expirate reached bag 1 would have been 1.5 m × 0.000314 m^2, or ~0.5 L. It usually took ~ 5 s to disconnect the Falconia from the first rack and connect it to the second. A further 5 s were then allowed before the 1st bag on the second rack was opened. Even during moderate intensity exercise, >3 L would be expired in any 5 s period ($\dot{V}_{E\,(ATPS)}$ would be >36 $L.min^{-1}$), so 5 s should have been sufficient to ensure that the first 0.5 L of gas mixture that entered bag 1 was expirate as opposed to ambient air.

Even $\dot{V}_{E\,(ATPS)}$ is a calculated rather than a measured variable. For each Douglas bag collection, the average rate of ventilation over the duration of the collection is calculated by dividing the volume in the bag by the collection period ($\dot{V}_{E\,(ATPS)}$ = $V_{E\,(ATPS)}$/collection period). Therefore both the accuracy with which $V_{E\,(ATPS)}$ can be measured and the accuracy with which expirate collections can be timed will affect the accuracy with which $\dot{V}_{E\,(ATPS)}$ can be determined. (The same would also apply for precision.)

An attempt was made to link the timing of a collection of expirate with the opening and closing of the Douglas bag by constructing timers that started automatically when the bag was opened and stopped when it was closed, but the triggering mechanism used was not physically robust. As a consequence, there were occasions when a bag was opened but the timer failed to start and other occasions when a bag was closed and the timer failed to stop. This risk was considered to be unacceptable, and given that stopwatches capable of recording up to 60 split times with a resolution of 0.01 s are readily available, it was decided that each collection of expirate would be manually timed using a stopwatch. To ensure that a whole number of breaths was always collected, the bag was always opened and closed during inspiration. To ascertain when the subject was inspiring, the experimenter simply observed the inspiratory diaphragm on the valve-box.

The volume of expirate in each bag was measured by evacuating its contents through a dry gas meter (Harvard Apparatus Ltd, Edenbridge, UK), which was calibrated using a precision 7 litre syringe (Hans Rudolph Inc., Kansas, USA). This syringe was used to pump known volumes (ranging from 7 to 196 litres, in 7 litre increments) of room air into a Douglas bag, which was subsequently evacuated through the dry gas meter. This procedure was performed before and after each study, giving a total of 56 data pairs (meter volume vs. syringe volume) for each study. These data were used to derive, for each study, a linear regression equation relating the true (syringe) volume to the meter volume (abscissa). A typical set of data is given in figure 5.2 (below).

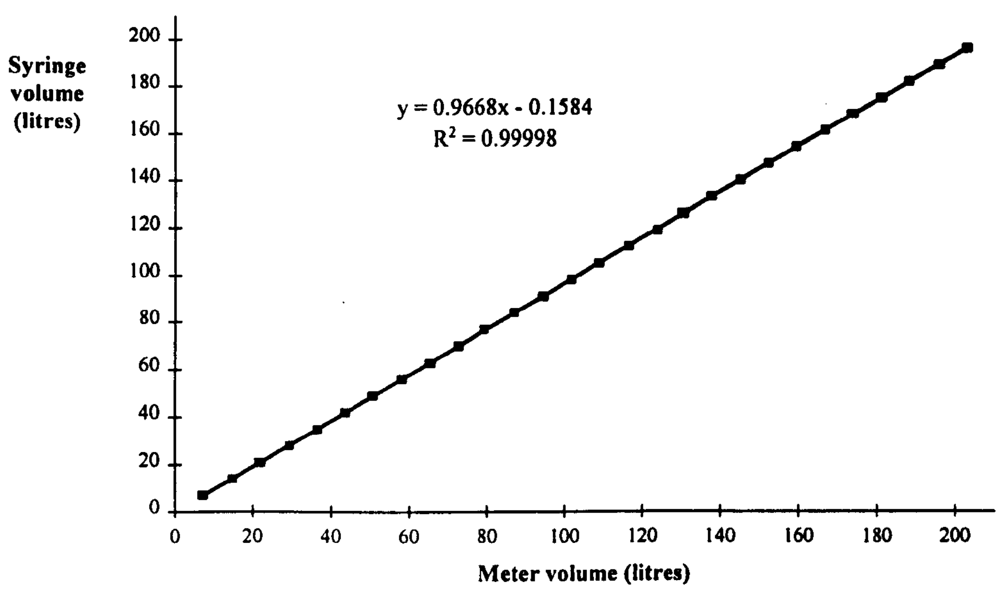

Figure 5.2. Volume measured by the dry gas meter versus that delivered by the syringe.

Figure 5.2 shows that the relationship between the volume delivered by the syringe and that measured by the dry gas meter is linear, and that the intercept of this relationship is, as would be expected, very close to zero. The absolute value of this intercept was always less than 0.2 L, but this parameter was included in the regression equation to ensure that the residuals were randomly distributed around zero (see below). For a particular study, the relevant regression equation was used to obtain a corrected meter volume (the predicted true volume) for each expired volume measurement made in the course of the study. It was this corrected volume that was used in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ [after a further correction had been made for the volume of expirate that was removed from the Douglas bag during the measurement of F_EO_2 and F_ECO_2 (see section 5.5.5.2)].

If an analogy is drawn between room air being pumped and expirate being exhaled into a Douglas bag, the data presented in figure 5.2 can be used to estimate the errors likely to be involved in the measurement of $V_{E\,(ATPS)}$. According to this analogy, the syringe volume represents the volume of expirate that is actually exhaled in a given time. If this expirate was collected in a Douglas bag, and the contents of this bag were subsequently evacuated through a dry gas meter (to obtain the meter volume, V_M), the (corrected) value for V_E that would be used in the calculation of $\dot{V}O_2$ is the value that would be obtained by multiplying this meter volume by 0.9668 and subtracting 0.1584 (assuming the data in figure 5.2 are applicable, and ignoring the volume of expirate lost in the course of measuring F_EO_2 and F_ECO_2). If this corrected V_E differs from the volume of expirate that is actually exhaled, an error will be introduced in the calculated $\dot{V}O_2$. This error will be proportional to the difference between the corrected V_E [$(0.9668 \times V_M$ - 0.1584) in this case] and the volume of expirate that is actually exhaled (equivalent to the syringe volume, V_S).

In figure 5.3 (below), the data that were given in figure 5.2 are given again, but this time the difference between V_S and $(0.9668 \times V_M - 0.1584)$ is plotted as a function of V_S. In terms of the analogy described above, this is equivalent to plotting the error in the corrected V_E as a function of the true V_E.

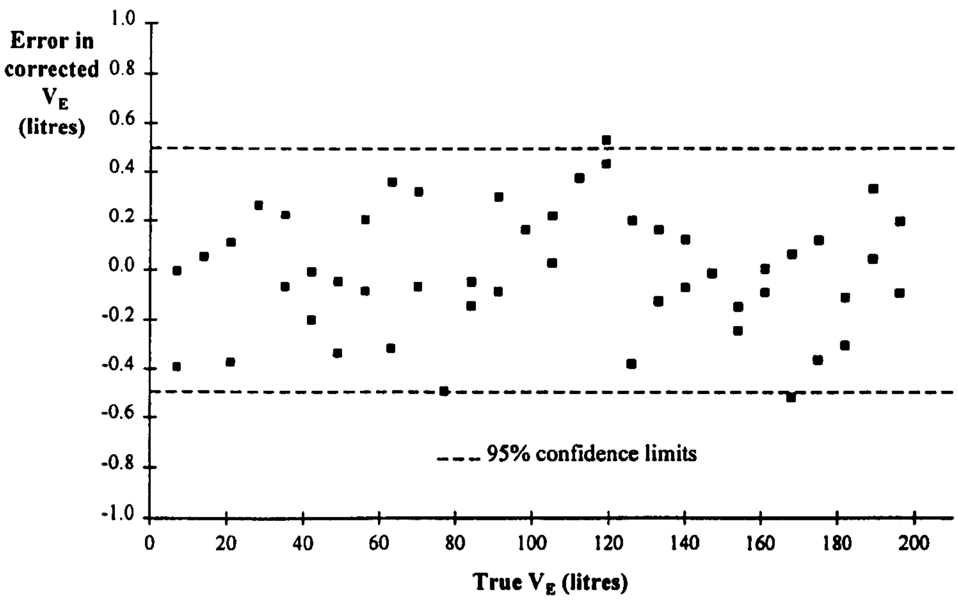

Figure 5.3. Estimated error in the corrected V_E as a function of the true V_E.

The data given in figure 5.3 are the residuals for the regression equation given in figure 5.2, so the fact that the data points in figure 5.3 are randomly distributed around zero can be taken as evidence that the relationship between V_M and V_S is in fact linear. As would be expected, the mean of the differences between V_S and the corrected V_M ($0.9668 \times V_M - 0.1584$) is zero. However, the standard deviation of these differences is 0.25 L, and the 95% confidence interval (equivalent to the 95% confidence interval for the error in the corrected $\dot{V}_E$) is -0.5 to +0.5 L (figure 5.3). It seems reasonable to conclude, therefore, that only rarely will the error in the corrected V_E exceed 0.5 L.

An important point that emerges from figure 5.3 is that the error in this corrected V_E is independent of the true V_E. This means that when expressed as a percentage of the true V_E, this error will decrease as exercise intensity increases. This in turn means that, for a given collection period, the error in $\dot{V}O_2$ (or $\dot{V}CO_2$) associated with the measurement of $V_{E\,(ATPS)}$ will decrease as exercise intensity increases. The data in table 5.1 (below) illustrate this effect. In compiling this table, three sets of values for F_EO_2, F_ECO_2, and $V_{E\,(ATPS)}$ (for a 30 s collection of expirate) were chosen. Values for F_EO_2 and F_ECO_2 were selected to span the range of values likely to be encountered during exercise in a normal subject. Fractional concentrations of O_2 and CO_2 were combined in such a way as to yield values for RER that might realistically be obtained during exercise of moderate, heavy, and severe intensity, and values for V_E were chosen which gave realistic values for $\dot{V}O_2$ and $\dot{V}CO_2$. Equation (5) was used to calculate $\dot{V}O_2$, whilst $\dot{V}CO_2$ was calculated using equation (6). For all calculations, it was assumed that the volume measurement was made at a time when the expirate temperature was 20 °C and the barometric pressure was 760 mmHg, and that the inspired fractions of O_2 and CO_2 were 0.2093 and 0.0003 respectively.

Table 5.1. Effect of a 0.5 L increase in the corrected V_E (for a 30 s collection period) on the calculated values for $\dot{V}O_2$, $\dot{V}CO_2$, and RER, at 3 levels of exercise intensity.

Exercise intensity	True F_EO_2	True F_ECO_2	Corrected V_E (L, ATPS)	$\dot{V}O_2$ ($L.min^{-1}$)	$\dot{V}CO_2$ ($L.min^{-1}$)	RER
moderate	0.150	0.050	25.0	2.815	2.262	0.804
moderate	0.150	0.050	25.5	2.871	2.307	0.804
Change in the calculated value [$L.min^{-1}$ (%)]				0.056 (2.0%)	0.045 (2.0%)	0.000 -
heavy	0.165	0.041	45.0	3.707	3.334	0.899
heavy	0.165	0.041	45.5	3.748	3.371	0.899
Change in the calculated value [$L.min^{-1}$ (%)]				0.041 (1.1%)	0.037 (1.1%)	0.000 -
severe	0.180	0.032	90.0	4.696	5.194	1.106
severe	0.180	0.032	90.5	4.722	5.223	1.106
Change in the calculated value [$L.min^{-1}$ (%)]				0.026 (0.6%)	0.029 (0.6%)	0.000 -

Table 5.1 shows that, for a given collection period, the increase in $\dot{V}O_2$ or $\dot{V}CO_2$ associated with a 0.5 L increase in the corrected V_E decreases, in both absolute and relative terms, as exercise intensity increases. However, because both $\dot{V}O_2$ and $\dot{V}CO_2$

increase by the same relative amount in response to a given increase in the corrected V_E, an error in the corrected V_E has no effect on RER.

The implication is that if the volume of expirate collected in the Douglas bag is low, the variability in the calculated $\dot{V}O_2$ will be high, and vice versa (assuming a dry gas meter is used to measure this volume). For a given collection period, the volume of expirate collected in the Douglas bag will increase with increasing exercise intensity, whilst for a given exercise intensity, this volume will increase as the collection period increases. Indeed, calculations similar to those used to compile table 5.1 suggest that for heavy intensity exercise the random error in $\dot{V}O_2$ would be 1.1, 0.6 and 0.3% for sampling periods of 30, 60, and 120 s respectively.

5.5.2 *Measurement of ambient pressure*

Barometric pressure (P_B) was measured using a mercury barometer (Stanley and Co., London, UK), immediately after the last Douglas bag had been evacuated. This barometer is equipped with a vernier scale, and has a resolution of 0.05 mmHg. It was calibrated by obtaining the sea level barometric pressure from the Meteorological Office and correcting for the height above sea level of the laboratory, so the systematic error involved in the measurement of ambient pressure is likely to be small (<1 mmHg). The random error associated with the use of this barometer is also likely to be small (<1 mmHg). The percentage error in $\dot{V}O_2$ and $\dot{V}CO_2$ that would be associated with an error of 1 mmHg in the measurement of ambient pressure is $1/(P_B - P_{H_2O})$ [see equations (5) and (6)]. For a typical ambient pressure of 760 mmHg and a temperature of 20 °C (SVP = 17.4 mmHg), an error of 1 mmHg in the measurement of ambient pressure would introduce an error of 1/(760 - 17.4), or 0.13%, in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$ and thus also in the calculation of $\dot{V}O_2$ or $\dot{V}CO_2$.

5.5.3 *Measurement of temperature*

The important considerations here are that it is the temperature of the expirate that should be measured and that this temperature should be measured at the time when the volume measurement is made. This was achieved by placing a thermistor probe (Hanna

Instruments NS920; RS Components, Corby, UK) in the inlet port of the Harvard dry gas meter. This thermistor, which measured temperature with a resolution of 0.1 °C, was factory calibrated to give a maximum systematic error of 0.2 °C. Given the stability of the temperature readings obtained from this thermistor, a reasonable estimate of the upper limit for the random error associated with temperature measurement for this thermistor would be 0.2 °C. The percentage error in $\dot{V}O_2$ or $\dot{V}CO_2$ that would be associated with an error of 0.2 °C in the measurement of T_{EXP} is $T_{EXP}/(T_{EXP} + 0.2) - 1$, where T_{EXP} is the true expirate temperature in Kelvin [see equations (5) and (6)]. For a T_{EXP} (at the time its volume is measured) of 20 °C (293 K), an error of +0.2 °C in the measurement of this T_{EXP} would introduce an error of 293/(293 + 0.2) -1, or -0.07%, in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$, and thus also in the calculation of $\dot{V}O_2$ or $\dot{V}CO_2$.

The calculations above illustrate the effect that a given error in the measured T_{EXP} would have on the conversion of $\dot{V}_E$ from ambient to standard temperature. However, this temperature is also used to calculate P_{H_2O}, which in turn is used in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$. The relationship between temperature and P_{H_2O} is non-linear (Hall and Brouillard, 1985), but over the temperature range likely to be encountered in the laboratory (15-25 °C), this relationship can be reasonably well represented by a linear function with a slope of 1 (see Appendix 2). An error of 0.2 °C in the measured T_{EXP} would therefore be associated with an error of ~0.2 mmHg in the calculated P_{H_2O}. Such an error in P_{H_2O} would introduce an error of $-0.2/(P_B - P_{H_2O})$ in the calculation of $\dot{V}_{E\,(STPD)}$ from $\dot{V}_{E\,(ATPS)}$, and thus also in the calculation of $\dot{V}O_2$ or $\dot{V}CO_2$. For a typical ambient pressure (760 mmHg) and temperature [20 °C (P_{H_2O} = 17.4 mmHg)], the error in the calculated $\dot{V}O_2$ or $\dot{V}CO_2$ associated with an error in the calculated P_{H_2O} of +0.2 mmHg would be -0.2/(760 - 17.4), or -0.03%.

For a given error in the measured T_{EXP}, the error introduced into the calculation of $\dot{V}_{E\,(STPD)}$ as a result of using an incorrect value for P_{H_2O} is in the same direction as that which is introduced as a result of using an incorrect value for T_{EXP}. Nevertheless, across the full range of values for ambient pressure and temperature likely to be encountered in the laboratory (745-775 mmHg; 15-25 °C), the total error in the calculated $\dot{V}_{E\,(STPD)}$ will be <0.11% provided the error in the measured T_{EXP} is ≤0.2 °C.

5.5.4 *Concentration of O_2 and CO_2 in inspired air*

To calculate $\dot{V}O_2$ it is necessary to insert values for both F_IO_2 and F_ICO_2 in equation (5), whilst to calculate $\dot{V}CO_2$ it is necessary to insert a value for F_ICO_2 in equation (6). Typically inspired gas fractions are not measured when the Douglas bag method is used; instead it is assumed that F_IO_2 is 0.2093 and that F_ICO_2 is 0.0003 (Davis, 1995; McArdle et al., 1991). To assess the validity of these assumptions, measurements of both F_IO_2 and F_ICO_2 were made during various exercise tests. This was accomplished by calibrating the gas analysers to outside air (see section 5.5.5), and running a sample line from the analysers to a position at the front of the treadmill, within 1 m of the mouth of the subject. Initially it was found that the average F_IO_2 ranged from 0.2081 to 0.2087 whilst the average F_ICO_2 ranged from 0.0008 to 0.0012 for three exercise tests. The extent to which the inspired gas fractions deviated from those of outside air appeared to depend on how many subjects were exercising in the lab at the time the measurements were made. Furthermore, during lengthy tests, F_IO_2 tended to decrease and F_ICO_2 tended to increase over the course of the test.

For a typical subject exercising close to $\dot{V}O_{2peak}$, F_EO_2, F_ECO_2, and $\dot{V}_{E\,(STPD)}$ might be 0.175, 0.04, and 150 $L.min^{-1}$, respectively. These figures can be used in conjunction with values for F_IO_2 and F_ICO_2 to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ (equations (5) and (6), respectively). Using values of 0.2093 and 0.0003 for F_IO_2 and F_ICO_2 in these equations yields values of 4.931 $L.min^{-1}$, 5.955 $L.min^{-1}$, and 1.208, respectively, for $\dot{V}O_2$, $\dot{V}CO_2$, and RER. However, using values of 0.2081 and 0.0012 for F_IO_2 and F_ICO_2 yields values for $\dot{V}O_2$ (4.74 $L.min^{-1}$), $\dot{V}CO_2$ (5.82 $L.min^{-1}$), and RER (1.228) that are 3.9% lower, 2.3% lower, and 1.9% higher, respectively, than those which would be obtained were F_IO_2 and F_ICO_2 assumed to be 0.2093 and 0.0003. The data presented in the previous paragraph suggest that F_IO_2 might be as low as 0.2081 and F_ICO_2 might be as high as 0.0012 when an exercise test is conducted in a poorly ventilated laboratory. Furthermore, since it was always the case that when F_IO_2 was low F_ICO_2 was high, it is reasonable to suggest that the situation in which F_IO_2 is 0.2081 and F_ICO_2 is 0.0012 represents a realistic worst case scenario.

The above calculations show that in such a situation meaningful errors would be incurred if standard "outdoor" values for F_IO_2 and F_ICO_2 (0.2093 and 0.0003) were used in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. Because the extent to which the observed values for F_IO_2 and F_ICO_2 differed from the corresponding "outdoor" values varied both within and between tests it was not possible to eliminate these errors by using an alternative set of standard values for F_IO_2 and F_ICO_2. In fact, the implication was that the actual concentrations of O_2 and CO_2 in a subject's inspirate should be repeatedly measured over the course of an exercise test. Such measurements are not easy to make, and hence a further investigation was carried out to ascertain whether the consistency of the inspired gas fractions, both between and within tests, could be improved by improving the ventilation to the laboratory.

The measurements of F_IO_2 and F_ICO_2 mentioned above were obtained when all windows in the laboratory were shut. To evaluate the effect of increasing the ventilation to the laboratory, measurements of F_IO_2 and F_ICO_2 were made as described above during 16 exercise tests, all of which were conducted with one window open a small amount (~0.5 m). During these tests, F_IO_2 averaged 0.2091, with a standard deviation of 0.00008, whilst F_ICO_2 averaged 0.00062, with a standard deviation of 0.00007. Moreover, both F_IO_2 and F_ICO_2 remained essentially constant throughout all of these tests.

Because the consistency of both F_IO_2 and F_ICO_2 was very high when the window was open, it was decided that there was no need to routinely measure the inspired gas fractions for all exercise tests. Instead it was decided that all tests would be conducted with one window open, and that values of 0.2091 and 0.0006 would be used for F_IO_2 and F_ICO_2 in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$. For the situation in which F_IO_2 is 0.2091 and F_ICO_2 is 0.0006, the term $F_IO_2/(1 - F_IO_2 - F_ICO_2)$ in equation (5) simplifies to 0.2091/(1 - 0.2091 - 0.0006), or 0.2646. Thus equation (5) can be simplified to give the following equation [equation (7)] for the determination of $\dot{V}O_2$

$$\dot{V}O_{2\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \times \left(0.2646 \times (1 - F_EO_2 - F_ECO_2) - F_EO_2\right).$$

Similarly, equation (6) can be simplified to give the following equation [equation (8)] for the determination of $\dot{V}CO_2$

$$\dot{V}CO_{2\,(STPD)} = \dot{V}_{E\,(ATPS)} \times \frac{273 \times (P_B - P_{H_2O})}{T_{EXP} \times 760} \times \left(F_ECO_2 - 0.0006\right).$$

If equation (7) is used to calculate $\dot{V}O_2$, the calculated $\dot{V}O_2$ will be in error if F_IO_2 differs from 0.2091 or F_ICO_2 differs from 0.0006. From the measurements of F_IO_2 and F_ICO_2 made during 16 exercise tests (see above), confidence limits can be derived for both F_IO_2 and F_ICO_2. The 95% confidence limits for F_IO_2 are 0.2091 ± (1.96 × 0.00008), or 0.20894 to 0.20926, whilst those for F_ICO_2 are 0.00062 ± (1.96 × 0.00007), or 0.00048 to 0.00076. However, it was always the case that a relatively low F_IO_2 was associated with a relatively high F_ICO_2, and it can therefore be argued that there are effectively two extreme situations: one where F_IO_2 is 0.20894 and F_ICO_2 is 0.00076; and another where F_IO_2 is 0.20926 and F_ICO_2 is 0.00048. In the former situation, a value of 0.2644 is obtained for the term $F_IO_2/(1- F_IO_2 - F_ICO_2)$, whilst in the latter, a value of 0.2648 is obtained. Equation (7) assumes a value of 0.2646 for this term, and when this equation is used to calculate $\dot{V}O_2$ from the example data given above (F_EO_2 = 0.175, F_ECO_2 = 0.04, and $\dot{V}_{E\,(STPD)}$ = 150 L.min^{-1}), a $\dot{V}O_2$ of 4.907 L.min^{-1} is obtained. Replacing the 0.2646 in equation (7) with 0.2644 decreases the calculated $\dot{V}O_2$ by ~0.5% (to 4.883 L.min^{-1}), whilst replacing it with 0.2648 increases the calculated $\dot{V}O_2$ by ~0.5% (to 4.930 L.min^{-1}). Thus, provided the laboratory is well ventilated, the variation in the inspired gas fractions should be such that the error incurred in using equation (7) to calculate $\dot{V}O_2$ will rarely exceed 0.5%. Since inspired gas fractions were found to be constant throughout even lengthy exercise tests when the window was open, negligible variability in $\dot{V}O_2$ should occur within a test as a result of variation in the true inspired gas fractions. Even between tests, only rarely should the variability in $\dot{V}O_2$ associated with variation in these fractions exceed ±0.5%.

Similar calculations to those outlined above for $\dot{V}O_2$ can be performed for $\dot{V}CO_2$. These calculations reveal that the (inter-test) variability in $\dot{V}CO_2$ associated with variation in the inspired gas fractions should rarely exceed ±0.4%. However, as was stated previously, when F_IO_2 was low, F_ICO_2 was always high, and vice versa. When F_IO_2 is <0.2091, equation (7) will overestimate $\dot{V}O_2$, but similarly, when F_ICO_2 is >0.0006, equation (8) will overestimate $\dot{V}CO_2$. This means that the error incurred in $\dot{V}CO_2$ as a result of variation in the inspired gas fractions will always be in the same direction as that incurred in $\dot{V}O_2$. The implication is that the effect of such variation on the calculated RER is small. Indeed it can be calculated that when equations (7) and (8) are used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ respectively, only rarely should the (inter-test) variability in RER associated with variation in the inspired gas fractions exceed ±0.2%.

5.5.5 *Determination of F_EO_2 and F_ECO_2*

5.5.5.1 Potential impact on the determination of $\dot{V}O_2$ and $\dot{V}CO_2$

Errors in the measurement of expired gas fractions, particularly errors in the measurement of F_EO_2, can have a considerable impact on the determination of $\dot{V}O_2$, $\dot{V}CO_2$, and RER. Tables 5.2 and 5.3 show the effect of a 1% increase in F_EO_2 and F_ECO_2, respectively, on the calculated values for $\dot{V}O_2$, $\dot{V}CO_2$, and RER. In compiling these tables, three sets of values for F_EO_2, F_ECO_2, and $\dot{V}_E$ were chosen. Values for F_EO_2 and F_ECO_2 were selected to span the range of values likely to be encountered during exercise in a normal subject. Fractional concentrations of O_2 and CO_2 were combined in such a way as to yield values for RER that might realistically be obtained during exercise of moderate, heavy, and severe intensity, and values of $\dot{V}_E$ were chosen which gave realistic values for $\dot{V}O_2$ and $\dot{V}CO_2$. Equation (7) was used to calculate $\dot{V}O_2$, whilst $\dot{V}CO_2$ was calculated using equation (8).

Table 5.2. Effect of a 1% increase in F_EO_2 on calculated values for $\dot{V}O_2$, $\dot{V}CO_2$, and RER, at 3 levels of exercise intensity.

Exercise intensity	$\dot{V}_{E\,(STPD)}$ (L.min^{-1})	F_EO_2	F_ECO_2	$\dot{V}O_2$ (L.min^{-1})	$\dot{V}CO_2$ (L.min^{-1})	RER
moderate	40	0.1500	0.050	2.467	1.976	0.801
moderate	40	0.1515	0.050	2.391	1.976	0.826
percent change		+1.0%	-	-3.1%	-	+3.2%
heavy	80	0.1650	0.041	3.608	3.232	0.896
heavy	80	0.1667	0.041	3.441	3.232	0.939
percent change		+1.0%	-	-4.6%	-	+4.9%
severe	160	0.1800	0.032	4.561	5.024	1.102
severe	160	0.1818	0.032	4.197	5.024	1.197
percent change		+1.0%	-	-8.0%	-	+8.7%

Table 5.3. Effect of a 1% increase in F_ECO_2 on calculated values for $\dot{V}O_2$, $\dot{V}CO_2$, and RER, at 3 levels of exercise intensity.

Exercise intensity	$\dot{V}_{E\,(STPD)}$ (L.min^{-1})	F_EO_2	F_ECO_2	$\dot{V}O_2$ (L.min^{-1})	$\dot{V}CO_2$ (L.min^{-1})	RER
moderate	40	0.150	0.05000	2.467	1.976	0.801
moderate	40	0.150	0.05050	2.462	1.996	0.811
percent change		-	+1.0%	-0.21%	+1.0%	+1.2%
heavy	80	0.165	0.04100	3.608	3.232	0.896
heavy	80	0.165	0.04141	3.599	3.265	0.907
percent change		-	+1.0%	-0.24%	+1.0%	+1.3%
severe	160	0.180	0.03200	4.561	5.024	1.102
severe	160	0.180	0.03232	4.547	5.075	1.116
percent change		-	+1.0%	-0.30%	+1.0%	+1.3%

It is apparent from table 5.2 that a small error in the measured value of F_EO_2 will translate into a large error in the calculated values for both $\dot{V}O_2$ and RER. This "magnification" of the error occurs because the measured value of F_EO_2 is used twice in the calculation of $\dot{V}O_2$ and the error introduced at the first stage of the calculation is in the same direction as that which is introduced at the second stage [see equation (7)]. Of all the variables used in the calculation of $\dot{V}O_2$, F_EO_2 is the only one that is used more than once, and consequently it is the only variable for which this magnification effect occurs. In the calculation of $\dot{V}CO_2$, no variable is used twice, so this magnification effect does not occur. This is illustrated in tables 5.2 and 5.3, which show that a 1% increase in F_ECO_2 results in a 1% increase in the calculated $\dot{V}CO_2$ and a small (0.2 to 0.3%) decrease in the calculated $\dot{V}O_2$.

The data presented in table 5.2 suggest that the calculation of $\dot{V}O_2$ (and consequently RER) is most sensitive to errors in the measurement of F_EO_2 for those values of F_EO_2

and F_ECO_2 that would typically be observed during severe exercise. This suggests that for the accurate determination of $\dot{V}O_2$ at intensities close to that at which $\dot{V}O_2$ might plateau, accurate measurement of F_EO_2 is paramount. It is for this reason that considerable attention has been focused on the development of equipment and procedures for the accurate measurement of F_EO_2. Though F_ECO_2 is considered of secondary importance, many of the factors that affect the accuracy and precision with which F_EO_2 can be determined also affect the accuracy and precision with which F_ECO_2 can be determined. It is likely therefore that use of the equipment and procedures outlined below will also allow F_ECO_2 to be determined with a high degree of accuracy and precision.

5.5.5.2 Measured vs. true gas fractions

When equation (7) is used to determine $\dot{V}O_2$, and the values for F_EO_2 and F_ECO_2 used in this equation are the fractional concentrations of O_2 and CO_2 determined by passing a sample of expirate (from a Douglas bag) through O_2 and CO_2 analysers, the accuracy and precision with which $\dot{V}O_2$ can be determined will depend on two factors (in addition to those factors already discussed). Firstly, it will depend on the accuracy and precision with which the fractional concentration of each of these gases can be determined, and secondly, it will depend on how accurately the composition of the sample of expirate passed through the analysers reflects that of the actual expirate that was collected from the subject. Most physiologists seem to be aware of the importance of the first factor, but presently there appears to be a lack of awareness of the potential importance of the second factor. Issues surrounding the calibration of O_2 and CO_2 analysers are related to the first factor, and such issues tend to be given considerable attention in the method sections of physiology papers published in scientific journals. However, in the same papers, the implication of the fact that a plastic Douglas bag can never be completely emptied tends to be overlooked. The implication is that the concentrations of O_2 and CO_2 in a sample of expirate collected in such a bag will be affected by the volume and the composition of the air present in the bag before collection begins.

If an uncontaminated sample of expirate could be collected, and the fractional concentrations of O_2 and CO_2 in this sample could be measured, completely free from measurement error, the true values of F_EO_2 and F_ECO_2 could be established. However, in practice it is not possible to collect a completely uncontaminated sample of expirate in a plastic Douglas bag, and it is equally impossible to obtain a value for the fractional concentration of O_2 or CO_2 in a sample of expirate that is completely free from measurement error. The aim should be to use values for F_EO_2 and F_ECO_2 in the calculation of $\dot{V}O_2$ and $\dot{V}CO_2$ that are as close as possible to the true values. This will only be achieved if steps are taken to ensure that both the effect of contamination on the composition of a sample of expirate and the errors associated with measuring the concentrations of O_2 and CO_2 in this sample are minimised. The following sections describe the procedures that were used to derive values for F_EO_2 and F_ECO_2 for each of the studies reported in this thesis.

5.5.5.3 System for the measurement of O_2 and CO_2 concentrations in expirate

The system used to analyse samples of expirate for the concentration of O_2 and CO_2 is shown in figure 5.4 below.

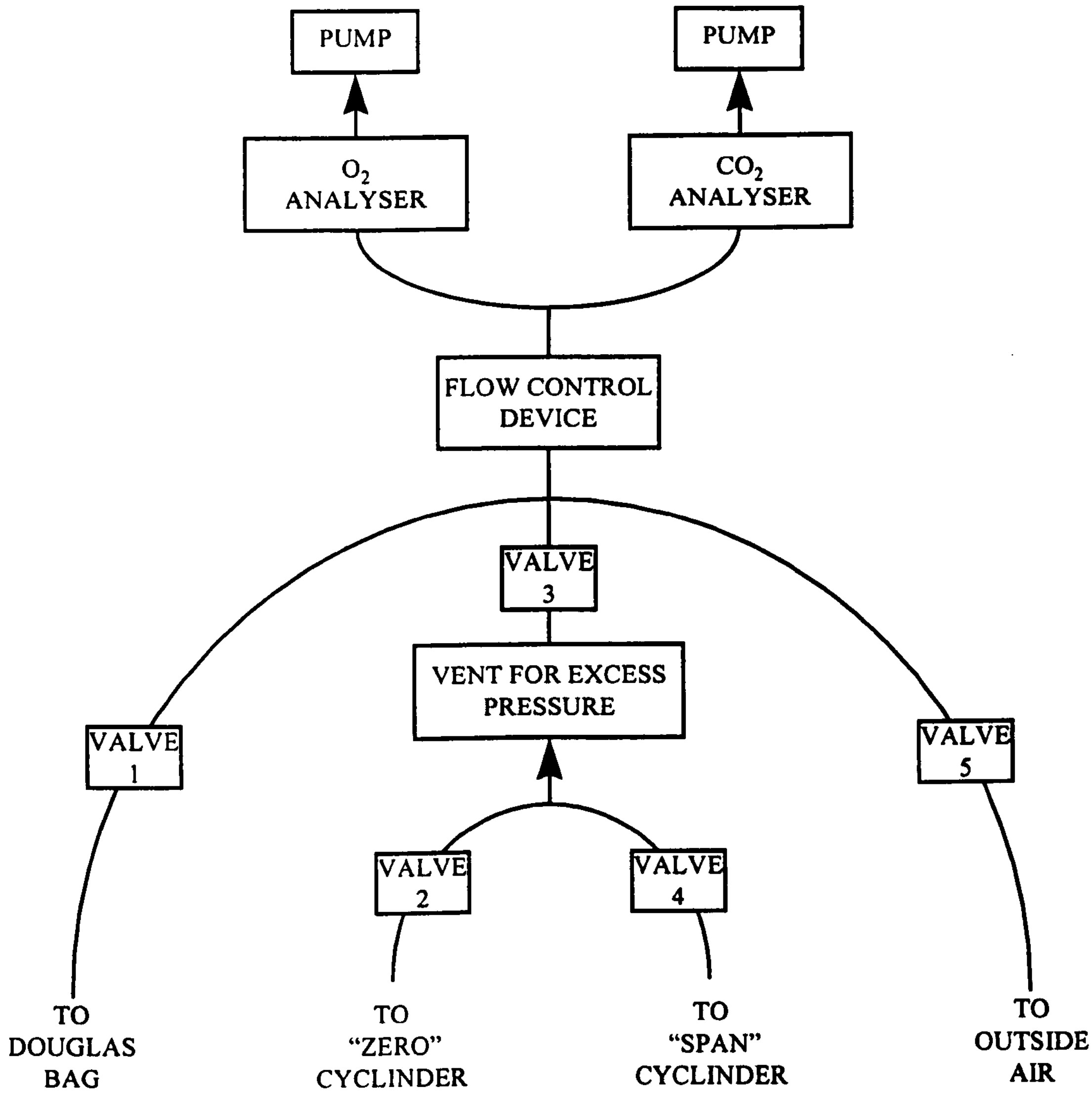

Figure 5.4. Schematic of the basic system used to analyse samples of expirate for the concentration of O_2 and CO_2.

The concentrations of O_2 and CO_2 in expirate were measured using a paramagnetic oxygen analyser and an infrared CO_2 analyser (series 1400; Servomex plc, Crowborough, UK). The O_2 analyser was calibrated using reference gases and outside air, and the CO_2 analyser was calibrated using reference gases only (see section 5.5.5.6). The reference gases used for calibration were stored under pressure (200 bar), and it was important that the gas analysers were not exposed to these high pressures, so a flow control device [a needle-valve controlled flow meter (Griffin and George, Loughborough, UK)] was introduced "upstream" of the analysers, with a pressure vent introduced upstream of this flow meter. Flow to the gas analysers was controlled at 400 ml.min^{-1}, and the pressure regulators on the bottles in which the reference gases were stored were set to ensure that the rate at which these gases were released was just above 400 ml.min^{-1}; the excess was expelled through the vent. It was important that expirate, outside air, and each of the reference gas mixtures entered the analysers at the same flow rate because, for a given concentration of O_2 or CO_2 in a gas mixture, the reading obtained on a partial pressure analyser is proportional to the rate at which this sample passes through the analysers. Additionally, it was important that this flow rate was known because, provided expirate was passed through the analysers for a known period of time, the volume of expirate lost in this process could be calculated and this volume could be added to the reading obtained when the Douglas bag was evacuated through the dry gas meter.

The five valves shown in figure 5.4 are electronically controlled solenoid valves (Pneumax, Gosport, UK). When expirate is sampled, only valve 1 is open, and similarly when outside air is sampled only valve 5 is open. (In both these situations, valve 3 is shut to prevent any inflow of room air through the pressure vent.) When either of the reference gases is sampled, valves 1 and 5 are closed, and valve 3 is open. However, when gas from the "zero" cylinder is sampled, valve 2 is open and valve 4 is closed, whilst when gas from the "span" cylinder is sampled, valve 4 is open and valve 2 is closed.

5.5.5.4 Control of water vapour content in gases entering the analysers

Both the (paramagnetic) O_2 analyser and the (infrared) CO_2 analyser shown in figure 5.4 are partial pressure analysers (i.e. both analysers measure the partial pressure generated by the specified gas, not the absolute concentration of this gas). In this type of analyser water vapour acts as a diluent, such that if a sample of expirate (which is saturated with water vapour at room temperature) was analysed wet, and the same sample was then dried and re-analysed, both the O_2 and the CO_2 analyser would give a higher reading for the dry expirate than they gave for the wet expirate (Beaver, 1973; Norton and Wilmore, 1975). The O_2 analyser was calibrated using both outside air and a reference (bottled) gas mixture. Outside air is partially saturated (its water vapour content is proportional to the ambient temperature and the relative humidity), whilst bottled gases are dry, and expirate is fully saturated (at normal room temperature). It is theoretically possible to calibrate a partial pressure analyser and make subsequent measurements of expirate with this analyser without controlling the water vapour content of the gas mixtures entering the analyser, but in practice this approach is problematic. The problem is that gas mixtures are not passed directly into the analysers; they must first travel along a length of tubing and, in the case of the system in figure 5.4, through 1 or 2 valves and a flow meter. Norton and Wilmore (1975) pointed out that when a dry (bottled) gas mixture is sampled after a moist mixture (e.g. expirate), this dry mixture will "pick up" moisture from the inlet tubing, and will thus become at least partially humidified, before it reaches the analyser. The end result, they suggest, is that the concentration read by the analyser will gradually increase to the nominal (dry) value as this moisture is carried away and the calibration mixture reaching the analyser becomes progressively drier.

Although Norton and Wilmore only consider the situation where dry calibration gases are sampled after moist gases, it seems likely that a similar effect might occur when a moist gas mixture (e.g. expirate) is sampled after a dry gas, particularly when the system in figure 5.4 is used. That is, it is likely that some of the water vapour in the expirate will initially be lost as water condenses in the (dry) tubing and on the (dry) valves. Were this to occur, the measured concentrations of O_2 and CO_2 would continue to decrease for some time because the water vapour content of the expirate reaching the analysers would increase slowly.

To investigate the extent to which this occurs, repeat measurements were made on the same sample of expirate under two conditions. In the first of these, the system shown in figure 5.4 was used, but no attempt was made to control the water vapour content of the gas mixtures entering the analysers. In the second, the system shown in figure 5.4 was again used, but this time a condenser was added to the system, between the flow meter and the analysers. The idea was that as expirate passed through this condenser, the majority of the water vapour would condense out, and the water vapour content of the expirate would be maintained at a constant, low level.

The results of this investigation are presented in table 5.4 (below). Note the gradual decrease in the measured O_2 and, to a lesser extent, CO_2 concentrations that occurred over the first 5 min of sampling when the water vapour content was not controlled. This decrease did not occur when the water vapour content of the expirate entering the analysers was controlled by means of the condenser.

Table 5.4. Change in concentrations of O_2 and CO_2 for repeated analyses of a sample of expirate, with and without water vapour control.

	Without condenser		With condenser	
Time from start of sampling (min)	Measured %O_2	Measured %CO_2	Measured %O_2	Measured %CO_2
1	16.31	4.46	16.37	4.47
2	16.26	4.46	16.38	4.47
3	16.24	4.45	16.38	4.47
4	16.22	4.45	16.37	4.47
5	16.21	4.44	16.38	4.47
6	16.20	4.45	16.37	4.47
7	16.20	4.44	16.36	4.47
8	16.19	4.44	16.37	4.47

On the basis of these results it was decided that all gas mixtures would be passed through a condenser on their way to the analysers. The aim was to ensure that, regardless of whether the mixture being analysed was a calibration mixture, outside air, or expirate, by the time it reached the analysers its water vapour content was at a constant (low) level. The condenser used was a specialist piece of equipment (Bühler PKE 3; Paterson Instruments, Leighton Buzzard, UK). It consists of an aluminium core, the temperature of which is maintained within a narrow range (5.0 ± 0.1 °C) by an electrical cooling unit. At this temperature, the saturated vapour pressure of water is 6.47 ± 0.05 mmHg, so when expirate is passed through this condenser prior to analysis, the water vapour content of the sample that enters the analysers should be controlled within a very narrow range. It is, however, also important that the outside air and the bottled gas mixtures used for calibration enter the analysers with the same water vapour content as this expirate. Since bottled gases are dry, and the vapour pressure of water in outside air will, on some days, be less than 6.5 mmHg (see Appendix 2), it was decided that each gas mixture should be saturated with water vapour before it entered the condenser. This was achieved by passing all gases through a length of Nafian tubing, which was submerged in water (at room temperature) (see figure 5.5, below).

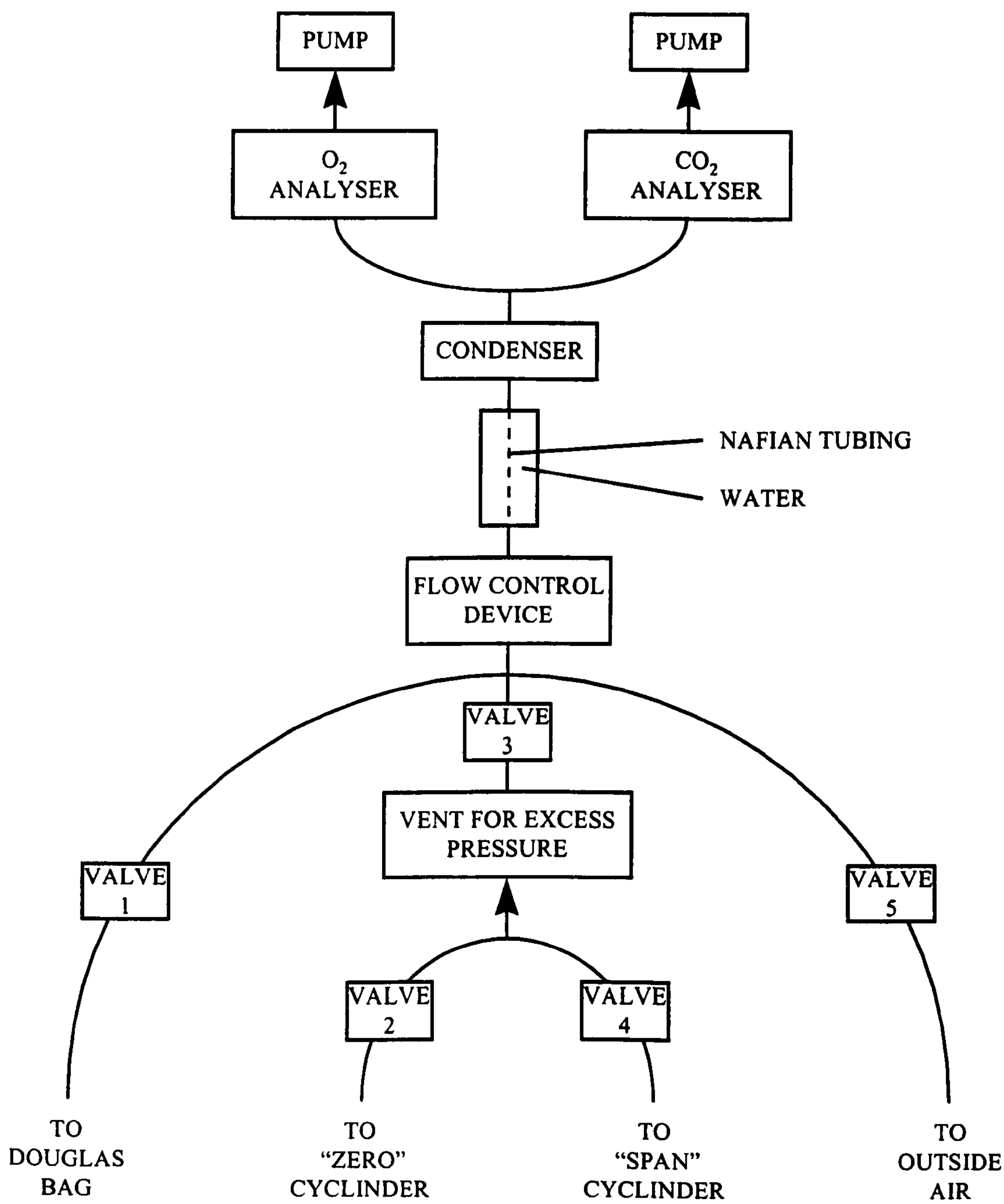

Figure 5.5. Schematic of the complete system used to analyse samples of expirate for the concentration of O_2 and CO_2.

Nafian tubing (Omnifit Ltd, Cambridge, UK) is specialist tubing that is selectively permeable to water vapour. An initial attempt was made to saturate all gas mixtures by bubbling them through water but this approach was associated with an exceptionally long response time for both the O_2 and the CO_2 analyser. This effect was most pronounced for CO_2 and it was most pronounced when a mixture with a relatively high CO_2 concentration was sampled. The amount of water used was ~150 ml, so it is likely that the slow response reflects the fact that CO_2, in particular, dissolves in this water when expirate is sampled. Only once this water has been effectively saturated with CO_2 would a mixture which has the same CO_2 concentration as the sample of expirate reach the analysers.

5.5.5.5 Response time for the gas analysers

The time to full response was determined for each analyser by sampling expirate at regular intervals. The system shown in figure 5.5 was used, so the response times thus determined represent the response times for this system as a whole. For each analyser, the measured response time will reflect the time required to wash-out the dead space of this system, as well as the response kinetics of the analyser. In table 5.5 (below), the values given for each time point are mean values for 16 measurements of F_EO_2 or F_ECO_2.

Table 5.5. Response kinetics of entire gas analysis system for O_2 and CO_2.

Time from start of sampling (sec)	Measured %O_2 (mean ± SD)	Measured %CO_2 (mean ± SD)
20	16.00 ± 0.15	4.70 ± 0.12
30	15.96 ± 0.15	4.72 ± 0.12
40	15.96 ± 0.15	4.73 ± 0.12
50	15.96 ± 0.15	4.73 ± 0.12
60	15.96 ± 0.15	4.73 ± 0.12

These results show that a stable reading was obtained on the O_2 analyser after 30 seconds and on the CO_2 analyser after 40 seconds. Throughout this thesis, expirate (and, where appropriate, a calibration gas mixture or outside air) was sampled for 60 seconds. Readings were taken in the last 10 seconds of this period, by which time stable values had always been reached on both analysers.

5.5.5.6 Calibration of gas analysers

A two point calibration (zero and span) was available for both the O_2 and the CO_2 analyser. In each case, adjusting the zero setting was equivalent to altering the intercept of a (linear) function relating the analyser reading to the output from the sample cell, whilst adjusting the span was equivalent to altering the slope of this relationship. For both analysers, the zero setting was adjusted to ensure that the reading on the analyser was zero when bottled nitrogen was passed through the analyser (i.e. the "zero" gas in figures 5.4 and 5.5 was nitrogen). For the O_2 analyser, the span setting was adjusted to ensure that the reading on the analyser was 20.93% when outside air was passed through the analyser, whilst for the CO_2 analyser the span setting was adjusted to ensure that the reading on the analyser was 6.00% when a sample from a gravimetrically prepared cylinder of a reference gas mixture (6.00% CO_2, 15.00% O_2, balance nitrogen), the "span" gas in figures 5.4 and 5.5, was passed through the analyser. The procedure adopted was as follows:

1) the zero adjustment was made for both analysers;
2) the span adjustment was made for the O_2 analyser;
3) the span adjustment was made for the CO_2 analyser.

This procedure allowed the linearity of the O_2 analyser to be checked each time the analysers were calibrated by comparing the reading obtained on this analyser at stage 3 with the nominal concentration of O_2 in the reference ("span") gas mixture. The linearity of the CO_2 analyser was not checked this often, but it was checked before and after each study by passing a sample from a second (gravimetrically prepared) reference gas mixture (3.00% CO_2, balance nitrogen) through the analysers after stage 3. For a nominal concentration of 15.00 %O_2, the O_2 analyser always gave a reading of 15.00 or 14.99%, and for a nominal concentration of 3.00 %CO_2, the CO_2 analyser consistently gave a reading of 3.02%.

The justification for the use of gravimetrically prepared calibration gas mixtures (Linde gas UK Ltd, London, UK) is that the precision with which these mixtures can be prepared is equal to, if not better than, that of the common volumetric techniques available for measuring the concentration of O_2 or CO_2 in a gas mixture. When a gas mixture is prepared gravimetrically, high precision load cells are used. These cells are calibrated regularly against British Standards, and are capable of measuring mass with a maximum error of 1 g for all masses from 0 to 10 kg. It can be calculated (by using the ideal gas equation and correcting for the non-ideal behaviour of the real gases in the mixture) that in a 50 L cylinder of 15% O_2 and 6% CO_2 in nitrogen the mass of the O_2 component is 2.043 kg and that of the CO_2 component is 1.124 kg (at a pressure of 200 bar). The worst case scenario would be an error of +1 g in the component of interest and an error of -1 g in both of the other components (or vice versa). In such a situation, the actual O_2 concentration associated with a nominal concentration of 15.00% would be 14.992 or 15.008%, whilst the actual CO_2 concentration associated with a nominal concentration of 6.00% would be 5.994 or 6.006%. It seems reasonable to conclude, therefore, that the true concentrations of O_2 and CO_2 in a gravimetrically prepared gas mixture will always be within 0.01% (absolute) of the nominal concentrations.

Howley et al. (1995) appear to be sceptical of the precision with which such gas mixtures can be prepared. They recommend that the concentrations of O_2 and CO_2 in gas mixtures used for the calibration of manometric analysers are measured using volumetric techniques such as those developed by Haldane (Haldane and Priestly, 1935) and Scholander (Scholander, 1947). The precision of these two methods is similar, but for both methods the precision is lower than that with which gas mixtures can be prepared gravimetrically. For the Haldane method, Consolazio et al. (1963) suggest that operators should be considered unreliable if they cannot obtain results from duplicate analyses of a given gas mixture that agree within 0.03% (absolute) for CO_2 and 0.04% (absolute) for O_2. For gas analysis using the Scholander apparatus, Hermansen (1973) reports a standard deviation for 10 repeat analyses of the same gas mixture (15.8% O_2, 6.2% CO_2) of 0.03% for O_2 and 0.02% for CO_2. From these data, it can be estimated that if repeat analyses of the same gas mixture are performed, and the Scholander method is used, the (absolute) concentrations could conceivably differ by as much as 0.06% for O_2 and 0.05% for CO_2.

Volumetric methods could certainly be used in the production of gravimetrically prepared gas mixtures. A gas mixture could be prepared by using the ideal gas equation to calculate the mass of each component and then the true concentration of each component could be determined volumetrically. This would allow the predicted mass to be compared with the actual mass, and provided this was done enough times it would be possible to derive an appropriate correction to the ideal gas equation for each component in a particular mixture. These corrected equations could then be used to prepare gas mixtures for which the actual concentration of O_2 or CO_2 is within ±0.01% (absolute) of the nominal concentration (see above). Such a mixture could also be analysed volumetrically to check the actual concentrations of O_2 and CO_2 as Howley et al. suggest. However, because the precision of the available volumetric techniques is relatively low it would be necessary to make repeat determinations of the true O_2 and CO_2 concentrations for a given gas mixture. Given that the maximum likely error in the actual O_2 or CO_2 concentration for a typical gravimetrically prepared mixture is 0.01% (absolute), it seems that there is little to be gained by analysing such mixtures with either the Haldane or the Scholander method prior to using them to calibrate electronic (manometric) gas analysers.

5.5.5.7 Accuracy and precision of measured O_2 and CO_2 concentrations in expirate

In the above section, data have been presented which suggest that the concentrations of O_2 and CO_2 in a gas mixture can be measured very accurately with the system shown in figure 5.5. These data suggest that the systematic error in the measurement of O_2 concentration is unlikely to exceed 0.01% (absolute) and the corresponding error for CO_2 is unlikely to exceed 0.02% (absolute). To determine the precision with which the concentrations of O_2 and CO_2 in expirate can be measured with the system shown in figure 5.5, repeat analyses were performed on two different samples of expirate. The data obtained from these analyses are given in table 5.6 below.

Table 5.6. Percentage concentrations of O_2 and CO_2 for repeated analyses of two samples of expirate.

	Sample 1		Sample 2	
Measurement number	Measured $\%O_2$	Measured $\%CO_2$	Measured $\%O_2$	Measured $\%CO_2$
1	15.37	5.01	18.10	3.05
2	15.37	5.01	18.10	3.06
3	15.37	5.01	18.10	3.05
4	15.37	5.01	18.10	3.05
5	15.37	5.01	18.10	3.05
6	15.38	5.01	18.10	3.05
7	15.37	5.01	18.10	3.06
8	15.38	5.01	18.10	3.05

Table 5.6 shows that the variability in repeated measurements made on the same sample of expirate is low. Indeed, on the basis of these data, it seems reasonable to conclude that the random error in the measured concentration is unlikely to exceed 0.01% (absolute) for O_2 or CO_2. Equation (7) can be used to calculate that the maximum likely error in the calculated $\dot{V}O_2$ associated with an (absolute) error of 0.01% in the measured F_EO_2 is 0.4%. The calculated $\dot{V}O_2$ is, however, also sensitive to errors in the measured F_ECO_2. Whilst an error of 0.01% in F_EO_2 is associated with an error of 0.4% in $\dot{V}O_2$, the situation in which an error of +0.01% is present for both F_EO_2 and F_ECO_2 is associated with an error of -0.5% in $\dot{V}O_2$, and if the error in F_ECO_2 is +0.02%, the associated error in $\dot{V}O_2$ is 0.6%. Hence it can be concluded that, for $\dot{V}O_2$, the worst case scenario is that there will be a systematic error of 0.6% and a random error of 0.5%.

Calculations can also be performed for $\dot{V}CO_2$ [using equation (8)]. These calculations are straight forward because F_EO_2 does not enter into the calculation of $\dot{V}CO_2$; they lead to the conclusion that, for $\dot{V}CO_2$, the worst case scenario would be a systematic error of 0.7% and a random error of 0.3%. To estimate the errors that might be incurred in RER, it is necessary to consider errors in both F_EO_2 and F_ECO_2. In terms of systematic errors, the worst case scenario would be a +0.01% error in F_EO_2 (this would decrease $\dot{V}O_2$) with a +0.02% error in F_ECO_2 (this would both decrease $\dot{V}O_2$ and increase $\dot{V}CO_2$). Similarly, in terms of random errors, the worst case scenario would be a +0.01% error in F_EO_2 with a +0.01% error in F_ECO_2. The former scenario would be associated with a (systematic) error in RER of 1.3%, whilst the latter would be associated with a (random) error of 0.9%.

5.5.5.8 Potential significance of the contamination of expirate that occurs when the Douglas bag method is used

The above consideration of the potential errors involved in the measurement of O_2 and CO_2 concentrations has focused on the accuracy and precision with which these concentrations can be measured in a sample of expirate. Little consideration has so far been given to the contamination of samples of expirate that is likely to occur when expirate is collected in Douglas bags. However, as has been mentioned previously, the fact that a plastic Douglas bag can never be completely evacuated has potentially important implications for the determination of the true values for F_EO_2 and F_ECO_2. For example, suppose a subject exhales a volume of 40 L (ATPD) into a Douglas bag and when the contents of this bag are analysed the (dry) concentrations of O_2 and CO_2 are found to be 15.0% and 5.0% respectively. Further suppose that before any of the subject's expirate reached the bag, 1 L (ATPD) of room air (20.91% O_2, 0.06% CO_2) was present in the bag. The subject's expirate would mix with this room air and the measured concentrations of O_2 and CO_2 would reflect this mixing. If $F_EO_{2\,(TRUE)}$ is the true concentration of O_2 in the subject's expirate and V_{RES} is the residual volume of the Douglas bag (the volume of air that is present in the bag before any expirate has entered), the total volume of O_2 present in the bag after 40 L of expirate have been collected is equal to $F_EO_{2\,(TRUE)} \times 40 + 0.2091 \times V_{RES}$. But the volume of O_2 present in the bag at this time is also equal to the product of the measured F_EO_2 [$F_EO_{2\,(MEAS)}$] and the total volume of air in the bag ($40 + V_{RES}$). That is,

$$F_EO_{2\,(TRUE)} \times 40 + 0.2091 \times V_{RES} = F_EO_{2\,(MEAS)} \times (40 + V_{RES}),$$

which means that

$$F_EO_{2\,(TRUE)} = F_EO_{2\,(MEAS)} + \frac{V_{RES}}{40} \times (F_EO_{2\,(MEAS)} - 0.2091) \quad .. \quad .. \quad (9).$$

Similarly, if $F_ECO_{2\,(TRUE)}$ is the true concentration of CO_2 in the subject's expirate, then

$$F_ECO_{2\,(TRUE)} = F_ECO_{2\,(MEAS)} + \frac{V_{RES}}{40} \times (F_ECO_{2\,(MEAS)} - 0.0006) \quad .. \quad (10).$$

Inserting values of 0.15 for $F_EO_{2\,(MEAS)}$ and 1.0 L for V_{RES} in equation (9) gives a value for the true F_EO_2 of 0.1485, and inserting values of 0.05 for $F_ECO_{2\,(MEAS)}$ and 1.0 L for V_{RES} in equation (10) gives a value for the true F_ECO_2 of 0.0512. When values for F_EO_2 and F_ECO_2 of 0.15 and 0.05 are used in equation (7), the $\dot{V}O_2$ obtained is 2.30 L.min^{-1} (for a $\dot{V}_{E\,(ATPD)}$ of 40 L.min^{-1}, assuming ambient temperature and pressure to be 20 °C and 760 mmHg), but when values of 0.1485 and 0.0512 are used, the $\dot{V}O_2$ obtained is 2.36 L.min^{-1} (i.e. 2.6% higher). When $F_EO_{2\,(TRUE)}$ and $F_ECO_{2\,(TRUE)}$ are calculated for values of $F_EO_{2\,(MEAS)}$ and $F_ECO_{2\,(MEAS)}$ that might realistically be observed during severe exercise (18 %O_2 and 3.2 %CO_2), values of 0.1793 and 0.0328 are obtained (assuming a residual volume of 1 L and a V_E of 40 L). Although the differences between the true and the measured gas fractions are smaller in this situation, $\dot{V}O_2$ is very sensitive to changes in F_EO_2 in this intensity domain (see table 5.2), so the impact on $\dot{V}O_2$ is still considerable (the $\dot{V}O_2$ obtained when gas fractions of 0.1793 and 0.0328 are used is 2.4% higher than that which is obtained when gas fractions of 0.18 and 0.032 are used).

Equations (9) and (10) are very similar. For both F_EO_2 and F_ECO_2, the extent to which the true gas fraction differs from the measured gas fraction depends on two factors: the ratio of V_{RES} to V_E (V_{RES}/V_E) and the composition of this residual air. The smaller the residual volume, relative to V_E, the better the estimate of the true F_EO_2 (or F_ECO_2) that is provided by the measured F_EO_2 (or F_ECO_2). Similarly, the smaller the difference between the O_2 or the CO_2 concentration of the residual air and the true F_EO_2 or F_ECO_2, the better the estimate of the true F_EO_2 (or F_ECO_2) that is provided by the measured F_EO_2 (or F_ECO_2).

5.5.5.9 Controlling for the effect of contamination

The example given above where V_{RES} = 1 L (of room air), $V_{E\,(ATPD)}$ = 40 L, F_EO_2 = 0.15, and F_ECO_2 = 0.05 is a worst case scenario in that the O_2 and CO_2 fractions of the residual air are very different from those of the subject's expirate and the volume of expirate collected is small. If steps can be taken to ensure that the composition of the residual air is very similar to that of the subject's expirate, this will ensure that the differences between the measured and the true gas fractions are also very small. This approach was apparently adopted by Taylor et al. (1955) in their classic study on maximal oxygen uptake. These authors report (p. 74) that during each 3 minute run "the gas collection apparatus was flushed at least twice", with the last flushing being "completed at about 1 minute and 30 seconds of running". In Taylor et al.'s study, collection of expirate for analysis occurred "between 1 minute and 45 seconds and 2 minutes and 45 seconds of running", and it is unclear how Taylor et al. managed to evacuate a Douglas bag and recommence collecting expirate within ~15 s. Nevertheless, these quotes suggest that Taylor et al. were aware of the potential problems associated with contamination. The fact that no reports of an attempt to control for this effect could be found in the contemporary literature suggests that today's researchers may be unaware of this problem.

An approach similar to that adopted by Taylor et al. was adopted for Study 1 (Chapter 7). Prior to each test, all of the Douglas bags that were to be used in the test were evacuated, and 50-60 L of expirate was collected in each bag before all bags were evacuated again. The aim was to ensure that all these bags contained residual air of a similar composition to the expirate that would be collected during the test. In an attempt to ensure that the composition of this residual air was similar, both for all bags used in a single test and for all tests, the expirate was always collected from the same experimenter, who always performed a standard bout of moderate intensity exercise.

The basis for the procedure described above was the belief that it would be possible to decrease the effect of contamination on the measured values of F_EO_2 and F_ECO_2 to such an extent that the differences between these measured values and the true values would be trivial by flushing all Douglas bags with expirate prior to use. However, the expirate used for this flushing was collected during moderate intensity exercise and would therefore have had a relatively high CO_2 concentration and a relatively low O_2 concentration. As $\dot{V}O_2$ approaches $\dot{V}O_{2peak}$, F_EO_2 typically increases and F_ECO_2 typically decreases, so for the higher exercise intensities the expirate reaching the analysers would have had an artificially high CO_2 concentration and, importantly, an artificially low O_2 concentration. The calculated value for $\dot{V}O_2$ is very sensitive to errors in F_EO_2 (Table 5.2), and were an artificially low value for F_EO_2 to be used in this calculation $\dot{V}O_2$ would be overestimated. Thus, in Study 1, $\dot{V}O_2$ would have been overestimated for those intensities approaching that at which $\dot{V}O_{2peak}$ is attained and there might have been occasions when the presence of a $\dot{V}O_2$-plateau would have been obscured. This problem was overcome in studies 2 and 3 by using corrected values for F_EO_2 and F_ECO_2 in the calculation of $\dot{V}O_2$ (see below).

5.5.5.10 Correcting for the effect of contamination

It was decided that rather than attempting to minimise the effect of this contamination, it might be possible to correct for this effect if the size of the residual volume could be determined. The same 200 L plastic Douglas bags were used for all the studies reported in this thesis. For 4 of these bags 8 determinations of the residual volume were made and on another 8 bags 4 determinations were made. The procedure was as follows:

1) a Douglas bag was evacuated;
2) this bag was used to collect 50-60 L of expirate from a subject who was cycling at a moderate intensity (to ensure that there was a marked difference between the concentrations of O_2 and CO_2 in the expirate collected and those in ambient air);
3) the contents of the bag were mixed and the O_2 and CO_2 concentrations in the expirate were determined;
4) the Douglas bag was evacuated once more;

5) the O_2 and CO_2 concentrations in the ambient air were determined;
6) a calibration syringe was used to deliver 7 L of this ambient air to the evacuated Douglas bag;
7) the contents of the bag were mixed and a sample of its contents was analysed to determine the new O_2 and CO_2 concentrations;
8) the volume of expirate that was present in the Douglas bag after evacuation was calculated using the calculations outlined below.

If $Fo_{2\,(EXP)}$ is the fraction of O_2 in the expirate (as measured at stage 3 above), $Fo_{2\,(AIR)}$ is the fraction of O_2 in the ambient air (as measured at stage 5 above), and $Fo_{2\,(MIX)}$ is the fraction of O_2 in the air/expirate mix (as measured at stage 7 above), then

$$Fo_{2\,(MIX)} = \frac{Fo_{2\,(EXP)} \times V_{RES} + Fo_{2\,(AIR)} \times 6.9}{(6.9 + V_{RES})} \quad .. \quad .. \quad .. \quad .. \quad (11),$$

where V_{RES} is the functional residual volume for this particular Douglas bag (in L, ATPD). Although 7 L of room air were added at stage 6, it must be recognised that the analysers used were calibrated to measure gas fractions relative to the total volume of a dry gas mixture (see sections 5.5.5.4 and 5.5.5.6). A figure of 6.9 L was used in equation (11) because, for typical values of relative humidity (50%), ambient temperature (20 °C), and barometric pressure (760 mmHg), 7 L (ATPS) is equivalent to ~6.9 L (ATPD). Equation (11) can be rearranged to give

$$V_{RES} = 6.9 \times \frac{(Fo_{2\,(AIR)} - Fo_{2\,(MIX)})}{(Fo_{2\,(MIX)} - Fo_{2\,(EXP)})} \quad .. \quad .. \quad .. \quad .. \quad ... \quad .. \quad (12).$$

Similarly for CO_2,

$$Fco_{2\,(MIX)} = \frac{Fco_{2\,(EXP)} \times V_{RES} + Fco_{2\,(AIR)} \times 6.9}{(6.9 + V_{RES})},$$

which can be rearranged to give

$$V_{RES} = 6.9 \times \frac{(Fco_{2\,(AIR)} - Fco_{2\,(MIX)})}{(Fco_{2\,(MIX)} - Fco_{2\,(EXP)})} \quad .. \quad .. \quad .. \quad .. \quad .. \quad (13).$$

In each case, two residual volumes were calculated, one according to equation (12) and the other according to equation (13). The two figures were then averaged and these average values were analysed. This analysis was performed because it was suspected that the residual volume might vary between Douglas bags, depending, for instance, on how the bags hang when empty; the aim was to evaluate the variability in V_{RES} for different bags relative to that for repeat determinations on the same bag. There were effectively 2 data sets for V_{RES}: the set of values derived from the 4 determinations that were made on each of the 8 different bags (between bag data) and the set of values for the 8 determinations that were made on each of the 4 different bags (within bag data). The former set was sub-divided into 4 separate data sets, each of which contained 8 values for V_{RES} that were determined on 8 different bags. Similarly, the latter set was sub-divided into 4 data sets, each of which contained 8 values for V_{RES} that were determined on the same bag. For each of these data sets the mean V_{RES} and the SD about this mean were calculated. Thus 4 sets of values (mean and SD) were obtained from the between bag data and another 4 were obtained from the within bag data.

The mean V_{RES} ranged from 0.55 to 0.60 L for the 4 within bag data sets and from 0.55 to 0.61 L for the 4 between bag data sets. The SD about this mean V_{RES} ranged from 0.15 to 0.21 L for the within bag data and from 0.11 to 0.19 L for the between bag data. These data do not support the notion that V_{RES} varies systematically for different Douglas bags. Instead they suggest that a common V_{RES} can be assumed for all bags. This common V_{RES} was estimated from the between bag data. For the entire data set (4 values for each of 8 bags, or 32 values in total), the (mean ± SD) V_{RES} was 0.57 ± 0.15 L (95% confidence interval = 0.28 to 0.86 L).

In studies 2 and 3, all Douglas bags were flushed with room air prior to use. Each bag was flushed twice, and each time at least 50 L of air was used [the aim was to ensure that the composition of the residual air was essentially the same as that of room air (20.91% O_2; 0.06% CO_2)]. Corrected values for F_EO_2 and F_ECO_2 were calculated for each sample by assuming that the expirate that entered the analysers was contaminated with 0.57 L of room air, and these corrected values were then used in equations (7) and

(8) for the determination of $\dot{V}O_2$ and $\dot{V}CO_2$. For F_EO_2, the corrected value was calculated as follows

$$F_EO_{2\,(CORR)} = F_EO_{2\,(MEAS)} + \frac{0.57}{V_E} \times (F_EO_{2\,(MEAS)} - 0.2091) \quad .. \quad .. \quad (14),$$

where V_E is the volume collected in the Douglas bag (at ATPD).

Similarly for F_ECO_2, the corrected value was calculated as follows

$$F_ECO_{2\,(CORR)} = F_ECO_{2\,(MEAS)} + \frac{0.57}{V_E} \times (F_ECO_{2\,(MEAS)} - 0.0006) \quad .. \quad (15).$$

Equations (14) and (15) are based on equations (9) and (10) respectively, and provided the true V_{RES} is 0.57 L, $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ should be equivalent to $F_EO_{2\,(TRUE)}$ and $F_ECO_{2\,(TRUE)}$. However, if V_{RES} differs from 0.57 L, $F_EO_{2\,(CORR)}$ will differ from $F_EO_{2\,(TRUE)}$ and $F_ECO_{2\,(CORR)}$ will differ $F_ECO_{2\,(TRUE)}$. For a given error in V_{RES}, the error incurred in the calculated value for $F_EO_{2\,(CORR)}$ is a function of both V_E and $F_EO_{2\,(MEAS)}$ [equation (14)]. Similarly the error incurred in the calculated value for $F_ECO_{2\,(CORR)}$ is a function of both V_E and $F_ECO_{2\,(MEAS)}$ [equation (15)]. In both cases, the error incurred in the calculated value will be highest when V_E is small. For F_EO_2 this error will be highest when $F_EO_{2\,(MEAS)}$ is low [it is proportional to ($F_EO_{2\,(MEAS)}$ - 0.2091)], whilst for F_ECO_2 it will be highest when $F_ECO_{2\,(MEAS)}$ is high [it is proportional to ($F_ECO_{2\,(MEAS)}$ - 0.0006)]. For a given WR, V_E will increase, and therefore the variation incurred in $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ as a result of variation in V_{RES} will decrease, as the sampling period increases. Similarly, for a given sampling period, V_E will increase as exercise intensity increases. However, F_EO_2 tends to increase and F_ECO_2 tends to decrease as exercise intensity increases, especially as $\dot{V}O_2$ approaches $\dot{V}O_{2peak}$. The result is that the variation incurred in $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ as a result of variation in V_{RES} decreases markedly as exercise intensity increases.

Table 5.7 (below) presents data on the variation that would be incurred in $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ as a result of variation in V_{RES} for 3 different sampling periods, whilst table

5.8 presents equivalent data for 3 levels of exercise intensity. In compiling table 5.7, exercise intensity was "controlled" (at a moderate level) while sampling period was varied. Similarly, in compiling table 5.8, sampling period was "controlled" (at 30 s) while exercise intensity was varied. For a given exercise intensity, the figures used for $\dot{V}_{E\,(STPD)}$, F_EO_2 and F_ECO_2 are those that were used in tables 5.2 and 5.3, and the figures used for V_{RES} are the mean (0.57 L), together with the upper (0.86 L) and lower (0.28 L) 95% confidence limits for V_{RES} (see above). In all cases it was assumed that the O_2 and CO_2 fractions in the residual mixture were 0.2091 and 0.0006 respectively.

Table 5.7. Variation incurred in $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ as a result of variation in V_{RES} for 3 sampling periods.

Sampling period	$\dot{V}_{E\,(STPD)}$ ($L.min^{-1}$)	$V_{E\,(ATPD)}$ (L) (30 s coll.)	True F_EO_2	True F_ECO_2	V_{RES} (L) (ATPD)	Meas. F_EO_2	Meas. F_ECO_2	Corr. F_EO_2	Corr. F_ECO_2
	40	21.4	0.150	0.050	0.28	0.1508	0.0494	0.1492	0.0507
30 s	40	21.4	0.150	0.050	0.57	0.1515	0.0487	0.1500	0.0500
	40	21.4	0.150	0.050	0.86	0.1523	0.0481	0.1508	0.0494
Error in corrected value			-	-	-	-	-	±0.53%	±1.3%
	40	42.9	0.150	0.050	0.28	0.1504	0.0497	0.1496	0.0503
60 s	40	42.9	0.150	0.050	0.57	0.1508	0.0494	0.1500	0.0500
	40	42.9	0.150	0.050	0.86	0.1512	0.0490	0.1504	0.0497
Error in corrected value			-	-	-	-	-	±0.26%	±0.7%
	40	85.9	0.150	0.050	0.28	0.1502	0.0498	0.1498	0.0502
120 s	40	85.9	0.150	0.050	0.57	0.1504	0.0497	0.1500	0.0500
	40	85.9	0.150	0.050	0.86	0.1506	0.0495	0.1502	0.0498
Error in corrected value			-	-	-	-	-	±0.13%	±0.3%

Table 5.8. Variation incurred in $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ as a result of variation in V_{RES} for 3 levels of exercise intensity.

Intensity	$\dot{V}_{E\,(STPD)}$ (L.min^{-1})	$V_{E\,(ATPD)}$ (L) (30 s coll.)	True F_EO_2	True F_ECO_2	V_{RES} (L) (ATPD)	Meas. F_EO_2	Meas. F_ECO_2	Corr. F_EO_2	Corr. F_ECO_2
	40	21.4	0.150	0.050	0.28	0.1508	0.0494	0.1492	0.0507
moderate	40	21.4	0.150	0.050	0.57	0.1515	0.0487	0.1500	0.0500
	40	21.4	0.150	0.050	0.86	0.1523	0.0481	0.1508	0.0494
Error in corrected value			-	-	-	-	-	±0.53%	±1.3%
	80	42.9	0.165	0.041	0.28	0.1653	0.0407	0.1647	0.0413
heavy	80	42.9	0.165	0.041	0.57	0.1656	0.0405	0.1650	0.0410
	80	42.9	0.165	0.041	0.86	0.1659	0.0402	0.1653	0.0407
Error in corrected value			-	-	-	-	-	±0.18%	±0.7%
	160	85.9	0.180	0.032	0.28	0.1801	0.0319	0.1799	0.0321
severe	160	85.9	0.180	0.032	0.57	0.1802	0.0318	0.1800	0.0320
	160	85.9	0.180	0.032	0.86	0.1803	0.0317	0.1801	0.0319
Error in corrected value			-	-	-	-	-	±0.05%	±0.3%

The above tables show that the variation incurred in $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ as a result of variation in V_{RES} decreases when either sampling period or exercise intensity increases. In absolute terms, the variation in both $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ decreases as exercise intensity increases, independent of the effect on V_E (because F_EO_2 increases and F_ECO_2 decreases). For $F_ECO_{2\,(CORR)}$, the decrease in the absolute variation is matched by the decrease in the actual value, so in relative terms the variation remains constant. However, for $F_EO_{2\,(CORR)}$ the decrease in the absolute variation is accompanied by an increase in the actual value and so, in relative terms, the variation in $F_EO_{2\,(CORR)}$ decreases as exercise intensity increases. The consequence for F_EO_2 is that the extent to which the variation in the corrected value decreases with increasing exercise intensity is greater, both in absolute and in relative terms, than would be predicted on the basis of the increase in V_E alone. For F_ECO_2 it is that the extent to which the variation in the corrected value decreases with increasing exercise intensity is greater, in absolute but not in relative terms, than would be predicted on the basis of the increase in V_E alone. However, whilst the impact that a given (relative) error in F_EO_2 has on the calculated value for $\dot{V}O_2$ increases with exercise intensity (see table 5.2), the error incurred in $\dot{V}CO_2$ for a given error in F_ECO_2 is independent of exercise intensity (see table 5.3). This means that whilst the errors incurred in the calculated values for $\dot{V}O_2$ and $\dot{V}CO_2$ as a result of variation in V_{RES} do decrease as exercise intensity increases they do not decrease more than would be predicted on the basis of the increase in V_E alone. This is illustrated in the following tables.

Table 5.9. Errors incurred in the calculated values for $\dot{V}O_2$ and $\dot{V}CO_2$ as a result of variation in V_{RES} for 3 sampling periods.

Sampling period	V_{RES} (L) (ATPD)	True $\dot{V}O_2$ (L.min^{-1})	Corr. $\dot{V}O_2$ (L.min^{-1})	True $\dot{V}CO_2$ (L.min^{-1})	Corr. $\dot{V}CO_2$ (L.min^{-1})	True RER	Corr. RER
	0.28	2.465	2.498	1.974	2.001	0.801	0.801
30 s	0.57	2.465	2.465	1.974	1.974	0.801	0.801
	0.86	2.465	2.433	1.974	1.949	0.801	0.801
Error in corrected value [ml.min^{-1} (%)]		-	±32	-	±26	-	-
		-	(±1.3%)	-	(±1.3%)	-	-
	0.28	2.465	2.482	1.974	1.988	0.801	0.801
60 s	0.57	2.465	2.465	1.974	1.974	0.801	0.801
	0.86	2.465	2.449	1.974	1.961	0.801	0.801
Error in corrected value [ml.min^{-1} (%)]		-	±16	-	±13	-	-
		-	(±0.7%)	-	(±0.7%)	-	-
	0.28	2.465	2.473	1.974	1.981	0.801	0.801
120 s	0.57	2.465	2.465	1.974	1.974	0.801	0.801
	0.86	2.465	2.457	1.974	1.968	0.801	0.801
Error in corrected value [ml.min^{-1} (%)]		-	±8	-	±7	-	-
		-	(±0.3%)	-	(±0.3%)	-	-

Table 5.10. Errors incurred in the calculated values for $\dot{V}O_2$ and $\dot{V}CO_2$ as a result of variation in V_{RES} for 3 levels of exercise intensity.

Intensity	V_{RES} (L) (ATPD)	True $\dot{V}O_2$ ($L.min^{-1}$)	Corr. $\dot{V}O_2$ ($L.min^{-1}$)	True $\dot{V}CO_2$ ($L.min^{-1}$)	Corr. $\dot{V}CO_2$ ($L.min^{-1}$)	True RER	Corr. RER
	0.28	2.465	2.498	1.974	2.001	0.801	0.801
moderate	0.57	2.465	2.465	1.974	1.974	0.801	0.801
	0.86	2.465	2.433	1.974	1.949	0.801	0.801
Error in corrected	-	±32	-	±26	-	-
value [$ml.min^{-1}$ (%)]	-	(±1.3%)	-	(±1.3%)	-	-
	0.28	3.609	3.633	3.233	3.255	0..896	0..896
heavy	0.57	3.609	3.609	3.233	3.233	0..896	0..896
	0.86	3.609	3.585	3.233	3.212	0..896	0..896
Error in corrected	-	±24	-	±22	-	-
value [$ml.min^{-1}$ (%)]	-	(±0.7%)	-	(±0.7%)	-	-
	0.28	4.562	4.578	5.026	5.042	1.102	1.102
severe	0.57	4.562	4.562	5.026	5.026	1.102	1.102
	0.86	4.562	4.547	5.026	5.009	1.102	1.102
Error in corrected	-	±15	-	±17	-	-
value [$ml.min^{-1}$ (%)]	-	(±0.3%)	-	(±0.3%)	-	-

Tables 5.9 and 5.10 show the error that would be incurred in the calculated value for $\dot{V}O_2$ or $\dot{V}CO_2$ when equations 14 and 15 are used to derive values for $F_EO_{2\,(CORR)}$ and $F_ECO_{2\,(CORR)}$ and these corrected values are used in the calculation of $\dot{V}O_2$ or $\dot{V}CO_2$. They suggest that the systematic error will be zero for any sampling period and any exercise intensity but that the random error will decrease as either exercise intensity or sampling period increases. Since both $\dot{V}O_2$ and $\dot{V}CO_2$ are affected in the same way, RER is unaffected.

The above data apply to the situation in which all Douglas bags are flushed with ambient air prior to use. An alternative would be to make sure that all bags are flushed with expirate prior to use. However, given that considerable variation might be present in the O_2 and CO_2 concentrations for samples of expirate collected during a particular exercise bout, it would be necessary to measure these concentrations for each bag. Furthermore, since a systematic error will always be incurred in the calculated values for $\dot{V}O_2$ and $\dot{V}CO_2$ as long as the composition of the residual expirate differs from that which is collected during the test, it will always be necessary to correct the measured values of F_EO_2 and F_ECO_2 for the effect of contamination. The former problem could be overcome by flushing the bags with a known gas mixture prior to use, but this would have financial implications. By using the same calculations that were used to compile table 5.10 it can be shown that were all bags to be flushed with a gas mixture containing 16.5% O_2 and 4.1% CO_2 the random error incurred in the calculated $\dot{V}O_2$ or $\dot{V}CO_2$ as a result of variation in V_{RES} would be ±0.2% for moderate, zero for heavy, and ±0.4% for severe intensity exercise. These errors are smaller than those that would be incurred were the bags to be flushed with ambient air. Nevertheless, for studies 2 and 3, all bags were flushed with ambient air. This was done to keep the cost of these studies down, but it should be acknowledged that the consequence would be that the variability in $\dot{V}O_2$ would decrease in response to an increase in either exercise intensity or sampling period.

5.6 Accuracy and precision of the derived data for $\dot{V}O_2$ and RER

In section 5.5, data were presented on the errors that might realistically be incurred in the calculated values for $\dot{V}O_2$ and RER, were incorrect values for a given variable to be used in the calculation of $\dot{V}O_2$ or $\dot{V}CO_2$. This approach is useful in that it can provide some insight into which factors are likely to exert the greatest influence on the accuracy and precision with which $\dot{V}O_2$ or $\dot{V}CO_2$ can be determined. However, it is limited in that it does not allow an estimate to be made of the overall accuracy or precision of the derived data for $\dot{V}O_2$ and RER. It would be of interest to estimate the total errors (random and systematic) that might realistically be incurred in the calculated values for $\dot{V}O_2$ and RER when the procedures outlined in the preceding section are followed.

As far as systematic errors are concerned, the situation is relatively straight forward. A systematic error (<0.1%) might be incurred in $\dot{V}O_2$ as a result of an error in the measurement of P_B (section 5.5.2) or T_{EXP} (section 5.5.3), and errors might be incurred in both $\dot{V}O_2$ (<0.6%) and RER (<1.3%) as a result of errors in the measurement of F_EO_2 and F_ECO_2 (section 5.5.5.7). Additionally, systematic errors would have been incurred in $\dot{V}O_2$ during Study 1 because in this study no correction was made for the fact that by the time it reaches the analysers expirate is always contaminated with the residual air that was in the Douglas bag before any expirate entered (section 5.5.5.9). In studies 2 and 3 correction procedures were employed to overcome this problem (section 5.5.5.10).

As far as random errors are concerned, the situation is more complicated. Random errors would be incurred in the measurement of $V_{E\,(ATPS)}$ (section 5.5.1), P_B (section 5.5.2), T_{EXP} (section 5.5.3), and the expired concentrations of O_2 and CO_2 (section 5.5.5.7). Variation in F_IO_2 and F_ICO_2 about their mean values of 0.2091 and 0.0006 would also introduce errors in the calculated values for both $\dot{V}O_2$ and RER (section 5.5.4), as would variation in V_{RES} about its mean value of 0.57 L (studies 2 and 3 only; see section 5.5.5.10).

Errors in the measured values for $V_{E\,(ATPS)}$, P_B, and T_{EXP} would affect $\dot{V}O_2$ but not RER, as would variation in V_{RES} (see section 5.5.5.10). The precision of the derived data for RER therefore depends solely on the extent to which F_IO_2 and F_ICO_2 differ from 0.2091 and 0.0006 and the extent to which the measured concentrations of O_2 and CO_2 are in error. The error that would be incurred in RER as a result of variation in F_IO_2 and F_ICO_2 would be <0.2% (see section 5.5.4), and the error that would be incurred as a result of errors in the measured values for F_EO_2 and F_ECO_2 would be <0.5% for moderate and

<0.9% for severe intensity exercise (see section 5.5.5.7). It seems reasonable to conclude, therefore, that the random error in the calculated RER will typically be <1%.

Errors incurred in the measurement of $V_{E\,(ATPS)}$, P_B, T_{EXP}, and the expired concentrations of O_2 and CO_2 will all affect the calculated $\dot{V}O_2$, and so too will variation in V_{RES}. In addition, the calculated value for $\dot{V}O_2$ will be influenced by variation in F_IO_2 and F_ICO_2. It is possible to estimate the total error that would be incurred in $\dot{V}O_2$ for the situation in which the direction of each of the individual errors is such that the total error is maximal. However, this estimate would be an overestimation of the total error that might realistically be incurred because in practice some of these errors would cancel. Formulae are available which allow an estimate to be made of the total random error that would be incurred in the dependent variable for the situation in which one variable is a function of several independent variables (Challis, 1997; Holman and Gajda, 1989; Taylor, 1982; Topping, 1972). The requirements are that an estimate of the random error that would be present is available for each of the independent variables and that the dependent variable can be expressed algebraically as a function of the independent variables. For a function of the form $P = f(X_1, X_2, \ldots, X_3)$, the formula is:

$$\delta P = \sqrt{\sum_{i=1}^{n}\left[\frac{\partial P}{\partial X_i}\delta X_i\right]^2} \quad \ldots \quad (16),$$

where δP is the error in the dependent variable, δX_i is the error in the independent variable X_i, and $\partial P/\partial X_i$ is the partial derivative of the function P with respect to X_i. This formula can be applied to equation (7) to determine the total error that would be incurred in the calculated value of $\dot{V}O_2$. In this case, the dependent variable is $\dot{V}O_2$, and the independent variables are $V_{E\,(ATPS)}$, P_B, T_{EXP}, F_EO_2, and F_ECO_2. However, whilst an important assumption underpinning this approach is that the errors in the independent variables are independent of each other, a given error in T_{EXP} will influence $\dot{V}O_2$ in two related ways. Firstly it will introduce an error into the determination of $V_{E\,(STPS)}$ from $V_{E\,(ATPS)}$. And secondly, because it will introduce an error into the calculation of P_{H_2O}, it will introduce an error into the determination of $V_{E(STPD)}$ from $V_{E(STPS)}$. The combined effect, for a realistic error of 0.2 °C in T_{EXP}, is that an error of 0.11% will be incurred in the calculated $\dot{V}O_2$ (see section 5.5.3). A similar effect can be obtained, however, by assuming that the error in T_{EXP} is 0.3 °C and ignoring the effect that this error would have on P_{H_2O}. This is what was done when equation (16) was used with equation (7).

The effect of variation in V_{RES} was quantified in terms of the effect that this variation would have on the corrected values for F_EO_2 and F_ECO_2 (see tables 5.7 and 5.8), and it was the error in this corrected value that was used in equation (16). That is equation (16) was used twice for the error in F_EO_2 and twice for the error in F_ECO_2. One of these calculations was for a constant error of 0.01% (absolute) because the error incurred in the measurement of F_EO_2 (or F_ECO_2), which appears to be independent of exercise intensity, is unlikely to exceed 0.01% (table 5.6). The other was for an error which, for a given sampling period or exercise intensity, is equivalent to the difference between $F_EO_{2\,(CORR)}$ [or $F_ECO_{2\,(CORR)}$] and $F_EO_{2\,(TRUE)}$ [or $F_ECO_{2\,(TRUE)}$] (see tables 5.7 and 5.8). For $V_{E(ATPS)}$, an error of 0.5 L was assumed (see section 5.5.1), and for P_B an error of 1 mmHg was assumed (see section 5.5.2). The effect of variation in F_IO_2 and F_ICO_2 about their average values of 0.2091 and 0.0006 was ignored because this variation would only have contributed to the day-to-day variability in $\dot{V}O_2$; it would not have contributed to the variability that was observed within a test (see section 5.5.4).

The total error in the calculated $\dot{V}O_2$ was estimated for sampling periods of 30, 60, and 120 s (moderate intensity exercise), and for moderate, heavy, and severe intensities (30 s samples). Data for $\dot{V}_{E(ATPS)}$, $F_EO_{2\,(TRUE)}$, and $F_ECO_{2\,(TRUE)}$ were as shown in tables 5.7 and 5.8, and T_{EXP} and P_B were assumed to be 20 °C and 760 mmHg, respectively. For sampling periods of 30, 60, and 120 s, the estimated random error in the calculated $\dot{V}O_2$ was 69, 35, and 19 $ml.min^{-1}$, or 2.8, 1.4, and 0.8% of the mean $\dot{V}O_2$, respectively. Similarly, for moderate, heavy, and severe intensities, the estimated error was 69, 53, and 40 $ml.min^{-1}$, or 2.8, 1.5, and 0.9%, respectively.

Two important conclusions can be drawn from the data presented in this chapter. First, since it has been shown that the systematic error in the calculated $\dot{V}O_2$ will always be <1%, it can be concluded that the procedures adopted in this thesis allow $\dot{V}O_2$ to be determined accurately across a wide range of metabolic rates (this conclusion also applies for RER). Second, it can be concluded that whilst the random error in the calculated $\dot{V}O_2$ is likely to be very small when a long sampling period is used or when severe intensity exercise is studied, the variability in $\dot{V}O_2$ is likely to be considerable when short sampling periods are used to study moderate intensity exercise. The possibility that the variability (i.e. random error) in $\dot{V}O_2$ decreases as either exercise intensity or sampling period increases has important implications for the assessment of $\dot{V}O_{2max}$. This possibility is investigated further in Study 2 (Chapter 8).

CHAPTER 6: SPECIFIC CONSIDERATIONS FOR MOTORISED TREADMILL RUNNING

6.1 Introduction

All the exercise data presented in this thesis were collected during running on a motorised treadmill. It could be argued that since physiological models of running performance are typically applied to running on the road or the track, the question of whether the $\dot{V}O_2$-running speed relationship plateaus at high speeds should be evaluated in one of these situations. However, in order to address this question, it is essential to study progressive exercise in which subjects have to maintain the required speed right up to the point at which they terminate the exercise. This would not necessarily be the case for overground running. For example, were an incremental running test to be performed on the track, subjects might start to run at speeds below the target speed before they terminate the test. In contrast, the advantage of motorised treadmill running is that the target speed must be maintained (otherwise the subject would fall off the back of the treadmill). Hence motorised treadmill running was selected as the mode of exercise for all the studies reported in this thesis.

Tests were performed in which WR was increased by increasing the belt speed, the treadmill grade, or both. It was important, therefore, to establish:

1. that the belt speed given on the treadmill display was an accurate indication of the true belt speed, even when a relatively massive subject was running on the belt;
2. that the treadmill grade given on the treadmill display was an accurate indication of the true grade.

All exercise tests commenced with the subject lowering himself onto the moving treadmill. An important question, therefore, was whether the reading given on the treadmill display was an accurate indication of the true belt speed for an exercise bout which commenced in such a way.

6.2 The Quinton Q65 treadmill

All exercise tests were performed on a Quinton Q65 motorised treadmill (Quinton Instrument Co., Seattle, USA). This treadmill consists of a solid metal platform, over which runs a continuous nylon belt. The belt passes round two metal rollers, situated at the front and the back of the runway, and the front roller is driven by a DC motor. The friction between the two rollers and the belt must be sufficient to prevent slipping of the belt. However, the friction between the belt and the metal platform it runs over must not be too great so that the belt does not "stick" on footstrike. To ensure that this friction was kept to a low level, the underside of the treadmill belt was sprayed at regular intervals (typically once a month) with a silicon based lubricant.

6.3 Modifications made to the basic Q65 treadmill

Several modifications were made to the above treadmill to customise it for use in Studies 1-3. First, to ensure that the runway could be set to be completely horizontal when the treadmill grade was set to zero, adjustable feet were fitted to the back of the treadmill. Second, because the original manufacturer's controls for speed and grade were located on the front panel of the treadmill (facing the subject), which meant that when the experimenter wanted to adjust the speed or grade they had to reach across the front of the subject, an alternative speed/grade control was constructed. This alternative control was located on the side rail of the treadmill, in a position which allowed the experimenter to control the speed/grade without interfering with the subject. Finally, because the manufacturer's speed display was also located on this same front panel, which meant that it was not possible for the belt speed to be both obscured from the subject and visible to the experimenter, an alternative speed display was constructed. This alternative display was fixed in such a way that it could be rotated, and in those situations where it was important that the experimenter could see the speed but the subject could not, it was rotated so that it faced the outside of the treadmill.

6.4 Calibration of belt speed

True belt speed was determined by measuring the length of the belt and recording the time taken for a given number of revolutions. Display speed was recorded from the alternative speed display. A typical data set is given below (table 6.1).

Table 6.1. Agreement between true belt speed and display speed.

Display speed ($km.h^{-1}$)	Number of belt revs	Time taken (s)	True belt speed ($km.h^{-1}$)
4.0	15	49.92	4.01
8.0	30	50.10	8.00
12.0	45	49.99	12.02
16.0	60	50.05	16.01
20.0	75	49.96	20.04
24.0	90	50.04	24.02

Provided the display speed was recorded from the alternative display, excellent agreement was found between the display speed and the true belt speed, regardless of whether or not the measurements were made with a subject running on the treadmill. However, the agreement between the speed displayed on the manufacturer's display and that displayed on the alternative display was not good. These two speeds typically agreed when there was no runner on the treadmill, but when a runner jumped onto the moving treadmill the speed shown on the alternative display decreased whereas that shown on the manufacturer's display remained constant. Similarly, when the runner jumped off, the speed shown on the alternative display increased whilst that shown on the manufacturer's display again remained constant. It is surprising that these displays gave different readings, given that both receive information from the same sensor. However, in all cases, the true belt speed decreased or increased in parallel with the speed shown on the alternative display. Moreover, the magnitude of the drop in both the true belt speed and the (alternative) display speed observed when a particular subject jumped on to the treadmill was proportional to the mass of the subject. The probable explanation is that considerable (electrical) smoothing of the speed reading occurred before it was fed to the manufacturer's display.

For each of the studies reported in this thesis, the belt speed was taken from the alternative display. The agreement between true belt speed and the speed shown on this alternative display was assessed at the start and the end of each study. This agreement was assessed over a range of speeds, and on all occasions excellent agreement was found (see table 6.1 for typical data), regardless of whether or not the data were collected with a runner on the treadmill. This finding is important because it indicates that there was not a problem with the belt slipping on the roller, even when subjects of substantial mass ran at considerable speeds. Such slipping would be manifest as the true belt speed being lower than the displayed speed; this situation was never encountered.

6.5 Calibration of treadmill grade

The vertical height gained per metre travelled along the horizontal was determined using the apparatus shown in figure 6.1.

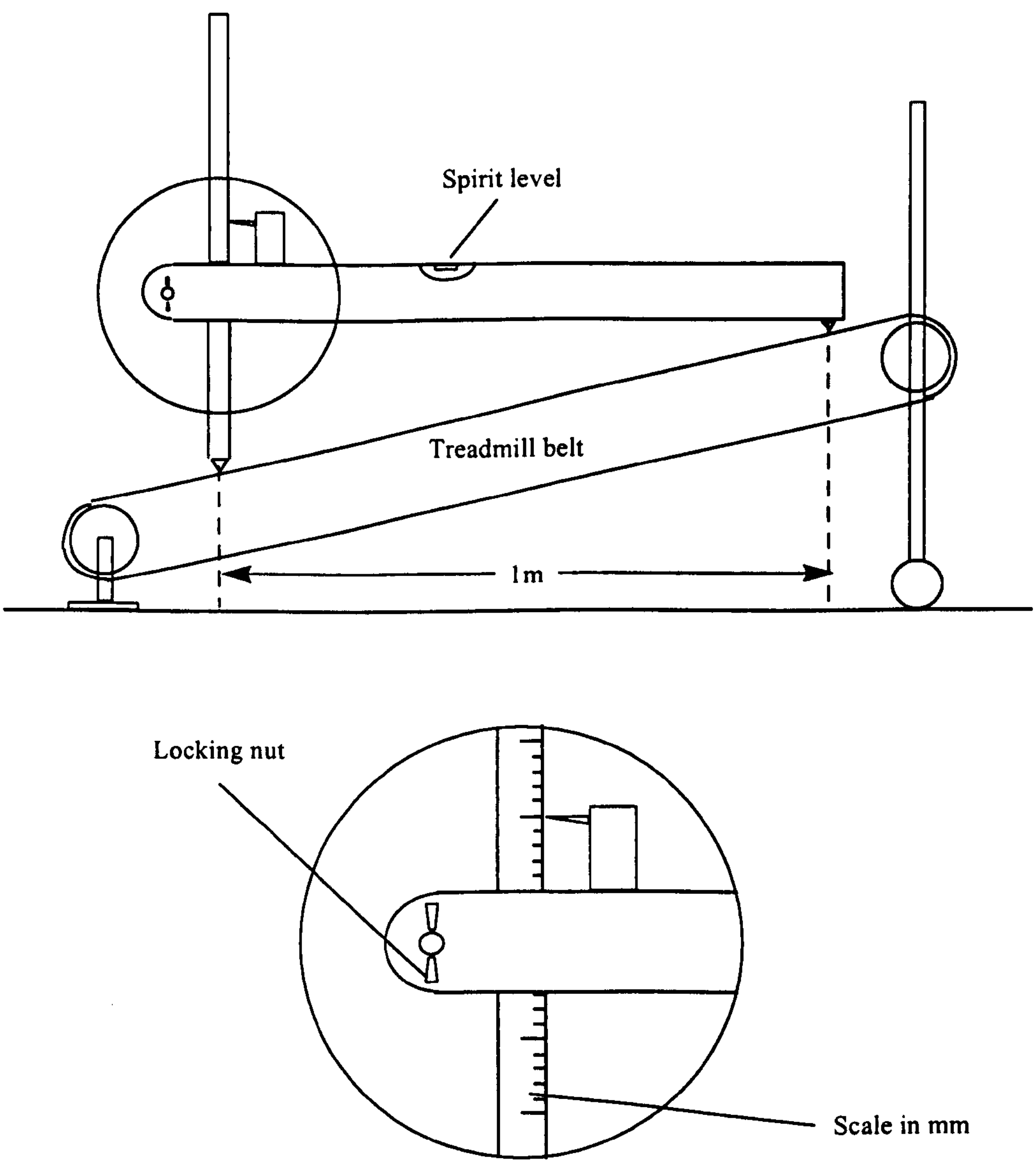

Figure 6.1. Diagram of the apparatus used for measuring the treadmill grade.

The apparatus illustrated in the above figure was based on straight forward geometry. Although the piece which held the scale was free to move through the piece which held the spirit level, the former piece fitted tightly inside the latter; this tight fit was necessary to ensure that a right angle was maintained between the two pieces. The horizontal distance between the two points of contact with the belt was 1 m, and the contact points were tapered so that this distance could be maintained without altering the vertical distance across a wide range of grades. Provided the top piece which held the spirit level was horizontal, the vertical distance could be read from the scale. The horizontal distance was always 1 m, so the percent grade (vertical distance/horizontal distance × 100) was obtained by taking the scale reading and expressing it in cm. This scale, which was taken from a standard metre rule, was fixed in such a way that the pointer was at zero when the apparatus was placed on a surface which was shown to be level by means of another spirit level.

The procedure for making a measurement of the treadmill grade was as follows:

1) the locking nut was loosened;
2) the scale was moved through the piece containing the spirit level until the bubble was central;
3) the locking nut was tightened;
4) the spirit level was inspected and further adjustment was made if necessary;
5) the % grade was read from the scale (% grade = scale reading in cm).

Initially, the rear of the treadmill was raised or lowered so that a reading of zero was obtained when a grade of zero was shown on the display panel of the treadmill. The treadmill grade was then increased in increments of 1%, and the height gained per horizontal m was measured for each grade. This procedure was repeated for (displayed) grades up to 15%, and for each grade the measured % grade was noted. The procedure was not performed with a runner on the treadmill, although it was always performed with one experimenter on the treadmill. As the treadmill grade was altered by means of a rack and pinion system, it seems unlikely that the true grade would have been further reduced by a subject running on the belt.

This procedure was performed at the start and the end of each study. On some occasions, a small adjustment of the feet was required to level the treadmill at zero grade. However, on all occasions, once this adjustment had been made, the calculated grade was found to be within 0.1% of the displayed grade for all grades up to 15%.

PART III

ADRESSING THE ISSUES THAT AROSE FROM THE LITERATURE

CHAPTER 7: STUDY 1: EFFECT OF TEST PROTOCOL AND SAMPLING PERIOD ON $\dot{V}O_{2peak}$ AND THE INCIDENCE OF A $\dot{V}O_2$-PLATEAU

7.1 Introduction

7.1.1 *Identifying the issues*

This study addressed some of the issues that were raised in chapters 3 and 4. The focus was on CGIS rather than CSIG tests because the aim was not to establish whether the $\dot{V}O_2$-treadmill grade relationship plateaus at high grades but rather to establish whether the $\dot{V}O_2$-running speed relationship plateaus at high speeds. The aim was to investigate various factors that might potentially influence the frequency with which a $\dot{V}O_2$ plateau is observed in a CGIS treadmill test. Three general questions were addressed:

1. to what extent is the peak speed limited by non-metabolic factors when a CGIS test is performed on a level treadmill?
2. to what extent is the $\dot{V}O_2$ response for a progressive test influenced by $\dot{V}O_2$ kinetics?
3. to what extent is the peak $\dot{V}O_2$ or the incidence of a $\dot{V}O_2$-plateau for a CT a function of the sampling period over which $\dot{V}O_2$ is determined?

7.1.2 *Effect of treadmill inclination on the physiological responses for a CT*

Whilst the peak $\dot{V}O_2$ is typically higher for uphill than for level running (see section 4.3.3), it is unclear whether this is because the peak speed is limited by non-metabolic factors when a CGIS test is performed on a level treadmill, or whether the explanation is simply that the active muscle mass is greater for uphill running. To shed some light on this issue, the physiological responses were compared for two continuous (ramp) tests. Both tests were CGIS tests, but the treadmill grade was set at 5% for one and 0% for the other. The thinking was that if the peak speed for the 0% test was limited by non-metabolic factors the incidence of a $\dot{V}O_2$-plateau and the peak values for RER and [Bla] would all be lower for this test, whereas if the important factor was the active muscle mass this incidence and these values would all be similar for both tests (see section 4.3.3). Ramp tests were used because there is reason to believe that a $\dot{V}O_2$-plateau might be identified more often for a ramp than for an incremental test (see section 3.2.3).

7.1.3 *Influence of $\dot{V}O_2$ kinetics on the $\dot{V}O_2$ response for a progressive test*

7.1.3.1 Assumptions underlying the use of a DCT

All of the studies that have found the incidence of a $\dot{V}O_2$-plateau to be very high have used a DCT (see section 3.2.1). For a CT, an equivalent peak $\dot{V}O_2$ is attained but the incidence of a plateau tends to be lower. These findings apply to CSIG tests, and one aim of the present study was to establish whether the same is true for CGIS tests. However, it was necessary to do more than this because recent studies of $\dot{V}O_2$ kinetics during exercise suggest that the major assumption on which the majority of discontinuous tests are based is invalid (see section 4.4.3).

The type of DCT that is typically used is one in which $\dot{V}O_2$ is determined over a 60 s period commencing 1.5 to 2 min after the start of each stage (see section 3.2.1). When such tests are used, the implicit assumption is that $\dot{V}O_2$ increases rapidly, reaching a steady state within the first 1.5 or 2 min of each stage. This assumption is consistent with the notion that the $\dot{V}O_2$ response for a continuous and a discontinuous version of the same protocol would be identical except for that whilst the CT might only be continued to the point where $\dot{V}O_2$ starts to plateau, the DCT would be continued to a higher WR (because the potential for anaerobic energy production would be greater) and therefore a $\dot{V}O_2$-plateau would more easily be discerned. Given this scenario it would seem reasonable to treat the peak $\dot{V}O_2$ for a CT as a maximal $\dot{V}O_2$ provided the incidence of a $\dot{V}O_2$-plateau was high for an equivalent DCT. However, recent studies of $\dot{V}O_2$ kinetics during exercise suggest that this scenario is unrealistic.

These studies were reviewed in Chapter 4 (sections 4.4.3 to 4.4.5), where the implications for the assessment of $\dot{V}O_{2max}$ were emphasised. It is important to recognise though that because none of the published studies has specifically investigated the impact of $\dot{V}O_2$ kinetics on the $\dot{V}O_2$ response to a DCT various assumptions had to be made. One aim of the present study was to test some of these assumptions.

7.1.3.2 Influence of the $\dot{V}O_2$ slow component on the $\dot{V}O_2$ response to a progressive test

On the basis of what is currently known about $\dot{V}O_2$ kinetics (see section 4.4.3), it can be predicted that $\dot{V}O_2$ will continue to increase beyond the first 90 s of most stages of a typical DCT and that, as a result, the $\dot{V}O_2$-running speed relationship will differ, depending on whether it is derived from a CT or a DCT. To establish whether $\dot{V}O_2$ does increase beyond the first 90 s of exercise for the intensities encountered in a typical DCT, $\dot{V}O_2$ was determined over two consecutive periods (from 1.5 to 2 and from 2 to 3 min after the onset of exercise) for each stage of a DCT. Similarly, to establish whether the $\dot{V}O_2$-running speed relationship does differ between a continuous and a discontinuous test the $\dot{V}O_2$ response was compared for a continuous and a discontinuous version of the same CGIS test.

The basis for this second comparison was the notion that if $\dot{V}O_2$ increased rapidly so that a steady state $\dot{V}O_2$ was reached within the first 2 min of exercise for each stage of the DCT the two $\dot{V}O_2$-running speed relationships would be identical, whereas if $\dot{V}O_2$ continued to increase beyond 2 min, the $\dot{V}O_2$ would be higher for the CT from the 2nd stage onwards. Taylor et al. (1955) describe a DCT for which the mean $\Delta\dot{V}O_2$ between consecutive stages was 4.2 $ml.kg^{-1}.min^{-1}$. Taylor et al.'s subjects typically completed 4 or 5 stages so for an individual whose peak $\dot{V}O_2$ was 50 $ml.kg^{-1}.min^{-1}$ the first stage would have required a $\dot{V}O_2$ of ~30 $ml.kg^{-1}.min^{-1}$, or ~60% $\dot{V}O_{2peak}$. Given that it has been shown that a $\dot{V}O_2$ slow component is present for all supra-LT running speeds (Carter et al., 1997; Bernard et al., 1998; see also section 4.4.4), and that the LT typically occurs at a WR for which the steady state $\dot{V}O_2$ is equivalent to 50 to 70% of the peak $\dot{V}O_2$ (Davis et al., 1976, 1979, 1982; Whipp et al., 1981), it is likely that a

$\dot{V}O_2$ slow component will be present for most, if not all, of the speeds encountered in a typical DCT.

Were a $\dot{V}O_2$-slow component to be present for the 1st stage of the CT, the increase in $\dot{V}O_2$ observed during the 2nd stage would presumably reflect not only the first 3 min of the $\dot{V}O_2$ response to the increase in speed that was imposed at the end of the 1st stage but also the second 3 min of the $\dot{V}O_2$ response to the 1st stage. Were such an effect to occur, the increase in $\dot{V}O_2$ between the last minute of the 1st stage and the last minute of the 2nd stage would be greater for the CT than for the DCT. Similarly, were a $\dot{V}O_2$-slow component to be present for the 2nd stage of the CT, the increase in $\dot{V}O_2$ between the last minute of the 2nd stage and the last minute of the 3rd stage would be greater for the CT than for the DCT. It follows, therefore, that were a $\dot{V}O_2$-slow component to be present for most stages in the CT, the $\dot{V}O_2$-running speed relationship would be steeper for this test than for the DCT.

7.1.3.3 Effect of test duration and test type (progressive vs. constant intensity) on $\dot{V}O_{2peak}$

It is possible that the peak $\dot{V}O_2$ might be lower for a typical DCT than for a progressive CT or a relatively long (> 6 min) square wave (see section 4.4.5.1). It has not been conclusively demonstrated that this is the case, but if it were the implications would be far reaching. Of considerable importance is the fact that the significance of a $\dot{V}O_2$-plateau in a DCT would be brought into question were it to be shown that such a plateau typically occurs at a $\dot{V}O_2$ that is sub maximal. Attention would then have to be focused on those factors that might influence the frequency with which a $\dot{V}O_2$-plateau occurs in a CT.

The present study compared the peak $\dot{V}O_2$ attained in 3 different tests: the DCT mentioned above, a CGIS ramp test, and a constant speed (square wave) exhaustive run. The ramp test was designed so that the duration would be ~10 min for each subject, whilst for the square wave run it was anticipated that the time to exhaustion would average ~6 min. For these 3 tests, as well as for the CT described above, the treadmill grade was set at 5% to account for fact that subjects might be limited by non-metabolic factors when running on a level treadmill (see section 7.1.2).

7.1.3.4 Linearity of the $\dot{V}O_2$-running speed relationship for a typical ramp test

The $\dot{V}O_2$-running speed relationship derived from a typical DCT such as that mentioned above should reflect primarily the fast component of the $\dot{V}O_2$ response (see section 4.4.5.1). It is unlikely therefore that a spurious plateau will be observed in such a test provided the $\dot{V}O_2$-running speed relationship is linear for this component. It has been shown for cycle ergometer exercise that a linear $\dot{V}O_2$-WR relationship is obtained when only the fast component is considered (see section 4.4.3), but it is presently unknown whether this is the case for treadmill running. The $\dot{V}O_2$-running speed relationship was found to be non-linear for a test in which a substantial amount of time was spent at supra-LT speeds (Wood et al., 1997). A non-linear $\dot{V}O_2$-power relationship has also been observed for cycle ergometer exercise when a similar type of test has been used (Green and Dawson, 1995; Zoladz et al., 1995). However, Hansen et al. (1988) have shown that the $\dot{V}O_2$-power relationship for cycle ergometer exercise is linear when power is increased at a relatively fast rate and only a few minutes are spent at supra-LT powers. The reason for this may be that when a short test is performed there is not sufficient time for a substantial $\dot{V}O_2$-slow component to develop and so the $\dot{V}O_2$ response is dominated by the primary component. The implication is that it should be possible to shed some light on the question of whether the $\dot{V}O_2$-running speed relationship is likely to be linear when only the primary component is considered by determining whether this relationship is linear for progressive CT in which only a few minutes are spent at supra-LT speeds.

In the present study a CGIS ramp test for which the time to exhaustion averaged ~10 min was performed and $\dot{V}O_2$ was determined throughout. It was hypothesised that the time spent at supra-LT speeds would typically be <5 min for this test. The linearity of the $\dot{V}O_2$-running speed relationship was evaluated by dividing each individual data set ($\dot{V}O_2$ vs. speed) in half and comparing the slope of the $\dot{V}O_2$-running speed relationship for the 2nd half with that for the 1st.

7.1.4 *Effect of sampling period on $\dot{V}O_{2peak}$ and the incidence of a $\dot{V}O_2$-plateau for a continuous test*

It is possible that a $\dot{V}O_2$-plateau is something that occurs very late (perhaps within the last minute) in a ramp test. Were this the case, a plateau might be observed more often for such a test when a relatively short sampling period is used (see section 3.2.4). On the other hand, if a plateau does not occur, it is conceivable that the peak $\dot{V}O_2$ might increase as the sampling period decreases. In fact, given that the variability in $\dot{V}O_2$ increases as the sampling period decreases (Myers et al., 1990), it is possible that the peak $\dot{V}O_2$ will increase as the sampling period decreases even if the $\dot{V}O_2$-WR relationship does plateau.

In the present study, the influence of sampling period was evaluated by comparing the peak $\dot{V}O_2$ and the incidence of a $\dot{V}O_2$-plateau for two ramp tests. Both were CGIS tests, and both were conducted with the grade set at 5%, but for one the sampling period was 30 s and for the other it was 60 s.

7.2 Methods

7.2.1 *Subjects*

Ten male subjects volunteered to participate. All were well habituated with laboratory procedures in general and with motorised treadmill running in particular. Three were distance runners, one was a triathlete, another had been a good swimmer in the past but was sedentary at the time of testing, and the remaining five were games players.

Table 7.1. Physiological characteristics of the subjects (mean ± SD).

Age (years)	Height (m)	Mass (kg)	$\dot{V}O_{2peak}$ * (ml.kg^{-1}.min^{-1})
26.5 ± 8.1	1.77 ± 0.09	77.4 ± 12.4	58.4 ± 8.2

*taken from the preliminary 5% ramp test (see below).

7.2.2 *Preliminary tests*

All subjects initially completed, on separate days, a progressive incremental test and a 5% ramp test (see section 7.2.4 for a description of this ramp test). For the incremental test, the treadmill grade was maintained at 5% throughout and the speed was increased at the end of each 5 min stage. The starting speed and the amount by which the speed was increased at the end of each stage were varied depending on the subject's capabilities as a runner so that each subject completed between 4 and 6 stages. Expired gases were collected during the final 2 min of each stage, and $\dot{V}O_2$ was determined according to the methods described in Chapter 5. A linear relationship between $\dot{V}O_2$ and running speed was derived for each subject and this relationship was used, in conjunction with the peak $\dot{V}O_2$ attained from the 5% ramp test, to calculate the running speed (for a treadmill grade of 5%) associated with this $\dot{V}O_2$ ($v\dot{V}O_{2peak}$).

7.2.3 *Experimental design*

Each subject completed the following 6 tests:

1. a discontinuous, speed incremented test, conducted at a 5% grade (DCT);
2. a continuous version of the above protocol (CT);
3. an exhaustive (square wave) run, at a grade of 5% and a speed calculated to elicit 105% $\dot{V}O_{2peak}$ (105%T);
4. a CGIS ramp test conducted on a level treadmill (0%RT);
5. a CGIS ramp test conducted at a 5% grade, with expired gases sampled over 60 s periods (5%RT60);
6. the same 5% ramp test, with expired gases sampled over 30 s periods (5%RT30).

This experiment was designed to allow comparison among any subset of the above 6 protocols whilst accounting for any possible training effect that might have occurred over the course of the study. The preliminary tests described above were always completed first, but thereafter the 10 subjects were divided into two groups of 5, and within each group one subject was randomly assigned to each of 5 testing sequences. That is, all subjects completed the preliminary 5% ramp test on day 1 and the incremental test on day 2, but the order of testing for days 3 to 7 varied between pairs of subjects.

On each of days 3 to 7, subjects first completed one stage of the DCT, and then, having rested for at least 30 min, they completed one of the five continuous tests. (Both tests were preceded by a 10 min warm up at a 5% grade and a speed calculated to elicit 60% $\dot{V}O_{2peak}$, and a rest period of 5 min was always allowed between the end of the warm-up and the start of the test.) Five different testing sequences were used, and these sequences are shown in table 7.2 (below), as is the way in which particular subjects were assigned to particular sequences. In this table, DCT-1 refers to the 1st stage of the DCT , DCT-2 refers to the 2nd stage of the same test, and so on.

Table 7.2. Outline of, and allocation of subjects to, the five testing sequences.

Subjects	Tests completed on day 3	Tests completed on day 4	Tests completed on day 5	Tests completed on day 6	Tests completed on day 7
1 and 6	1) DCT-1 2) CT	1) DCT-2 2) 5%RT30	1) DCT-3 2) 105%T	1) DCT-4 2) 0%RT	1) DCT-5 2) 5%RT60
2 and 7	1) DCT-2 2) 105%T	1) DCT-3 2) 0%RT	1) DCT-4 2) 5%RT60	1) DCT-5 2) CT	1) DCT-1 2) 5%RT30
3 and 8	1) DCT-3 2) 5%RT60	1) DCT-4 2) CT	1) DCT-5 2) 5%RT30	1) DCT-1 2) 105%T	1) DCT-2 2) 0%RT
4 and 9	1) DCT-4 2) 5%RT30	1) DCT-5 2) 105%T	1) DCT-1 2) 0%RT	1) DCT-2 2) 5%RT60	1) DCT-3 2) CT
5 and 10	1) DCT-5 2) 0%RT	1) DCT-1 2) 5%RT60	1) DCT-2 2) CT	1) DCT-3 2) 5%RT30	1) DCT-4 2) 105%T

By assigning a pair of subjects to each test order as illustrated above, it was possible to ensure that a given stage of the DCT or a given CT was completed on day 3 in two subjects, day 4 in another two, and so on. This is important because it is conceivable that the subjects would have got a training effect from the testing, and that their $\dot{V}O_{2peak}$ values might have increased as a consequence. It was intended that the allocation of test orders illustrated above would ensure that all possible comparisons among the six protocols could be made without any being confounded by such a training effect. However, there was a problem with the DCT in that, for this test, the peak $\dot{V}O_2$ was not attained on the same stage in all subjects.

When the allocation of test orders was developed, it was assumed that all subjects would complete at least 5 stages of the DCT and that the peak $\dot{V}O_2$ would be attained either during the 5th stage or during a later stage. It was decided that any subject who completed a 5th stage would return to the laboratory on a subsequent day to attempt a 6th stage, and that this process would continue until the subject failed to complete a particular stage. (They would then continue to complete the remaining stages of this test, as well as the remaining continuous tests, following the test order to which they had originally been assigned.) However, in practice, although all subjects started a 5th stage (this is important because it means that each of the continuous tests was preceded by a bout of high intensity exercise), the number of stages completed ranged from 4 to 7. The peak $\dot{V}O_2$ was attained on stage 3 in one subject, on stage 4 in four subjects, on stage 5 in two subjects, on stage 6 in 2 subjects, and on stage 7 in one subject.

If the peak $\dot{V}O_2$ had been attained on the same stage of the DCT in all subjects, this $\dot{V}O_2$ would have been attained on day 3 in two subjects, day 4 in another two, and so on, and it could easily have been compared with that attained in any of the continuous tests because each of these tests would similarly have been completed on day 3 in two subjects, day 4 in another two, and so on. As it was, the peak $\dot{V}O_2$ for the DCT was attained on day 3 in one subject, day 5 in two subjects, day 6 in three subjects, and day 7 in four subjects. This means that, relative to the other tests, the peak $\dot{V}O_2$ for the DCT was attained towards the end of the sequence of testing. It follows, therefore, that to the extent to which a progressive increase in $\dot{V}O_{2max}$ did occur over the course of this testing, the peak $\dot{V}O_2$ attained from the DCT will be biased towards a high value. This should be kept in mind when the $\dot{V}O_{2peak}$ data for the DCT (section 7.3.2.3) are interpreted.

7.2.4 *Test protocols*

DCT

The protocol for this test was similar to that of Taylor et al. (1955). Each stage lasted 3 min, and subjects completed just one stage in each testing session. The entire test was completed with the treadmill grade set at 5%. The speed for the first stage was 2.4 $km.h^{-1}$ below $v\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$ - 2.4 $km.h^{-1}$). For each subsequent stage, the speed was increased by 1.2 $km.h^{-1}$, and this process was repeated until a speed was reached at which the subject was unable to complete 3 min of running. An increment of 1.2 $km.h^{-1}$ was chosen for both this test and the CT because this was the amount by which the belt speed was increased during each minute in the 5%RT (see below).

Testing sessions were always separated by at least 24 hours and prior to starting each stage of the test subjects completed a controlled 10 min warm-up (see section 7.2.3). Following this warm-up period subjects rested for 5 min before they lowered themselves onto the (moving) treadmill belt to start the appropriate stage of the DCT. For each stage, two collections of expirate were made, one from 1.5 to 2 and another from 2 to 3 min after the start of the stage. When a subject failed to complete the full 3 min at a particular speed, respiratory data were not determined, but the time for which this speed was sustained was recorded so that the peak speed attained could be calculated (see section 7.3.2.3). Subjects were always encouraged to continue running for as long as possible, even when they felt certain they would not be able to complete the full 3 min.

CT

The protocol for this test was identical to that for the DCT in terms of the stage duration (3 min), the speed used for the first stage ($v\dot{V}O_{2peak}$ - 2.4 $km.h^{-1}$), the amount by which the speed was increased between stages (1.2 km.h^{-1}), the sampling period used (60 s), and the fact that the entire test was completed with the treadmill grade set at 5%. These two tests differed however in terms of the extent to which rest periods were provided between stages. Whereas for the DCT subjects only completed one stage per testing session and at least 24 hours recovery was allowed between sessions, for the CT subjects completed as many stages as they could within the one session and the speed was increased at the end of each 3 min stage while the subject continued to run on the treadmill.

Expirate was collected during the last minute of each stage. Subjects were encouraged to continue running for as long as possible and they were instructed that they should always start the next stage even if they were not sure they would be able to complete it. The collection of expirate was never initiated earlier than the 3rd minute of the stage, and respiratory data were not determined if the duration of the collection period was less than 55 s. A fingertip capillary blood sample for the determination of [Bla] was drawn 1 min after the subject terminated the test. To obtain an estimate of the peak [Bla] attained in the test, the (whole blood) lactate concentration was determined for this sample (YSI 2300 Stat Plus analyser, Yellow Springs Instruments Ltd., Ohio, USA).

105%T

This test was a square wave exercise bout, completed at a 5% grade and at a speed for which the required $\dot{V}O_2$, which was calculated from the regression equation derived from the preliminary incremental test (section 7.2.2), was equivalent to 105% of the peak $\dot{V}O_2$ attained in the preliminary 5% ramp test. A speed equivalent to 105% $\dot{V}O_{2peak}$ was chosen on the basis of pilot testing which indicated that the time to exhaustion averaged ~6 min when subjects ran at this speed.

Subjects were encouraged to continue running for as long as possible. Serial 60 s collections of expirate were made from 2 min onwards (see section 5.5.1), although respiratory data were not determined for the final collection if the duration of this collection was less than 55 s. The time for which the subject managed to continue running (the time to exhaustion) was recorded for each subject.

0%RT

The treadmill grade was maintained at zero and the speed was continuously increased (by 0.1 $km.h^{-1}$ every 5 s) throughout the test. The starting speed was selected for each individual so that exhaustion was reached in ~10 min. Serial 60 s collections of expirate were made throughout the test, but once again respiratory data were not determined for the final collection if the duration of this collection was less than 55 s. Subjects were encouraged to continue running for as long as possible, and a fingerprick capillary blood sample for the determination of [Bla] was drawn one minute after the subject terminated the test.

For each subject, two (linear) $\dot{V}O_2$-running speed relationships were derived. Each subject's data were plotted, and the first and last 1-2 min of the test were excluded so that only the apparently linear portion remained. This portion was divided in half and a separate regression equation was derived for each half. There were always at least 6 data points so each equation was based on at least 3 points. When an odd number of data points were available the middle point was included in both regression lines.

For each subject, the $\dot{V}O_2$ at which the LT occurred was determined by means of the V-slope method (Beaver et al., 1986). The number of data points for which $\dot{V}O_2$ exceeded this threshold value was then determined, and this number was then converted to a time (the sampling period was always 60 s for this test). Thus the time spent at supra-LT speeds was determined for each subject.

5%RT60

Although this test has, and will be, described as a CGIS test, the speed was actually kept constant for the first 5 min of the test, while the grade was increased by 1% every minute (from 1% to 5%). From 5 min onwards, the grade was maintained at 5% and the belt speed was increased [by 0.1 $km.h^{-1}$ every 5 s (1.2 $km.h^{-1}$ per min)] until the subject could no longer maintain the required speed. The test can therefore be considered to consist of two parts: a preliminary part in which the grade is gradually increased to 5% and a final part in which the speed is increased in a ramp pattern whilst the grade is maintained at 5%. The starting speed was adjusted depending on the subject's running ability to ensure that the test duration was 10 ± 1 min, so at least 4 min of the speed ramped portion of the test were always completed. This is the important part of the test because it is during this part that a plateau in the $\dot{V}O_2$-WR relationship will be observed, if indeed such a plateau is observed at all. The preliminary part was included because it was felt that subjects would prefer a protocol which allowed them to run throughout the duration of the test. (Had the test commenced at a 5% grade, it would have been necessary, in order to ensure a test duration of ~10 min, to select a starting speed for all but the most capable runners that would have been below the minimum speed at which they would be able to run.) The data used to define a $\dot{V}O_2$-plateau were obtained from the speed ramped (constant grade) portion of the test, as were the data from which the peak values for $\dot{V}O_2$ and RER were obtained. It is for this reason that the test is described as a CGIS ramp test.

<u>5%RT30</u>

The protocol for this test was identical to that for the 5%RT60 in all respects except that in the 5%RT30 serial collections of expirate were made over consecutive 30 s periods whereas in the 5%RT60 these collections were made over 60 s periods. The same starting speed was used for both tests, and in both cases expirate was collected from 6.5 min onwards. In the 5%RT60, respiratory data were not derived for the final collection if the duration of this collection was less than 55 s, whereas in the 5%RT30, these data were not derived if the duration of this final collection was less than 25 s. In both tests subjects were encouraged to keep running for as long as possible, and in both a fingertip capillary blood sample for the determination of [Bla] was drawn 1 min after the subject terminated the test.

7.2.5 *Controlling for the effect of test duration and sampling period*

Both the period over which expirate is sampled (section 3.2.4) and the duration of the test (Buchfuhrer et al., 1983) could potentially exert an effect on the peak $\dot{V}O_2$ for a progressive test. It was important therefore that when the effect of treadmill inclination was evaluated these two factors were controlled. Similarly, sampling period had to be controlled when the DCT, the 105%T, and the 5%RT60 were compared, and test duration had to be controlled when the effect of sampling period was evaluated.

Whenever sampling period was controlled, the nominal sampling period was 60 s. A whole number of breaths was always collected, so typically the sampling period was not exactly 60 s, but an effort was made to ensure that this period was as close to 60 s as possible. This sampling period was usually between 58 and 62 s, and on no occasion was it less than 55 or greater than 65 s. Similarly, for the 5%RT30 the sampling period was usually between 28 and 32 s, and on no occasion was it less than 25 or greater than 35 s. Data from the final sampling period were not used for the determination of $\dot{V}O_2$ or RER if this period was less than 55 s (or 25 s for the 5%RT30). However, as the starting speed was set on the basis of data obtained from the preliminary 5% ramp test, the actual test duration was usually very close to the predicted duration. Consequently, when the duration of the final expirate collection was less than 55 (or 25) s, it was typically no more than 10-15 s. This is important because it means that when $\dot{V}O_2$ and RER were not determined throughout the test, they were at least determined over all but 10-15 s of the test.

The comparisons for which it was important that test duration was controlled were that between the 0%RT and the 5%RT60, and that between the 5%RT30 and the 5%RT60. This control was exerted by selecting the starting speed, for each subject and for each test, so that each of these tests lasted ~10 min. This duration was chosen because it has been suggested (Buchfuhrer et al., 1983) that 10 ± 2 min is the optimal duration for a progressive CT if this test is to be used for the determination of $\dot{V}O_{2peak}$. For each individual, the starting speed used for the preliminary 5% ramp test (section 7.2.2) was adjusted upwards or downwards depending on whether the duration of this test was above or below 10 min, and this adjusted speed was used as the starting speed for the 5%RT60 and the 5%RT30. For the 0%RT, a starting speed was selected for each individual by assuming that the peak speed reached in this test would be 3 $km.h^{-1}$ higher than that which was reached in the preliminary 5% ramp test because pilot testing indicated that the peak speed reached typically decreased by ~3 $km.h^{-1}$ when the treadmill grade was increased from zero to 5%. For a particular individual, the starting speed was set so as to ensure that this expected peak speed would be reached after 10 min of the test.

7.2.6 *Development of criteria to define a $\dot{V}O_2$-plateau*

For the DCT, the $\Delta\dot{V}O_2$ between the first and the second stage of the test was determined for each of the 10 subjects, and from these individual data the 95% confidence limits for this $\Delta\dot{V}O_2$ were established. A plateau was defined as a $\Delta\dot{V}O_2$ between two consecutive stages of less than the lower 95% confidence limit. When the criterion used to define a $\dot{V}O_2$-plateau was developed or a judgement was made as to whether a $\dot{V}O_2$-plateau had occurred, only data from the second (60 s) collection period were used.

For the 5%RT60, the $\Delta\dot{V}O_2$ between the 60 s collection that started 6.5 min into the test and that which started 7.5 min into the test was determined. For the 5%CT-30, the $\Delta\dot{V}O_2$ between the 30 s collection that started 7 min into the test and that which started 7.5 min into the test was determined. And for the 0%CT, the $\Delta\dot{V}O_2$ between the 60 s collection that started 6 min into the test and that which started 7 min into the test was determined. For each protocol, the appropriate $\Delta\dot{V}O_2$ was determined for each of the 10 subjects. The mean $\Delta\dot{V}O_2$ for the 10 subjects was then determined, as was the standard deviation about this mean, and from these data the 95% confidence limits for this (sub-$\dot{V}O_{2peak}$) $\Delta\dot{V}O_2$ were established (separate limits were established for each protocol). Once again, a plateau was defined as a $\Delta\dot{V}O_2$ between two consecutive sampling periods of less than the lower 95% confidence limit for this (sub-$\dot{V}O_{2peak}$) $\Delta\dot{V}O_2$. Thus a separate criterion was used to define a $\dot{V}O_2$-plateau for each of the 3 protocols, although in all cases the data from which this criterion was derived were obtained from the 7th and the 8th minute of the test.

7.2.7 *Statistical analysis*

All tests were performed at an alpha level of 0.05, and all data are presented as mean ± SD (unless otherwise stated). Individual data can be found in Appendix 3, together with full results for each of the tests described below.

Paired t-tests were performed (5%RT60 vs. 0%RT) to ascertain whether the peak values for $\dot{V}O_2$, RER, and [Bla] were affected by treadmill inclination, and odds ratios were used to quantify the relative likelihood of a $\dot{V}O_2$-plateau being observed for the 5%RT60 (relative to that for the 0%RT). Additionally, the duration of the 5%RT60 was compared with that of the 0%RT (by means of a paired t-test) to ascertain whether the steps taken to control for the effect of test duration had been effective.

A two-way repeated measures (RM) ANOVA was used to compare the $\dot{V}O_2$ determined over 1.5 to 2 min with that determined over the 3rd minute of exercise for the last 4 stages of the DCT. As was the case for all of the RM ANOVAs reported in this thesis, the degrees of freedom for this ANOVA were corrected for a lack of sphericity. In all cases, this correction was performed in line with the recommendation of Huynh and Feldt (1976). That is, the Huynh-Feldt correction was used when an estimate of the true value for ε (the average of the Huynh-Feldt and the Greenhouse-Geisser ε) was ≥ 0.75 and the Greenhouse-Geisser correction was used when this estimate was < 0.75.

To establish whether the $\dot{V}O_2$ response differed between the CT and the DCT the individual values for the slope of the $\dot{V}O_2$-running speed relationship for the DCT were compared (by means of a paired t-test) with those for the CT (first 3 stages of each). Separate one-way RM ANOVAs were used to establish whether the peak $\dot{V}O_2$ and the peak RER differed between the DCT, the 105%T, and the 5%RT60, and Newman-Keuls post hoc tests were used to locate significant differences between means. Odds ratios were used to quantify the relative likelihood of a $\dot{V}O_2$-plateau being observed for the DCT (relative to that for the 5%RT60).

The two $\dot{V}O_2$-running speed relationships derived from the 0%RT were compared to establish whether the slope of this relationship varied with running speed (i.e. whether the $\dot{V}O_2$-running speed relationship was non-linear for this test). Two slopes were derived for each subject (one for the lower speeds and another for the higher speeds), and these slopes were compared by means of a paired t-test.

Paired t-tests were performed (5%RT60 vs. 5%RT30) to ascertain whether the peak values for $\dot{V}O_2$, RER, and [Bla] were affected by sampling period, and odds ratios were used to quantify the relative likelihood of a $\dot{V}O_2$-plateau being observed for the 5%RT60 (relative to that for the 5%RT30).

7.3 Results

7.3.1 *Effect of treadmill inclination*

Table 7.3 (below) shows the peak physiological responses and the incidence of a $\dot{V}O_2$-plateau for the 0%RT and the 5%RT60.

Table 7.3. Peak physiological responses and the incidence of a $\dot{V}O_2$-plateau for the 0% and the 5% ramp test (n = 10).

	5%RT60	0%RT	Difference (5% - 0%)	p value (5% vs. 0%)
Peak $\dot{V}O_2$ (ml.kg^{-1}.min^{-1})	59.9 ± 7.9	57.8 ± 7.9	2.1 ± 1.6	0.003
Peak RER	1.17 ± 0.05	1.13 ± 0.06	0.04 ± 0.05	0.016
Peak [Bla] (mmol.L^{-1})	8.4 ± 1.5	7.6 ± 1.9	0.8 ± 1.2	0.078
Incidence of a plateau	50%	30%	-	-

The peak $\dot{V}O_2$ and the peak RER were higher for the 5% test, by 3.6 and 3.5% respectively, although the test duration was similar for the two tests (10.3 ± 0.9 min

(0%) vs. 10.4 ± 0.3 min (5%); p = 0.74). The peak [Bla] was also higher for the 5% test, although for the 10 subjects studied this difference did not reach significance at the 5% level. The mean difference in [Bla] between the two protocols (11%) was large relative to the corresponding differences in RER and $\dot{V}O_2$, but there was considerable inter-individual variation in the difference between the [Bla] for the two protocols (see table 7.3).

The incidence of a $\dot{V}O_2$-plateau was higher for the 5% test. The odds of a $\dot{V}O_2$-plateau being observed in the 5% test were 5/5, or 1, whilst the odds of such a plateau being observed in the 0% test were 3/7, or 0.43. Therefore the odds ratio was 1:0.43, or 2.3:1, in favour of the 5%CT. This means that a $\dot{V}O_2$-plateau is 2.3 times more likely to occur when the grade is maintained at 5% than when the treadmill is kept horizontal. This is illustrated in figures 7.1 and 7.2 (below), where the $\dot{V}O_2$ response is given for the last 4 min of each test. Data from a representative subject are presented in figure 7.1, and mean data (for the 9 subjects from whom four 60 s samples of expirate were collected during the 5% test) are presented in figure 7.2.

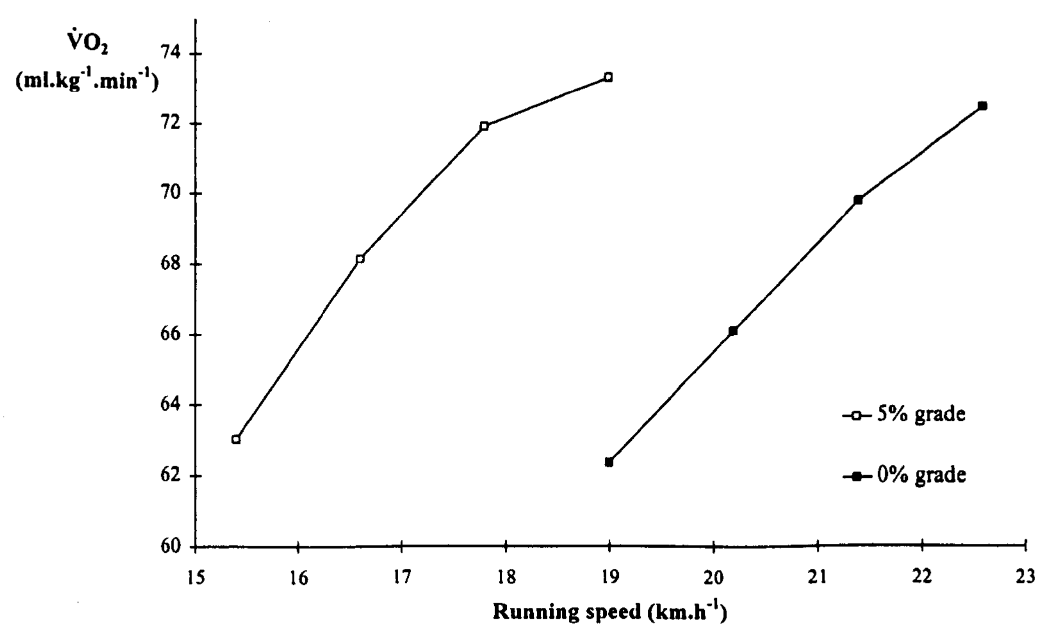

Figure 7.1. Data from a representative subject showing the $\dot{V}O_2$ response for the last 4 min of the 0%RT and the 5%RT60.

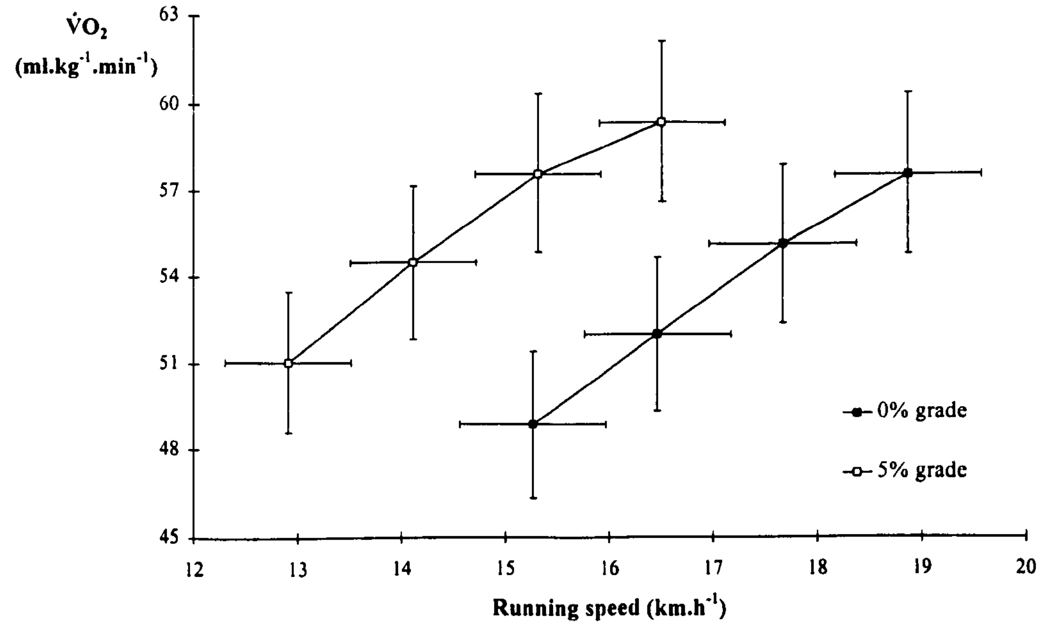

Figure 7.2. Group data (mean ± SEM; n = 9) showing the $\dot{V}O_2$ response for the last 4 min of the 0%RT and the 5%RT60.

The above figures show that, especially in the 5% test, the $\dot{V}O_2$-running speed relationship is not linear all the way up to maximum. For the 5% test, this relationship tends towards a plateau as the highest speed is approached. Although the effect is more subtle, the same trend is also apparent in the data from the 0% test.

When averaged over a 1 min period, the peak speed reached was 19.2 ± 1.9 km.h^{-1} for the 0% as opposed to 16.6 ± 1.6 km.h^{-1} for the 5% test. That is, increasing the treadmill grade from 0 to 5% decreased the peak speed reached by 2.6 km.h^{-1}, or 13.5%.

7.3.2 *Influence of $\dot{V}O_2$ kinetics*

7.3.2.1 $\dot{V}O_2$ response within each stage of the DCT

In figures 7.3 and 7.4 (below), data are presented for the last 4 stages of the DCT only because although all subjects started a 5th stage some failed to complete this stage. Data from a representative subject are presented in figure 7.3, and mean data are presented in figure 7.4. These mean data were derived, for each of the two sampling intervals, from 10 sets of individual data, each of which represented the $\dot{V}O_2$ response for the final 4 stages of the DCT in a particular subject. For clarity, the error bars for the abscissa (running speed) have been omitted.

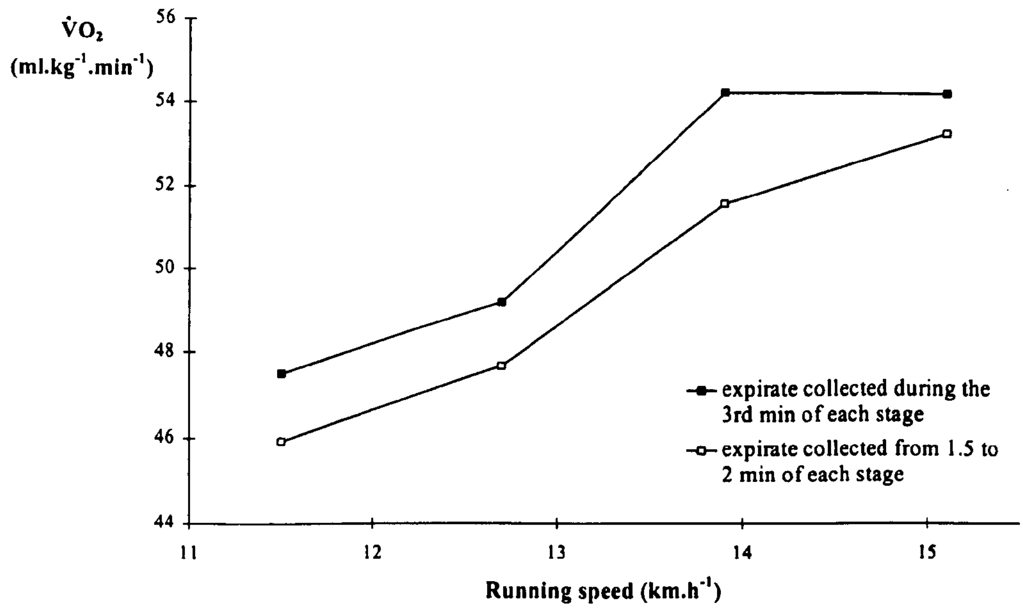

Figure 7.3. Data from a representative subject showing the $\dot{V}O_2$ response for the final 4 stages of the DCT, as determined using two different sampling intervals.

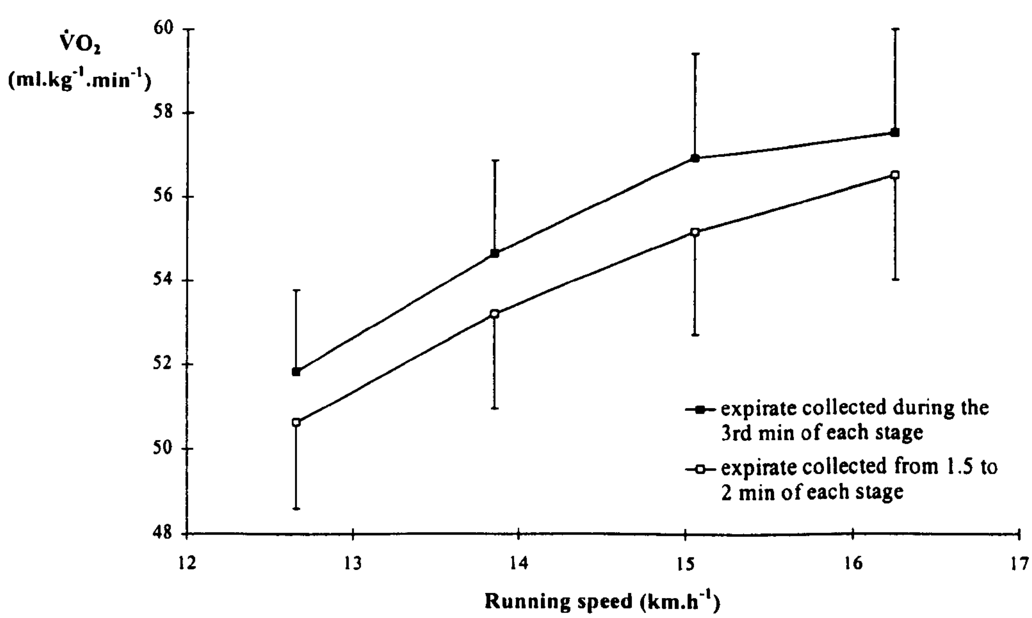

Figure 7.4. Group data (mean ± SEM; n = 10) showing the $\dot{V}O_2$ response for the final 4 stages of the DCT, as determined using two different sampling intervals.

It appears from the above figures that for each of the last 4 stages of the DCT the $\dot{V}O_2$ was higher for the second collection than for the first. The results of a repeated measures ANOVA performed across all 4 stages confirmed that this was the case ($p < 0.0005$). However, whilst it might also appear that the difference in $\dot{V}O_2$ between the first and the second collection varies across the 4 stages, no significant stage × $\dot{V}O_2$ interaction was found ($p = 0.103$). Figure 7.5 (below) shows that the $\Delta\dot{V}O_2$ from the first to the second collection period increased with increasing running speed up to the penultimate stage but that it then decreased dramatically for the final stage. All that can be said at this stage is that this $\Delta\dot{V}O_2$ does not continue to increase with running speed all the way up to the peak speed.

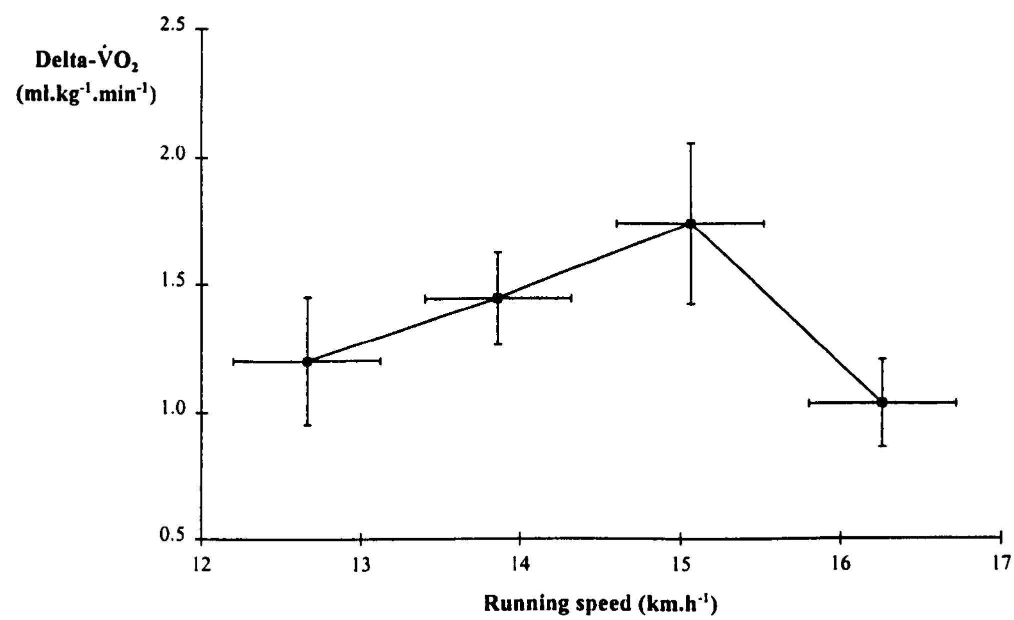

Figure 7.5. Group data (mean ± SEM; n = 10) showing the $\Delta\dot{V}O_2$ between the first and second collections for the final 4 stages of the DCT.

7.3.2.2 $\dot{V}O_2$ response for the DCT vs. that for the CT

Figures 7.6 and 7.7 (below) show the relationship between $\dot{V}O_2$ and running speed for the first 3 stages of both the CT and the DCT. Data from a representative subject are presented in figure 7.6, and mean data are presented in figure 7.7 [the error bars for the abscissa (running speed) have been omitted]. Mean data were compiled using data from 8 subjects only because two subjects failed to complete the 3rd stage of the CT.

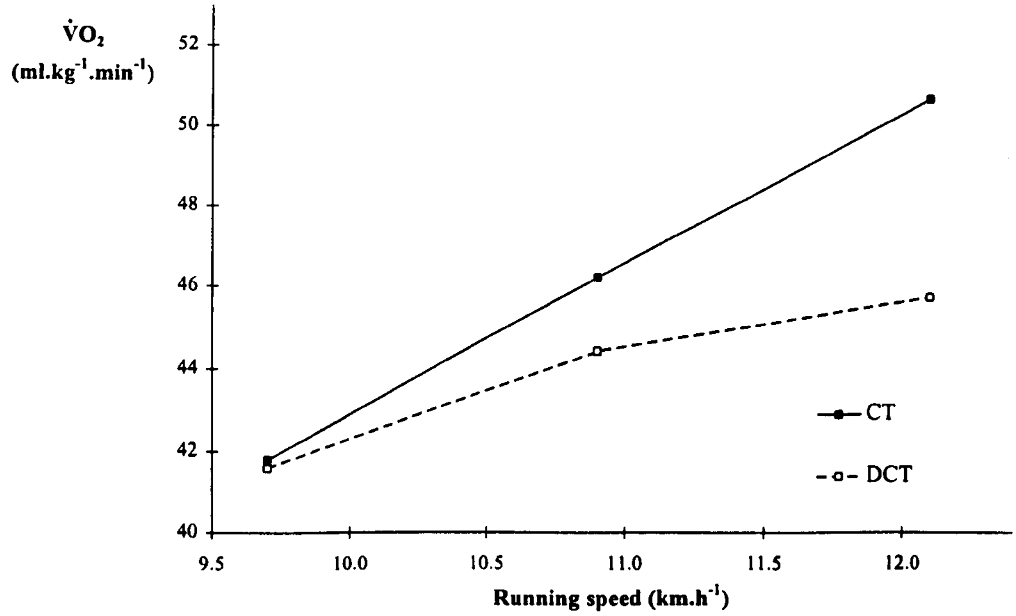

Figure 7.6. Data from a representative subject showing the relationship between $\dot{V}O_2$ and running speed for the first 3 stages of the DCT and the CT.

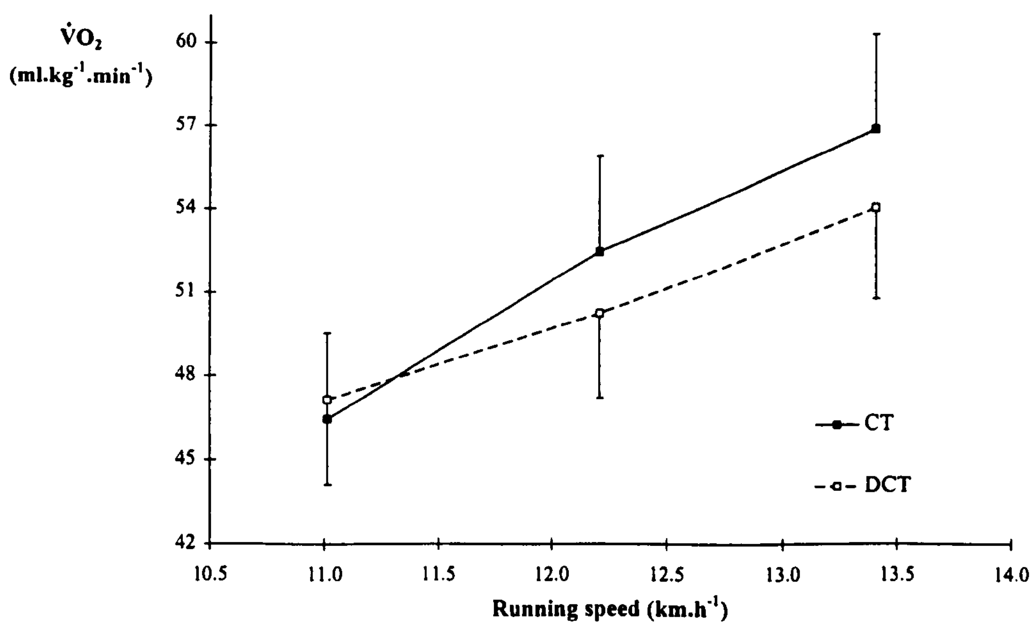

Figure 7.7. Group data (mean ± SEM; n = 8) showing the relationship between $\dot{V}O_2$ and running speed for the first 3 stages of the DCT and the CT.

The above figures suggest that the $\dot{V}O_2$-running speed relationship for the CT is steeper than that for the DCT. To establish whether this was in fact the case, individual linear regression equations relating $\dot{V}O_2$ to running speed were derived for each of the 8 subjects and for each of the 2 tests; the slopes of these relationships were then compared across the 2 tests by means of a paired t-test. Thus it was established that the slope of the $\dot{V}O_2$-running speed relationship was indeed steeper for the CT than for the DCT (4.3 ± 0.5 vs. 2.9 ± 0.8 $ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$; $p = 0.0008$).

Figures 7.8 and 7.9 (below) show the $\dot{V}O_2$-running speed relationship for the last 3 stages of both the DCT and the CT. Data from a representative subject are presented in figure 7.8, and mean data are presented in figure 7.9. The latter figure is based on the same 8 subjects that figure 7.7 was based on, and once again the error bars for the abscissa (running speed) have been omitted.

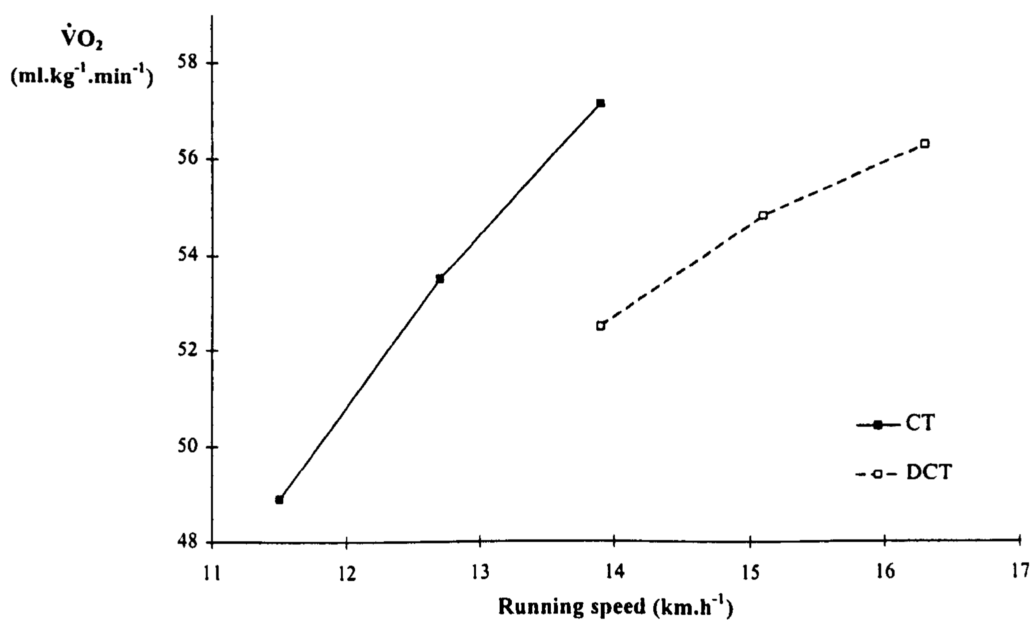

Figure 7.8. Data from a representative subject showing the relationship between $\dot{V}O_2$ and running speed for the last 3 stages of the DCT and the CT.

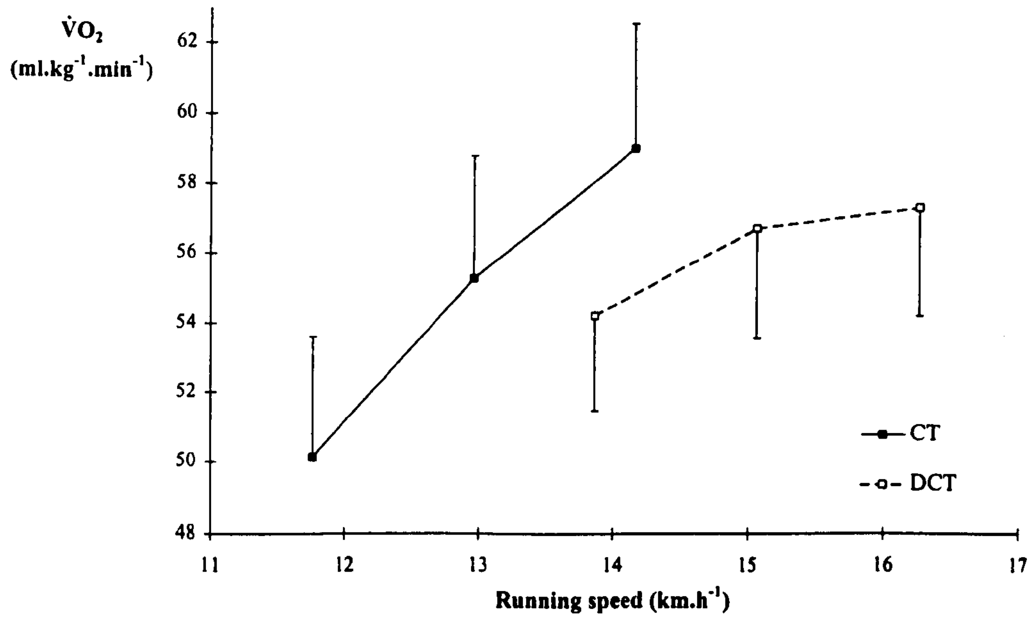

Figure 7.9. Group data (mean ± SEM; n = 8) showing the relationship between $\dot{V}O_2$ and running speed for the last 3 stages of the DCT and the CT.

The above figures show, as would be expected, that a higher peak speed was reached in the DCT. They might also appear to show that the peak $\dot{V}O_2$ was higher for the CT. However, the peak $\dot{V}O_2$ was attained on the penultimate stage of the DCT in several subjects, and even when just the 8 subjects on whom figures 7.7 and 7.9 are based were considered, the peak $\dot{V}O_2$ for this test (59.0 ± 9.9 ml.kg^{-1}.min^{-1}) was not different ($p = 0.285$) from that for the CT (57.7 ± 9.2 ml.kg^{-1}.min^{-1}).

It is apparent from figures 7.8 and 7.9 that the tendency for the $\dot{V}O_2$-running speed relationship to plateau is much more pronounced for the DCT. However, taken together, figures 7.7 and 7.9 show that marked differences in the $\dot{V}O_2$-running speed relationship are observed when a continuous and a discontinuous version of the same protocol are compared, and that these differences are observed at speeds well below that at which $\dot{V}O_2$ plateaus in the DCT.

7.3.2.3 $\dot{V}O_{2peak}$ for the DCT vs. that for the 105%T and the 5%RT

Table 7.4 (below) shows that the peak $\dot{V}O_2$ was higher for the 5%RT60 than for the DCT or the 105%T, whilst the peak RER was higher for the DCT than for the 5%RT60 or the 105%T.

Table 7.4. Peak values (n = 10) for $\dot{V}O_2$ and RER for the 5%RT60, the DCT, and the 105%T.

	5%RT60	DCT	105%T	p value (ANOVA)
Peak $\dot{V}O_2$ (ml.kg^{-1}.min^{-1})	59.9 ± 7.9	57.8 ± 8.1*	58.1 ± 6.8*	0.014
Peak RER	1.17 ± 0.05†	1.24 ± 0.07	1.14 ± 0.04†	0.001

*$p < 0.05$ vs. the 5%RT60; $^{\dagger}p < 0.05$ vs. the DCT.

The time to exhaustion for the 105%T was 6.2 ± 2.5 min, and the speed sustained for the duration of this test was 14.4 ± 2.0 km.h^{-1}. For the DCT, the highest speed that could be sustained for 3 min was 16.3 ± 1.5 km.h^{-1}. However, in 4 of the 10 subjects the peak $\dot{V}O_2$ was attained in the stage prior to this fastest stage, and hence the 3 min run from which the peak $\dot{V}O_2$ was actually attained was completed at a speed of 15.8 ± 1.6 km.h^{-1}. The fastest speed attempted in the DCT was 17.5 ± 1.5 km.h^{-1}, but this speed was sustained for just 2.1 ± 0.4 min. The peak speed for the 5%RT60 (averaged over the final minute of the test) was 16.6 ± 1.6 km.h^{-1}.

It should be emphasised at this point that whilst the mean time to exhaustion for the 105%T was 6.2 min the inter-individual variation in this time was considerable (range: 3.1 to 10.7 min). The mean test duration was shorter for the 105%T than for the 5%RT60 (6.2 ± 2.5 vs. 10.4 ± 0.3 min; $p < 0.001$) and the mean $\dot{V}O_{2peak}$ was also lower for the former test (table 7.4). However, just as there was considerable inter-individual variation in the time to exhaustion for the 105%T so there was considerable variation in the extent to which the peak $\dot{V}O_2$ for the 5%RT60 exceeded that for the 105%CT. It appears that those subjects in whom the time to exhaustion for the 105%T was longest were able to match or even exceed the $\dot{V}O_2$ they attained in the 5%RT60 during the 105%T, whilst those in whom this time was short attained a peak $\dot{V}O_2$ in the 105%T that was well below that which they attained in the 5%RT60 (figure 7.10).

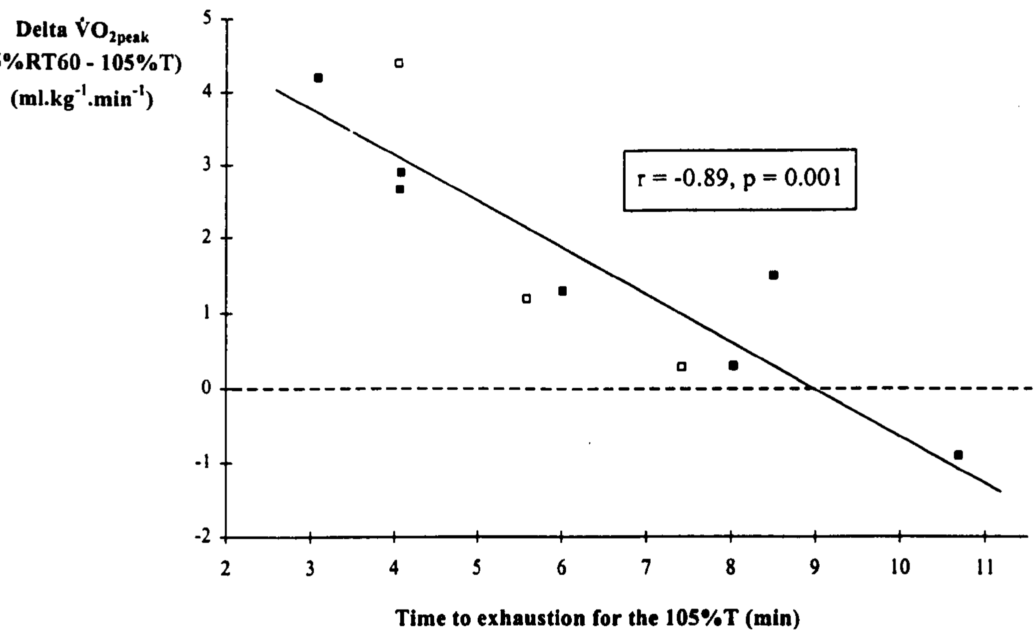

Figure 7.10. Difference in peak $\dot{V}O_2$ between the 5%RT60 and the 105%T as a function of the time to exhaustion for the 105%T (individual data). (Individuals represented by unfilled squares are distance runners.)

Figure 7.10 shows that there is a strong inverse relationship between the time to exhaustion for the 105%T and the extent to which the peak $\dot{V}O_2$ attained in the 5%RT60 exceeds that which is attained in the 105%T. These data suggest that a true $\dot{V}O_{2max}$ will only be attained from a square wave exercise bout when the duration of the bout is ~7 min or longer. Given that the time to exhaustion for the 5%RT60 ranged from 9.9 to 10.7 min, it is noteworthy that the only subject for whom the peak $\dot{V}O_2$ for the 105%T was higher than that for the 5%RT60 was the one for whom the time to exhaustion for the 105%T was longer than 9 min (figure 7.10).

In addition to the variation that was evident in the extent to which the peak $\dot{V}O_2$ for the 5%RT60 exceeded that for the 105%T, considerable inter-individual variation was also evident in the extent to which the $\dot{V}O_2$ for the 5%RT60 exceeded that for the DCT. In the latter case, it appeared that those subjects who were able to complete the greatest number of stages in the DCT were able to match or even exceed the $\dot{V}O_2$ they attained in the 5%RT60 in the DCT whilst those who completed only a few stages attained a $\dot{V}O_2$ in the DCT that was well below that which they attained in the 5%RT60. For all subjects, the starting speed for the DCT was $v\dot{V}O_{2peak}$ - 2.4 km.h^{-1}, so those who completed the greatest number of stages also attained the highest speed relative to $v\dot{V}O_{2peak}$. In figure 7.11 (below), the difference in peak $\dot{V}O_2$ between the 5%RT60 and the DCT is plotted as a function of the peak speed attained in the DCT (expressed relative to $v\dot{V}O_{2peak}$). In calculating this peak speed, account was taken not only of the number of stages that were completed but also of the time for which the final (incomplete) stage was sustained. For example, a subject who only completed 4 stages would have started a 5th stage at a speed equivalent to $v\dot{V}O_{2peak}$ + 2.4 km.h^{-1}. If this speed was sustained for 2 min, the peak speed for this subject would be $v\dot{V}O_{2peak}$ + 1.2 km.h^{-1} + (1.2 km.h^{-1} × 2/3), or $v\dot{V}O_{2peak}$ + 2.0 km.h^{-1}. [$v\dot{V}O_{2peak}$ + 1.2 km.h^{-1} represents the fastest speed for which this subject would have completed the full 3 min (i.e. the speed associated with the 4th stage of the test).]

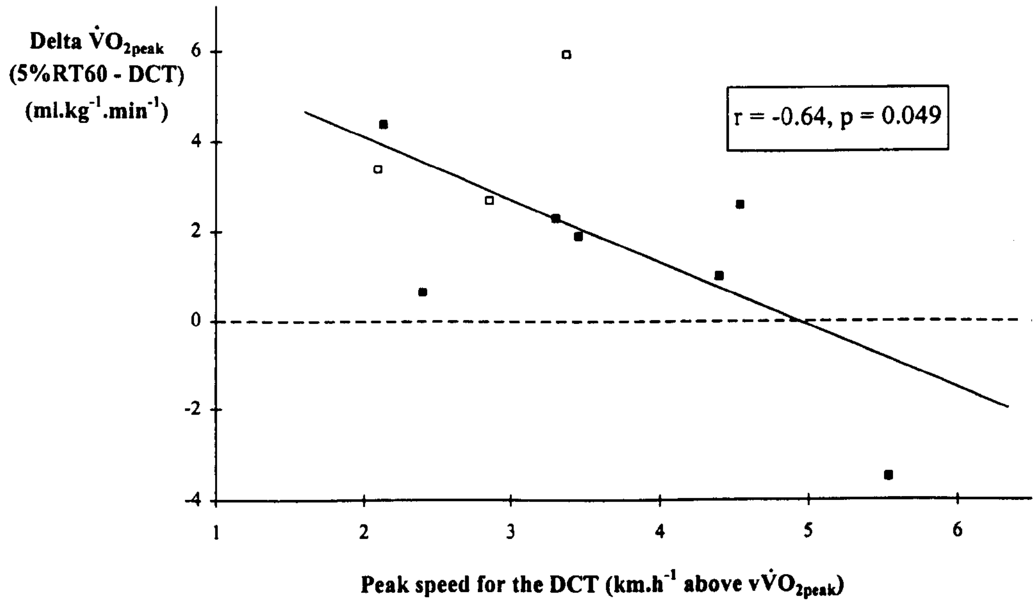

Figure 7.11. Difference in peak $\dot{V}O_2$ between the 5%RT60 and the DCT as a function of the peak speed attained in the DCT (individual data). (Individuals represented by unfilled squares are distance runners.)

Figure 7.11 shows that an inverse relationship exists between the extent to which the $\dot{V}O_2$ attained in the 5%RT60 exceeds that which is attained in the DCT and the extent to which the peak speed attained in the DCT exceeds $v\dot{V}O_{2peak}$. The subject who attained the highest peak speed (relative to $v\dot{V}O_{2peak}$) in the DCT was the one who continued the longest in the 105%T. Just as this subject was the only one for whom the peak $\dot{V}O_2$ for the 105%T was higher than that for the 5%RT60 (figure 7.10), so he was the only one for whom the peak $\dot{V}O_2$ for the DCT was higher than that for the 5%RT60 (figure 7.11).

The finding that $\dot{V}O_{2peak}$ was generally lower for the DCT than for the 5%RT60 is interesting given that a $\dot{V}O_2$-plateau was observed in 80% of subjects for the DCT but in only 50% of subjects for the 5%CT. The odds of a $\dot{V}O_2$ plateau being observed in the DCT are 8/2, or 4, whilst the odds of such a plateau being observed in the 5%RT60 are 5/5, or 1. The odds ratio is therefore 4:1 in favour of the DCT. This means that a

$\dot{V}O_2$-plateau is 4 times more likely to occur in a progressive test when a discontinuous protocol is used than when a continuous protocol is used.

Figures 7.12 and 7.13 (below) show the $\dot{V}O_2$ response for the final 4 min of the 5%RT60 and the final 4 stages of the DCT. Data from a representative subject are presented in figure 7.12, and mean data are presented in figure 7.13. The latter figure was compiled using only data from the 9 subjects from whom four 60 s samples were obtained in the 5%RT60.

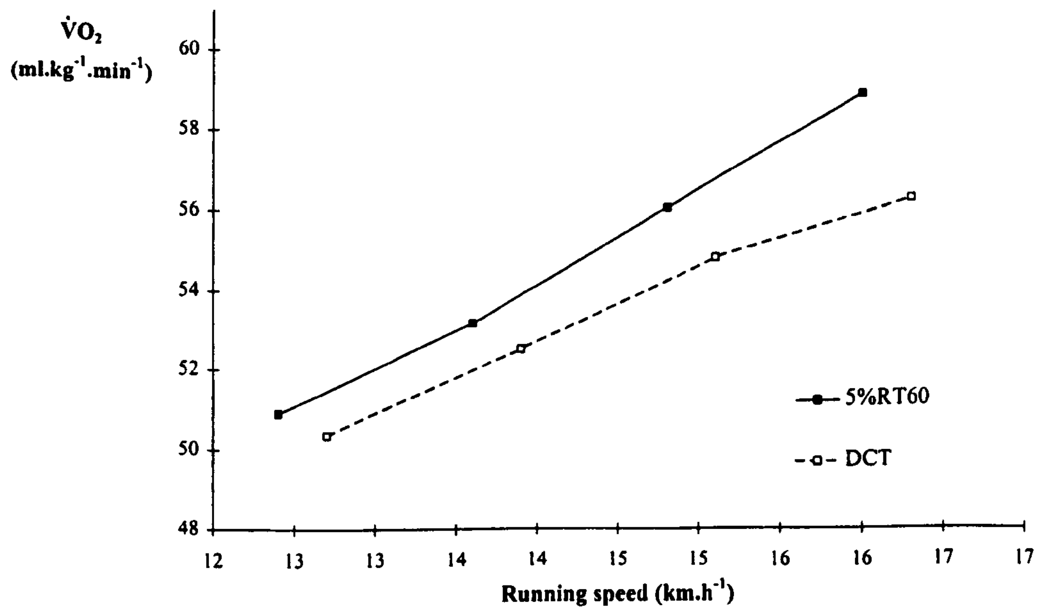

Figure 7.12. Data from a representative subject showing $\dot{V}O_2$ as a function of running speed for the final 4 min of the 5%RT60 and the final 4 stages of the DCT.

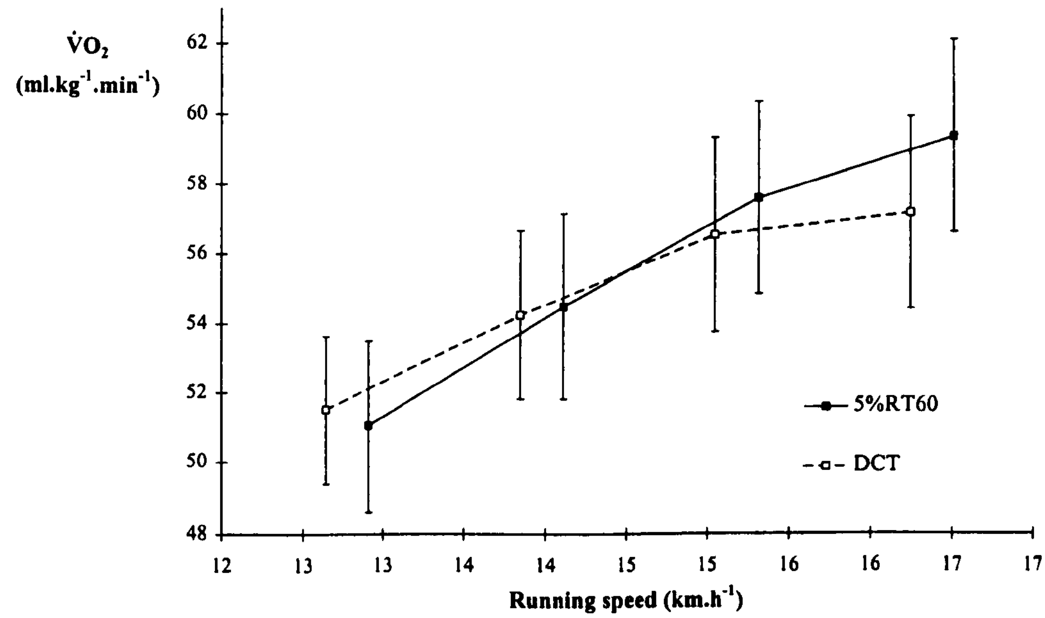

Figure 7.13. Group data (mean ± SEM; n = 9) showing $\dot{V}O_2$ as a function of running speed for the final 4 min of the 5%RT60 and the final 4 stages of the DCT.

7.3.2.4 Linearity of the $\dot{V}O_2$-running speed relationship for the 0%RT

Table 7.5 (below) shows that even a substantial increase in the speeds over which this relationship was derived had no effect on the slope of the $\dot{V}O_2$-running speed relationship for the 0%RT. The implication is that the $\dot{V}O_2$-running speed relationship was linear for this test. The time spent at supra-LT speeds was between 3 and 6 min for all subjects.

Table 7.5. Slope of the $\dot{V}O_2$-running speed relationship for the first and the second half of the 0%RT (n = 10).

	First half	Second half	Difference (2nd - 1st)	p value (2nd vs. 1st)
Start speed ($km.h^{-1}$)	9.4 ± 1.5	14.0 ± 1.7	4.6 ± 0.9	-
End speed ($km.h^{-1}$)	13.6 ± 1.8	18.2 ± 2.2	4.5 ± 0.9	-
Slope ($ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$)	2.88 ± 0.38	2.82 ± 0.34	-0.06 ± 0.41	0.67

That $\dot{V}O_2$ increased linearly with running speed during the 0%RT is evident from figures 7.14 and 7.15 (below). Data from a representative subject are presented in figure 7.14, and mean data are presented in figure 7.15.

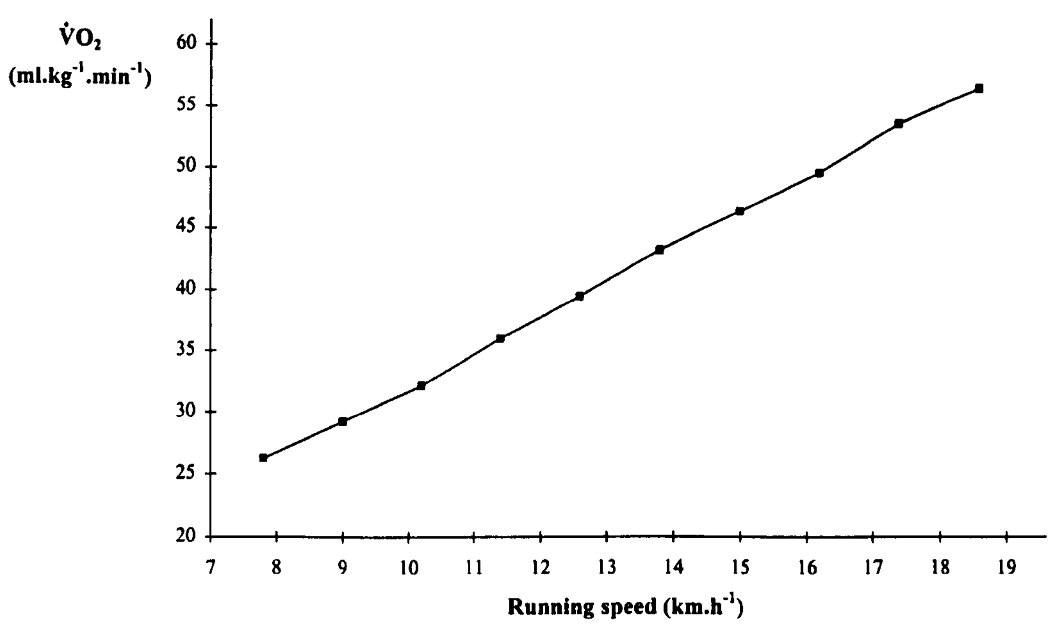

Figure 7.14. Data from a representative subject showing the relationship between $\dot{V}O_2$ and running speed for the 0%RT.

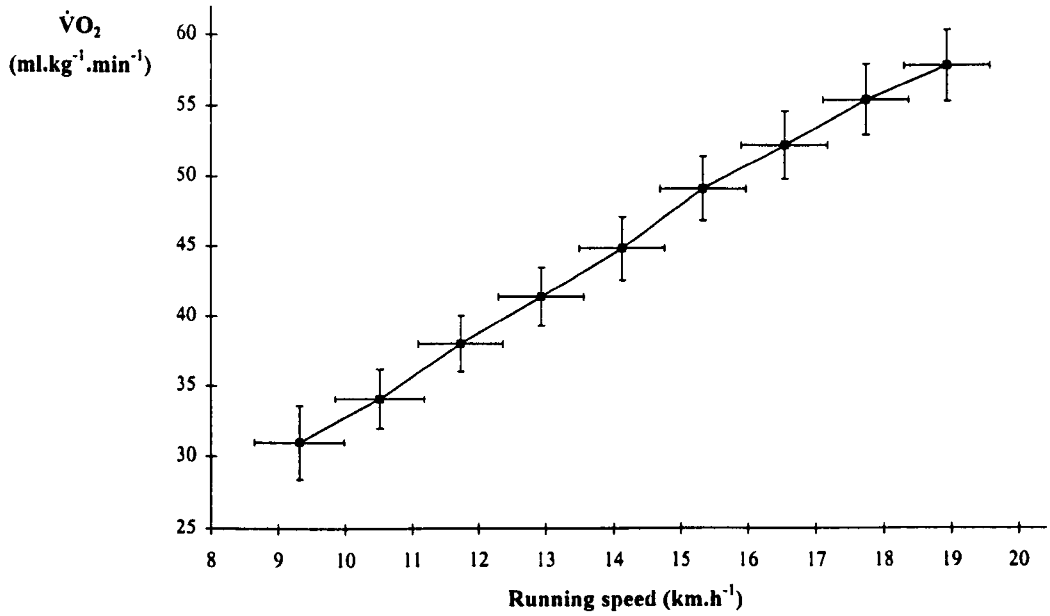

Figure 7.15. Group data (mean ± SEM; n = 10) showing the relationship between $\dot{V}O_2$ and running speed for the 0%RT.

7.3.3 *Effect of sampling period*

Table 7.6 (below) shows the peak physiological responses and the incidence of a $\dot{V}O_2$-plateau for the 5%RT60 and the 5%RT30.

Table 7.6. Peak physiological responses and the incidence of a $\dot{V}O_2$-plateau for the 5%RT60 and the 5%RT30 (n = 10).

	5%RT60	**5%RT30**	**Difference (60 s - 30 s)**	**p value (60 s vs. 30 s)**
Peak $\dot{V}O_2$ (ml.kg^{-1}.min^{-1})	59.9 ± 7.9	59.4 ± 7.2	0.5 ± 1.3	0.276
Peak RER	1.17 ± 0.05	1.17 ± 0.04	0.00 ± 0.03	0.819
Peak [Bla] (mmol.L^{-1})	8.4 ± 1.5	8.2 ± 1.4	0.14 ± 0.69	0.533
Incidence of a plateau	50%	20%	-	-

The above table shows that reducing the sampling period from 60 to 30 s had no effect on the peak values for $\dot{V}O_2$, RER, and [Bla] attained in a continuous ramp test. The incidence of a $\dot{V}O_2$-plateau was, however, higher when a 60 s sampling period was used than when a 30 s period was used. The odds of a $\dot{V}O_2$-plateau being observed in the 5%RT60 were 5/5, or 1, whilst the odds of such a plateau being observed in the 5%RT30 were 2/8, or 0.25. Therefore the odds ratio was 1:0.25, or 4:1, in favour of the 5%RT60. In other words, a $\dot{V}O_2$-plateau is 4 times more likely to occur when a 60 s sampling period is used than when a 30 s sampling period is used.

Figures 7.16 and 7.17 (below) show the $\dot{V}O_2$ response for the last 3 min of the 5%RT60 and the 5%RT30. Data from a representative subject are presented in figure 7.16, and mean data are presented in figure 7.17.

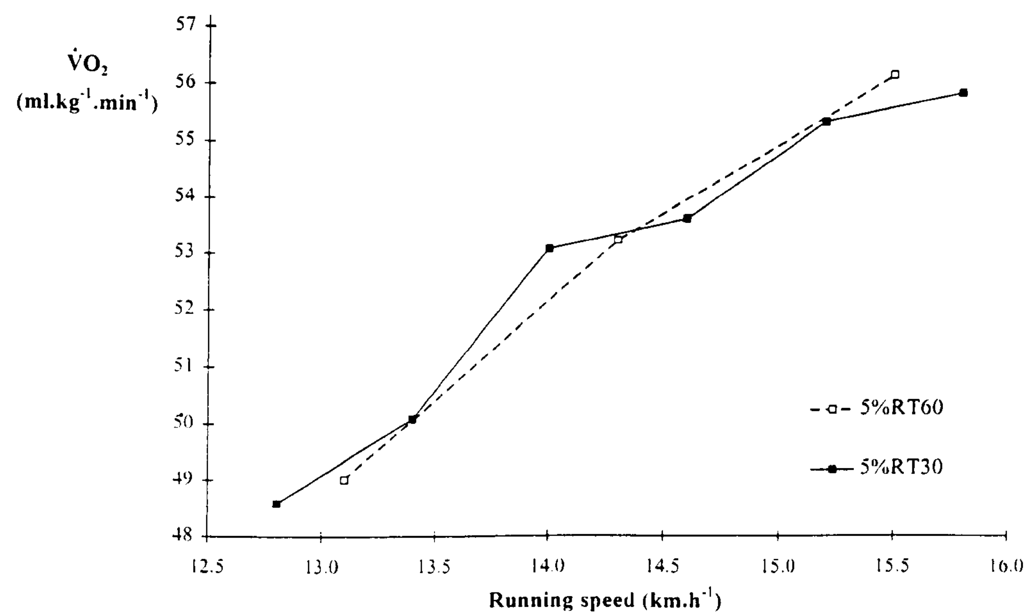

Figure 7.16. Data from a representative subject showing the $\dot{V}O_2$ response for the last 3 min of the 5%RT60 and the 5%RT30.

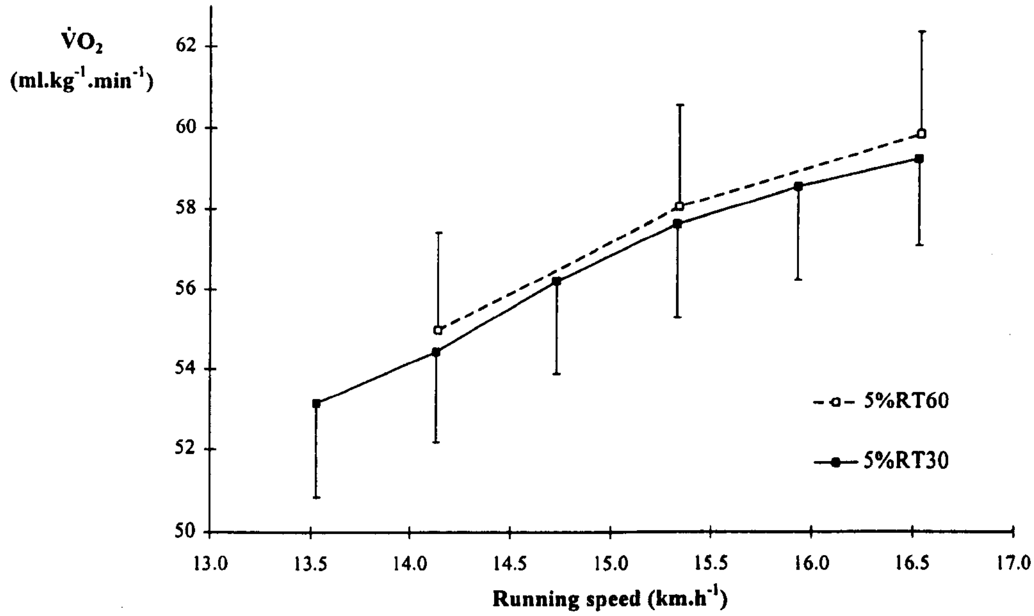

Figure 7.17. Group data (mean ± SEM; n = 10) showing the $\dot{V}O_2$ response for the last 3 min of the 5%RT60 and the 5%RT30.

Figure 7.17 is of interest because it shows that the tendency for the $\dot{V}O_2$-running speed relationship to plateau at high speeds is no more pronounced for the 5%RT60 than for the 5%RT30. This is surprising given that the incidence of a $\dot{V}O_2$-plateau was higher for the 5%RT60 (50% vs. 20%). The variability in the $\dot{V}O_2$ data obtained from the 30 s collections was relatively large though (see figure 7.16), and it appears that this large variability may have obscured the presence of a $\dot{V}O_2$-plateau. In this context, it is noteworthy that whilst the mean (sub-$\dot{V}O_{2peak}$) $\Delta\dot{V}O_2$ decreased by a factor of 2 (from 3.41 to 1.68 $ml.kg^{-1}.min^{-1}$) when the sampling period was reduced from 60 to 30 s, the SD about this mean $\Delta\dot{V}O_2$ decreased by only 4% (from 0.99 to 0.95 $ml.kg^{-1}.min^{-1}$). Consequently, whilst the criterion used to define a $\dot{V}O_2$-plateau for the 5%RT60 was an increase of less than +1.47 $ml.kg^{-1}.min^{-1}$ between consecutive 60 s samples, the corresponding criterion for the 5%30CT was an increase of less than -0.19 $ml.kg^{-1}.min^{-1}$ between consecutive 30 s samples.

7.4 Discussion

7.4.1 *Effect of treadmill inclination*

7.4.1.1 Effect of treadmill grade on the peak physiological responses for a CGIS test

Although the results of this study provide some support for the notion that the peak speed reached is limited by non-metabolic factors when a CGIS test is conducted on a level treadmill, they are by no means conclusive. In agreement with several previous studies that have compared level and uphill running (Taylor et al., 1955; Astrand and Saltin, 1961a; Hermansen and Saltin, 1969; Mayhew and Gross, 1975; Jones and Doust, 1996; Sloniger et al., 1997b), the present study found that the peak $\dot{V}O_2$ was higher for the 5% than for the 0% test. Published data on the effect of treadmill inclination on peak values for RER or [Bla] are scarce (see section 4.3.3). The present study found that the peak RER was higher for the 5% test, suggesting that subjects terminated the 0% test at a time when anaerobic metabolism was operating at a relatively low rate (relative to the 5% test). However, the difference in RER was small, and whilst there was a trend for the peak [Bla] to be higher for the 5% test the difference in [Bla] did not reach statistical significance.

If it is assumed that the peak speed reached on the 5% test was limited by an inadequate supply of O_2 and the associated demand for anaerobic metabolism, and that the peak values for RER and [Bla] attained on this test are representative of the highest level of anaerobic metabolism that can be attained in a progressive test, then the logical conclusion is that the peak speed reached in the 0% test was limited by factors other than the demand for a high level of anaerobic metabolism. However, whether the peak $\dot{V}O_2$ attained in the 0% test was similarly limited is open to debate. That is, if $\dot{V}O_{2max\,(0\%)}$ is the maximal $\dot{V}O_2$ that can be attained during running on a level treadmill, it is unclear whether the peak $\dot{V}O_2$ attained in the 0% test was equal to, or lower than, $\dot{V}O_{2max\,(0\%)}$. On the one hand, it is possible that subjects were able to continue in the 0% test for long enough to reach $\dot{V}O_{2max\,(0\%)}$, but that they terminated the test soon after they attained this $\dot{V}O_2$ because they were unable to increase their speed any further. But on the other, it is possible that they were unable to continue in this test for long enough to reach $\dot{V}O_{2max\,(0\%)}$.

The peak $\dot{V}O_2$ for the 5% test was 3.6% higher than that for the 0% test, so for the first of the above explanations to be correct, the increase in active muscle mass associated with an increase in treadmill grade from 0% to 5% would have to be sufficient to increase $\dot{V}O_{2max}$ by 3.6%. Several studies have compared the peak $\dot{V}O_2$ for level with that for uphill running. Sloniger et al. (1997b), who compared running up a 10% grade with level running, found a difference of ~3%, as did Mayhew and Gross (1975), who compared a CGIS test (0% grade) with a CSIG test for which the peak grade reached an average of 8.4%. A difference of 4.5% was reported by Astrand and Saltin (1961a) who compared running up a 7.9% grade with running on a level treadmill, whilst Jones and Doust (1996), who compared a CGIS test (0% grade) with a CSIG test for which the peak grade reached was between 8 and 11%, reported a difference of 6.1%.

On the basis of the above data, it is hard to draw any conclusions about whether the increase in active muscle mass associated with an increase in treadmill grade from 0 to 5% is likely to be sufficient to increase $\dot{V}O_{2max}$ by 3.6%. It appears that there is considerable variation in the size of the increase in $\dot{V}O_{2peak}$ associated with a given increase in treadmill grade. In fact the picture is more complex than the above data suggest because some investigators (Kasch et al., 1976; Davies et al., 1984) have found that increasing the treadmill grade has no effect on the peak $\dot{V}O_2$ attained. These latter findings are hard to explain, but it is conceivable that in subjects who are very accomplished at running fast the active muscle mass might be at least as high for running on a level treadmill as for running uphill. If it is assumed that these subjects are so skilled at fast running that they are able to run fast enough to attain a true $\dot{V}O_{2max}$ during level treadmill running, it is possible to see how they might be able to match or even exceed the peak $\dot{V}O_2$ they can attain during uphill running when they run on a level treadmill. This explanation is consistent with the observation that subjects who are able to attain the same $\dot{V}O_2$ during both level and uphill running also attain the same peak values for RER (Kasch et al., 1976) and [Bla] (Davies et al., 1984) during both types of running.

It is possible that whilst there are some subjects for whom the active muscle mass will be larger for uphill than for level running there are others for whom this will not be the case. Similarly, it is possible that whilst there are some subjects for whom the peak speed that can be attained in a CGIS test conducted on a level treadmill is limited by non-metabolic factors to the extent that they are unable to attain a true $\dot{V}O_{2max}$ during such a test, there are others for whom this is not the case. By taking all of these possibilities into account, it is possible to explain the findings that have been obtained in all of the published studies which have compared a progressive test conducted on a level treadmill with a similar test conducted on an inclined treadmill, as well as those that were obtained in the present study. This is illustrated in table 7.7 (below).

Table 7.7. Possible explanations for the various findings that have been obtained when the peak physiological responses for level and uphill running have been compared.

Findings	References	Explanation
no difference in $\dot{V}O_2$, RER, or [Bla]	Kasch et al. (1976); Davies et al. (1984)	non-metabolic limitation not encountered during level running, and no difference in the active muscle mass
higher $\dot{V}O_2$ for uphill running; no difference in RER or [Bla]	Mayhew & Gross (1975); Hermansen & Saltin (1969)	non-metabolic limitation not encountered during level running but a larger muscle mass recruited during uphill running
$\dot{V}O_2$, RER, and [Bla] all higher for uphill running	present study	slight non-metabolic limitation during level running and a larger muscle mass recruited during uphill running

Throughout the preceding discussion it has been assumed that whilst the peak speed reached in a progressive test conducted on a level treadmill (e.g. the 0%RT) might be limited by non-metabolic factors, the speed reached in a similar test conducted at a moderate grade (e.g. the 5%RT60) is always limited by an inadequate supply of O_2 and the associated demand for anaerobic metabolism. Indeed the assumption that the peak speed reached in a progressive test conducted on an inclined treadmill is limited by an inadequate supply of O_2 and the associated demand for anaerobic metabolism is implicit in all of the explanations given in table 7.7 (above). However, in the present study, evidence to confirm the validity of this assumption (i.e. a $\dot{V}O_2$-plateau) was obtained in only 50% of subjects for the 5%RT60, and for the 0%RT the incidence of a plateau was even lower. The finding that the incidence of a plateau was low for the 0% test is consistent with the notion that the peak speed reached in such a test might be limited by non-metabolic factors in the majority of individuals. However, the data suggest that a plateau is only 2.3 times more likely to occur when the treadmill grade is maintained at 5% than when the treadmill is kept horizontal. Further research is needed to clarify the effect of treadmill grade on the peak physiological responses for a CGIS test. Such research is warranted because at present it is impossible to draw any conclusions about whether the peak speed is likely to be limited by non-metabolic factors for downhill running only, for downhill and level running, or for uphill running also.

7.4.2.2 CGIS vs. CSIG tests

The results of the present study are consistent with those of previous studies in two respects. First, just as those studies which have compared the incidence of a $\dot{V}O_2$-plateau for a DCT and a CT (Duncan et al., 1997; Rivera-Brown et al., 1994; Sheehan et al., 1987) have found the incidence of such a plateau to be higher for the DCT, so this study found that the incidence of a $\dot{V}O_2$-plateau was higher for the DCT than for the 5%RT60 (80% vs. 50%). Second, just as several previous studies have found the incidence of a $\dot{V}O_2$-plateau to be ≥80% for a DCT (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979; Rivera-Brown et al., 1994; Taylor et al., 1955), so this study found that 8 of the 10 subjects demonstrated a plateau in the DCT. However, whereas in the studies cited above, continuous and discontinuous versions of a CSIG test were compared, the present study compared continuous and discontinuous versions of a CGIS test. Thus the results of the present study allow the findings that had previously been obtained for a CSIG test to be extended to a CGIS test.

A possible interpretation of these findings is that although there is a limit to the $\dot{V}O_2$ that can be attained during a particular type of exercise, a plateau in the $\dot{V}O_2$-running speed relationship is only observed when the test conditions are such that very high WRs can be attained (i.e. WRs for which the anaerobic contribution to energy production is large). If it is accepted that there is a limit to the amount of ATP that can be generated anaerobically (the anaerobic capacity; see Chapter 2), then it is possible to conceive that over the course of a continuous test this anaerobic capacity might become exhausted, and that, as a result, the test might be terminated at a time when anaerobic metabolism is operating at a relatively low rate. It is also conceivable that the rest periods in a discontinuous protocol might allow the ability to generate ATP anaerobically to be restored between stages so that a relatively high rate of anaerobic ATP production can be sustained throughout the final stages of the test.

Some support for this interpretation comes from the RER data obtained in the present study. The peak RER was higher for the DCT than for the 5%RT60 (1.24 vs. 1.17), thus lending some support to the notion that the continuous test was terminated at a time when anaerobic metabolism was operating at a relatively low rate (relative to the DCT). No comparison was made of the post-test [Bla] because it was considered likely that the muscle - blood gradient for [lactate] would be much higher at the end of the final completed stage of the DCT than at the end of the 5%RT60. Were this the case, the [Bla] would not provide a comparable index of muscle lactate production for the two tests.

7.4.2 *Influence of* $\dot{V}O_2$ *kinetics*

7.4.2.1 Influence of the $\dot{V}O_2$ slow component

The results of the present study show that the $\dot{V}O_2$-running speed relationship for a discontinuous CGIS test is different to that for a continuous version of the same test (see figures 7.4 and 7.5). The finding that the slope of the $\dot{V}O_2$-running speed relationship was higher for the CT than for the DCT can be explained if it is assumed that, provided sufficient time were available, $\dot{V}O_2$ would have continued to increase beyond the first 3 min of exercise for each of the intensities encountered in the DCT. That is, if it is assumed that a $\dot{V}O_2$ slow component would have been present for each of these intensities.

The $\dot{V}O_2$-response for a DCT in which $\dot{V}O_2$ is determined from 1.5 to 2.5 min of each stage will only be identical to that for a continuous version of the same test if $\dot{V}O_2$ reaches a steady state within the first 1.5 min of each stage. However, the present study found (see figures 7.2 and 7.3) that for each of the last 4 stages of the DCT $\dot{V}O_2$ was higher for the 2nd collection (2 to 3 min) than for the 1st (1.5 to 2 min). Of the 4 studies that, having used an appropriate criterion to define such a plateau, have reported that a $\dot{V}O_2$-plateau occurs in >75% of subjects (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979; Rivera-Brown et al., 1994; Taylor et al., 1955), $\dot{V}O_2$ has been determined over 1.5 to 2.5 min of each stage in 2 (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979), over 1.75 to 2.75 min in 1 (Taylor et al., 1955), and over 2 to 3 min in the other (Rivera-Brown et al., 1994). Given what is currently known about $\dot{V}O_2$ kinetics during exercise, it seems reasonable to suggest that in all of these studies $\dot{V}O_2$ would not have reached a steady state by the start of the period over which $\dot{V}O_2$ was determined. Noakes (1997) has suggested that spurious $\dot{V}O_2$ plateaus might have been identified in these studies. He argues that such a plateau might be identified because the $\dot{V}O_2$-WR relationship might appear to plateau were the time taken to reach the final $\dot{V}O_2$ to increase with increasing WR. Recent studies suggest, however, that the time taken to reach the final $\dot{V}O_2$ is more likely to decrease with increasing exercise intensity, at least for intensities close to that at which $\dot{V}O_{2peak}$ is attained (see section 4.4.5.1). In the present study the $\Delta\dot{V}O_2$ between the 1st and the 2nd collection tended to be smaller for the ultimate than for the penultimate stage (figure 7.3). It is likely, therefore, that the time taken for $\dot{V}O_2$ to reach its final value would also have been less for this final stage.

7.4.2.2 Effect of test duration and test type on $\dot{V}O_{2peak}$

The peak $\dot{V}O_2$ was higher for the 5%RT than for the DCT or the 105%T. Although it is perhaps surprising that the peak $\dot{V}O_2$ for the 105%T was not higher than that for the DCT, it should be stressed that the subjects in whom the difference in peak $\dot{V}O_2$ between the 105%T and the 5%RT was greatest were those in whom the time to exhaustion for the 105%T was shortest. The influence of test duration on the peak $\dot{V}O_2$ attained in a square wave run was not directly assessed in the present study, but it is tempting to suggest that had each of the subjects completed several square wave runs of varying intensity the peak $\dot{V}O_2$ attained would have increased as the duration of the run increased (up to ~9 min). Spencer et al. (1996) found that the peak $\dot{V}O_2$ attained was higher for an exhaustive square wave run that lasted ~4 min than for one that lasted ~2 min, and Åstrand and Saltin (1961b) report a similar, albeit more subtle, effect for cycle ergometer exercise. The findings of the present study have implications for the assessment of $\dot{V}O_{2max}$. Assuming such a maximal $\dot{V}O_2$ exists, they suggest that when a square wave run is used for the assessment of $\dot{V}O_{2max}$, it should be one for which the time to exhaustion is 8-10 min (see figure 7.6).

The finding that the peak $\dot{V}O_2$ for the 5%RT was higher than that for the DCT is an important one. Since both the 5%RT and the DCT were completed with the treadmill grade set at 5%, the implication is that the peak $\dot{V}O_2$ attained in the DCT was below the maximal $\dot{V}O_2$ that can be attained during running up a 5% grade. The present study differs from the previous studies that found no difference in $\dot{V}O_2$ between a CT and a DCT in 2 ways. First, in the present study a ramp protocol was used for the CT whereas in all of the previous studies an incremental protocol was used. Second, the present study compared continuous and discontinuous versions of a CGIS protocol whereas the previous studies all compared continuous and discontinuous versions of a CSIG protocol.

It is possible that subjects might be able to push themselves closer to the limit of tolerance when the WR is increased in a ramp pattern than when an incremental protocol is used. Prior experience with incremental tests suggested that subjects tend to terminate such tests at the time when the WR is incremented. Typically the subject sees the experimenter moving to increase the WR and immediately stops running. It appears that when it becomes very hard to maintain the required WR, subjects set themselves the target of making it to the end of the current stage. Once they have reached this point, they appear to be unable to motivate themselves to continue onto the next stage. It is possible, therefore, that were the WR to be increased continuously throughout the test subjects might push themselves to the limit of tolerance rather than to the end of a particular stage.

If this is correct, there are two possibilities. On the one hand, it is possible that whilst the incidence of a $\dot{V}O_2$-plateau would be higher for a ramp than for an incremental test, subjects would attain the same peak $\dot{V}O_2$ in both tests. But on the other, it is possible that the peak $\dot{V}O_2$ might be higher for the ramp protocol.

It was originally intended that as part of the present study an incremental CT (the CT) would be compared with a ramp test (the 5%RT), in terms of the incidence of a $\dot{V}O_2$-plateau and the peak $\dot{V}O_2$ attained. Insufficient data were available, however, for the incidence of a $\dot{V}O_2$-plateau to be determined for the CT because two subjects completed only 2 and a further three completed only 3 stages. It is for this reason that this comparison was not presented in the results section, despite the fact that a peak $\dot{V}O_2$ for the CT was obtained from each subject. This peak $\dot{V}O_2$ (58.5 ± 8.9 $ml.kg^{-1}.min^{-1}$) was slightly higher than that which was attained in the DCT (57.8 ± 8.1 $ml.kg^{-1}.min^{-1}$) and slightly lower than that which was attained in the 5%RT (59.9 ± 7.9 $ml.kg^{-1}.min^{-1}$), but only the difference between the 5%RT and the DCT was significant (at the 5% level).

Given that the incidence of a $\dot{V}O_2$-plateau was relatively low for the 5%RT, and that the incidence of such a plateau is likely to be lower for an incremental than for a ramp test (see section 3.2.3), it is perhaps not surprising that the peak $\dot{V}O_2$ attained in the 5%RT was higher than that which was attained in the CT, despite the fact that the test duration did not differ markedly for these two tests (11.2 ± 1.4 vs. 10.4 ± 0.3 min; $p = 0.08$). It is conceivable that previous studies have failed to find differences in $\dot{V}O_{2peak}$ between continuous and discontinuous protocols because they have used continuous incremental rather than continuous ramp protocols. However, it should be acknowledged that this is unlikely to be the only reason why these studies failed to find such a difference.

All of the studies that have compared a continuous protocol with a discontinuous version of the same protocol have studied treadmill running (Duncan et al., 1997; McArdle et al., 1973; Pirnay et al., 1966; Rivera-Brown et al., 1994; Sheehan et al., 1987; Shephard et al., 1968; Stamford, 1976; Wyndham et al., 1966), although in two of these studies (McArdle et al., 1973; Shephard et al., 1968) cycle ergometer protocols were also evaluated. Of these 8 studies, 6 compared a continuous and a discontinuous version of a CSIG test, whilst just 2 (Pirnay et al., 1966; Wyndham et al., 1966) compared a continuous and a discontinuous version of a CGIS test. Evidence to suggest that the active muscle mass is higher for uphill than for level running has already been presented (see section 3.3.4). Furthermore, as has been shown in a previous study (Stamford, 1976), and was confirmed in the present study (see figure 7.5), the peak WR reached is much higher for a DCT than for a continuous version of the same test. If it is assumed that the active muscle mass increases progressively with increasing treadmill grade it can be argued that when a discontinuous version of a CSIG test is compared with a continuous version of the same test, the peak $\dot{V}O_2$ attained should be higher for the DCT because the peak grade reached, and therefore the muscle mass recruited, should be higher for this test. It is possible that there may be opposing effects that combine to ensure that no difference in $\dot{V}O_{2peak}$ is observed when a discontinuous and a continuous version of a CSIG test are compared. That is, there might be a tendency for a higher $\dot{V}O_2$ to be attained in a CT but this tendency might be opposed by the tendency for the peak $\dot{V}O_2$ attained to increase with increasing treadmill grade.

In the present study, the incidence of a $\dot{V}O_2$-plateau was high for the DCT but the peak $\dot{V}O_2$ for this test was lower than that for the 5%RT. The important implication is that even when a $\dot{V}O_2$-plateau is observed it is not possible to be certain that a maximal $\dot{V}O_2$ has been attained. Indeed, it appears that a plateau in the $\dot{V}O_2$-running speed relationship was observed in the majority of subjects for the DCT despite the fact that $\dot{V}O_{2max}$ was not attained in this test. The question of what, other than the attainment of $\dot{V}O_{2max}$, could cause the $\dot{V}O_2$-running speed relationship to plateau during the DCT is of interest here. It should be emphasised, however, that there was considerable inter-individual variation in the extent to which the peak $\dot{V}O_2$ for the 5%RT exceeded that for the DCT. Those subjects who were able to reach the highest speeds (relative to $v\dot{V}O_{2peak}$) in the DCT were able to match or even exceed the $\dot{V}O_2$ they attained in the 5%RT, whilst those who completed only a few stages attained a $\dot{V}O_2$ in the DCT which was well below that which they attained in the 5%RT (see figure 7.7).

If $v\dot{V}O_{2peak}$ is taken as an index of aerobic running capabilities, and the peak speed reached in the DCT is expressed relative to $v\dot{V}O_{2peak}$, this peak speed can be taken as an index of anaerobic capabilities. It is uncertain whether the peak $\dot{V}O_2$ for the 5%RT was a maximal $\dot{V}O_2$ for all subjects, but it is certain that for the majority of subjects the peak $\dot{V}O_2$ attained in the DCT was sub maximal. The implication is that only individuals whose anaerobic capabilities are above average will be able to attain a maximal $\dot{V}O_2$ in a DCT. A ramp test appears to be preferable to a DCT for the assessment of $\dot{V}O_{2max}$ because a ramp test is more likely to allow an individual's aerobic capabilities to be assessed without the results being influenced by their anaerobic capabilities.

It is possible that the peak $\dot{V}O_2$ attained in the DCT was sub maximal because $\dot{V}O_2$ was still increasing throughout the 60 s over which this peak $\dot{V}O_2$ was determined. This explanation would suggest that a higher $\dot{V}O_2$ would be attained were a shorter sampling period to be used. In view of this, it is noteworthy that Åstrand and Saltin (1961a, p. 981) report, in reference to $\dot{V}O_2$ data collected during exhaustive supra-$\dot{V}O_{2peak}$ exercise bouts, that "a continuous collection of expired air, fractionized in short periods, revealed an oxygen uptake that was about 3% higher than the $\dot{V}O_2$ measured when strictly following the norms of Taylor et al. (1955)." However, the data of Spencer et al. (1996) suggest that $\dot{V}O_2$ should plateau before the start of the 3rd minute for an exhaustive square wave run. This group studied well-trained runners, and it is not certain that their data are applicable to the subjects used in the present study. Nevertheless, the mean $\Delta\dot{V}O_2$ between the 1st (1.5 to 2 min) and the 2nd (2 to 3 min) sampling interval was only ~1 $ml.kg^{-1}.min^{-1}$ for the final stage of the DCT, and some of this increase would have occurred during the 1st interval. It is conceivable, therefore, that $\dot{V}O_2$ might have reached a plateau (at a sub maximal level) during the final stage of the DCT for the subjects used in this study.

7.4.2.3 Linearity of the $\dot{V}O_2$-running speed relationship for a typical ramp test

It is important to establish whether the $\dot{V}O_2$-running speed relationship is linear for a typical ramp test for two reasons. First, if a ramp test is to be used for the assessment of $\dot{V}O_{2max}$ and a standard approach to defining a $\dot{V}O_2$-plateau is to be taken, it is necessary to be able to assume that the $\dot{V}O_2$-running speed relationship is linear (see section 4.4.5.2). Second, establishing whether the $\dot{V}O_2$-running speed relationship is linear for a fast ramp test should give an insight into whether this relationship is likely to be linear for the primary component of the $\dot{V}O_2$ response.

The results of the present study suggest that the $\dot{V}O_2$-running speed relationship is linear for a 10 min ramp test. A previous study (Wood et al., 1997) found the $\dot{V}O_2$-running speed relationship to be non-linear. However, the test protocol differed markedly between the two studies. In Wood et al.'s study, the time spent at supra-LT speeds ranged from 8-20 min, whereas in the present study the corresponding time ranged from 3-6 min. Since the $\dot{V}O_2$-slow component typically is not manifest until 2-3 min after the onset of (supra-LT) exercise, it is reasonable to conclude that, in the present study, the impact of this component on the $\dot{V}O_2$ response for the ramp test would have been small. In contrast, in Wood et al.'s study, the $\dot{V}O_2$ response would have been heavily influenced by the $\dot{V}O_2$ slow component. Further work is required to characterise fully the $\dot{V}O_2$ response to treadmill running, but these limited data suggest that, as is the case for the $\dot{V}O_2$-power relationship for cycling, the $\dot{V}O_2$-speed relationship for running is linear for the primary (fast) component and non-linear for the slow component. The important implication for the assessment of $\dot{V}O_{2max}$ is that a CGIS ramp test which lasts about 10 min is a suitable test to use.

7.4.3 *Effect of sampling period*

Neither the incidence of a $\dot{V}O_2$-plateau nor the peak $\dot{V}O_2$ was higher when the sampling period was 30 than when it was 60 s. In fact, the incidence of a plateau was lower for the shorter sampling period (20% vs. 50%). However, when the mean data were plotted (figure 7.9), a plateau in the $\dot{V}O_2$-running speed relationship was no more apparent for the 5%RT60 than for the 5%RT30. It appears that the low incidence of a $\dot{V}O_2$-plateau for the 5%RT30 is related to the criterion used to define a such a plateau. Essentially the problem is that although halving the sampling period halved the mean (sub-$\dot{V}O_{2peak}$) $\Delta\dot{V}O_2$, it had no effect on the SD about this mean value.

The SD about this mean $\Delta\dot{V}O_2$ is the SD of the 10 individual values for the 10 subjects. It should therefore reflect both inter-individual variation in the slope of the $\dot{V}O_2$-running speed relationship and random variation in the calculated $\Delta\dot{V}O_2$. Data from the preliminary incremental test (section 7.2.2) can be used to quantify this inter-individual variation. For each subject, the $\dot{V}O_2$-running speed relationship derived from this test can be used to calculate the $\Delta\dot{V}O_2$ corresponding to a given increase in running speed (for a 5% grade). Since this $\Delta\dot{V}O_2$ is derived from an individual regression equation, it should be relatively free from random variation, and the SD of the 10 values should provide a reasonable estimate of the inter-individual variation. For a speed increment of 1.2 $km.h^{-1}$ (equivalent to a 60 s sampling period for the 5%RT), the SD is 0.57 $ml.kg^{-1}.min^{-1}$, and for an increment of 0.6 $km.h^{-1}$ (equivalent to a 30 s period), it is 0.28 $ml.kg^{-1}.min^{-1}$.

These data suggest that inter-individual variation should be a relatively important component of the variation in $\Delta\dot{V}O_2$ for the 5%RT60 but a relatively unimportant component for the 5%RT30. Halving the sampling period should halve the inter-individual variation in $\Delta\dot{V}O_2$ and yet the SD for $\Delta\dot{V}O_2$ decreased by just 4% when the sampling period was reduced from 60 to 30s (see section 7.3.3). This means that the random variation in the calculated $\Delta\dot{V}O_2$ must have increased as the sampling period decreased. It was suggested previously (section 5.6) that the variability in $\dot{V}O_2$ should decrease as the sampling period increases, and the data obtained in the present study are consistent with this suggestion. It was also suggested that this variability should decrease as exercise intensity increases. A study investigating the effect of exercise intensity and sampling period on the variability in $\dot{V}O_2$ is presented in Chapter 8.

PART IV

ADDRESSING THE ISSUES THAT AROSE FROM STUDY 1

CHAPTER 8: STUDY 2: EFFECT OF SAMPLING PERIOD AND EXERCISE INTENSITY ON VARIABILITY IN $\dot{V}O_2$

8.1 Introduction

The first paper to emphasise that the random variation present in a set of data might obscure the presence of a $\dot{V}O_2$-plateau was that of Taylor et al. (1955). These investigators focused on a CSIG DCT for which they determined the $\Delta\dot{V}O_2$ between two consecutive stages. They obtained 30 values for this (sub-$\dot{V}O_{2peak}$) $\Delta\dot{V}O_2$ from measurements made on 13 subjects and decided that a $\dot{V}O_2$-plateau should be deemed to have occurred whenever a final $\Delta\dot{V}O_2$ was observed that was less than the lowest of these 30 values. Although there are inconsistencies in their paper (see section 3.2.1), an approach similar to theirs was adopted when criteria were developed to define a $\dot{V}O_2$-plateau for the various progressive tests that were evaluated in Study 1 (see section 7.2.6). In that study, the 95% confidence limits for the sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$ were derived for each protocol from the individual values for this $\Delta\dot{V}O_2$ (1 value for each of the 10 subjects) and a $\dot{V}O_2$-plateau was defined for each protocol as a $\Delta\dot{V}O_2$ of less than the lower 95% confidence limit for the appropriate sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$. This confidence interval based approach, which has been adopted in several published studies (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979; Mitchell et al., 1958; Rivera-Brown et al., 1994), was adopted in Study 1 because it was felt to be the most defensible of the various approaches that have been adopted when criteria to define a $\dot{V}O_2$-plateau have been developed (see section 3.2.1).

When the aim is to maximise the incidence of a $\dot{V}O_2$-plateau for a given test a relatively short sampling period should be used so that a $\dot{V}O_2$-plateau can be identified even if it occurs very late in the test (see section 3.2.4). However, Study 1 found that the incidence of a $\dot{V}O_2$-plateau was lower when the sampling period was 30 than when it was 60 s (table 7.5). It was suggested previously (section 5.6) that the variability in $\dot{V}O_2$ is likely to increase as the sampling period decreases. This suggestion was made on the basis of an analysis of the random errors that might realistically be incurred in the calculated value for $\dot{V}O_2$ and how these errors might be affected by sampling period. Myers et al. (1990), who studied cycle ergometer exercise that elicited a $\dot{V}O_2$ equivalent to ~50% $\dot{V}O_{2peak}$, found that the variability in $\dot{V}O_2$ did increase as the sampling period decreased. However, they determined $\dot{V}O_2$ on-line and then averaged the breath-by-breath data over various periods (from 5 to 60 s). To date, no studies have investigated the effect of sampling period on the variability in $\dot{V}O_2$ for the Douglas bag method.

There appears to be a conflict between the need to use a relatively short sampling period to maximise the incidence of a $\dot{V}O_2$-plateau and the need to use a relatively long sampling period to ensure that the presence of a $\dot{V}O_2$-plateau is not obscured by excessive variability in the $\dot{V}O_2$ data. It is possible, however, that were a short sampling period to be used, the variability in $\dot{V}O_2$ would be high for those (sub-$\dot{V}O_{2peak}$) intensities from which the confidence interval for $\Delta\dot{V}O_2$ is typically derived but not for those close to that at which $\dot{V}O_{2peak}$ is reached.

The important assumption that is made when a confidence interval based approach to defining a $\dot{V}O_2$-plateau is adopted is that the confidence interval for the $\Delta\dot{V}O_2$ (for a given increase in WR) is independent of WR. There are in fact two assumptions here. Firstly it is assumed that the mean $\Delta\dot{V}O_2$ is independent of WR (i.e. it is assumed that the $\dot{V}O_2$-WR relationship is linear) before $\dot{V}O_2$ starts to plateau. And secondly, it is assumed that the variation in the actual $\Delta\dot{V}O_2$ about this mean value is independent of WR. Were the slope of the $\dot{V}O_2$-WR relationship to vary with WR, the incidence of a $\dot{V}O_2$-plateau would be artificially low or artificially high, respectively, depending on whether the slope of this relationship increased or decreased with increasing WR. Similarly, were the variation in this $\Delta\dot{V}O_2$ to vary with WR the incidence of a plateau would be artificially high or artificially low, respectively, depending on whether this variation increased or decreased with increasing WR.

It was suggested previously (section 5.6) that the variability in $\dot{V}O_2$ might decrease as exercise intensity increases. Once again, this suggestion was made on the basis of an analysis of the random errors that might realistically be incurred in the calculated value for $\dot{V}O_2$ and how these errors might be affected by exercise intensity. Only one study (Lamarra et al., 1987) has investigated the effect of exercise intensity on the variability in $\dot{V}O_2$. These investigators determined $\dot{V}O_2$ on a breath-by-breath basis during both unloaded ("0 W") and moderate intensity (100 W) cycling; they found that the SD for the raw breath-by-breath data was the same for the two types of exercise.

This finding would appear to contradict the previous suggestion (see section 5.6) that the variability in $\dot{V}O_2$ will decrease as exercise intensity increases. However, it is important to recognise that the highest power output investigated by Lamarra et al. was 100 W. The analysis presented in section 5.6 suggests that the variability in $\dot{V}O_2$ should decrease as exercise intensity increases, but this effect was only evaluated for moderate, heavy, and severe intensity exercise. A power output of 100 W would have been either below or very slightly above the LT for each of the subjects studied by Lamarra et al. It is conceivable, therefore, that the variability in $\dot{V}O_2$ does decrease as exercise intensity increases but that this effect is seen only at supra-LT intensities.

If the variability in $\dot{V}O_2$ does decrease as exercise intensity increases, the true incidence of a $\dot{V}O_2$-plateau will be underestimated whenever a confidence interval based approach to defining a plateau is adopted. However, provided the variability in $\dot{V}O_2$ does increase as sampling period decreases, it should be possible to ensure that the variability in $\dot{V}O_2$ is independent of exercise intensity by adopting an approach in which the sampling period is progressively reduced as the exercise intensity increases.

The primary aim of the present study was to establish, for the equipment and procedures used in this thesis, the extent to which the variability in $\dot{V}O_2$ is a function of sampling period and exercise intensity. The secondary aim was to determine whether it is possible to ensure that the variability in $\dot{V}O_2$ is independent of exercise intensity by altering the sampling period as the exercise intensity increases. There were two parts to the study:

1) effect of sampling period on the variability in $\dot{V}O_2$;

2) effect of exercise intensity on the variability in $\dot{V}O_2$.

8.2 Methods

8.2.1 *Subjects*

Nine males volunteered to take part in the study. Eight completed Part 1 and 6 completed Part 2 (5 subjects completed both parts of the study). All were involved in some form of endurance training. Three were distance runners and 3 were triathletes.

Table 8.1. Physiological characteristics of the subjects (mean ± SD).

Study	Age (years)	Height (m)	Mass (kg)	$\dot{V}O_{2peak}$ (ml.kg^{-1}.min^{-1})
Part 1 (n=8)	29.0 ± 2.4	1.80 ± 0.08	75.4 ± 9.0	62.0 ± 4.8
Part 2 (n=6)	27.5 ± 3.5	1.81 ± 0.09	72.4 ± 10.5	64.5 ± 5.0

8.2.2 *Preliminary tests*

All subjects initially completed two preliminary tests: a progressive incremental test to determine the relationship between running speed and $\dot{V}O_2$ and a ramp test (the 5%RT described in section 7.2.4) to determine $\dot{V}O_{2peak}$. For each individual, the data from these tests were used to calculate the running speed required to elicit a $\dot{V}O_2$ of 70% $\dot{V}O_{2peak}$.

8.2.3. *Effect of sampling period*

Each subject completed 4 runs, all at a speed equivalent to 70% $\dot{V}O_{2peak}$. Each run was completed on a different day and 6 min were always allowed for $\dot{V}O_2$ to reach a steady state before any expirate was collected. The length of each Douglas bag collection (30, 60, 90, or 120 s) was different for each run but for all runs there were 12 consecutive collections, and therefore 12 values for $\dot{V}O_2$. The order in which these sampling periods were allocated was counterbalanced.

8.2.4 *Effect of exercise intensity*

Each subject completed two 13 min runs: a low intensity (LI) run at a speed equivalent to 70% $\dot{V}O_{2peak}$ and a high intensity (HI) run at the highest speed that could be sustained for 13 min (estimated from the results of the preliminary incremental test). For each run, 6 min were allowed for $\dot{V}O_2$ to reach a steady state before any expirate was collected. Twelve 30 s samples of expirate were taken, and hence 12 values for $\dot{V}O_2$ were derived. The order in which the runs were completed was counterbalanced.

8.2.5 *Sampling techniques*

Three racks of Douglas bags were used, each of which contained 4 bags. Sampling was continuous within each rack, but between racks there was a gap of 30 s. [The gap between racks had to be at least 10 s (see section 5.5.1); 30 s was allowed because this ensured that the timing of the subsequent collections was straight forward.] Each run was therefore 1 min longer than would be expected. For example, the HI run lasted 13 as opposed to 12 min. The $\dot{V}O_2$ data should have been unaffected by this because when the regression equation relating $\dot{V}O_2$ to time was derived the $\dot{V}O_2$ for a given sampling interval was associated with the mid-point of that interval. Thus the 30 s gaps were accounted for.

8.2.6 *Treatment of data*

It was originally envisaged that $\dot{V}O_2$ would reach a steady state during the first 6 min of every run so that it would be possible to quantify the variability in $\dot{V}O_2$ by calculating the SD of the 12 values for $\dot{V}O_2$. However, for the HI run $\dot{V}O_2$ continued to increase beyond the 6th min of exercise in the majority of the subjects. Also, in some subjects, $\dot{V}O_2$ continued to increase slightly after the 6th min of some of the LI runs. Had the SD for the 12 values simply been calculated as planned, this SD would not have been entirely representative of the random variation. Rather, it would have been influenced by the (systematic) increase in $\dot{V}O_2$ that occurred over the 12 samples. The greater this increase, the larger the SD would have been (for a given amount of random variation). Linear regression was used to correct the data for the effect of this increase because in general $\dot{V}O_2$ appeared to increase as an essentially linear function of time. A regression equation relating $\dot{V}O_2$ to time was derived for each run, and this equation was then used to correct the data for any increase in $\dot{V}O_2$ that occurred over the course of the entire collection period. Values that occurred before the mid-point of this period were increased, and those that occurred after were decreased; thus a modified data set was derived. For this data set, $\dot{V}O_2$ was independent of time, and only random variation was present.

This procedure is illustrated in figure 8.1 (below), which presents data from a representative subject showing $\dot{V}O_2$ as a function of time for the HI run. Uncorrected data are presented in the upper panel, and the same data, corrected for the increase in $\dot{V}O_2$ that occurred over the course of the entire collection period, are presented in the lower panel. Note that although the mean value is the same for the two data sets the confidence interval is much narrower for the corrected data.

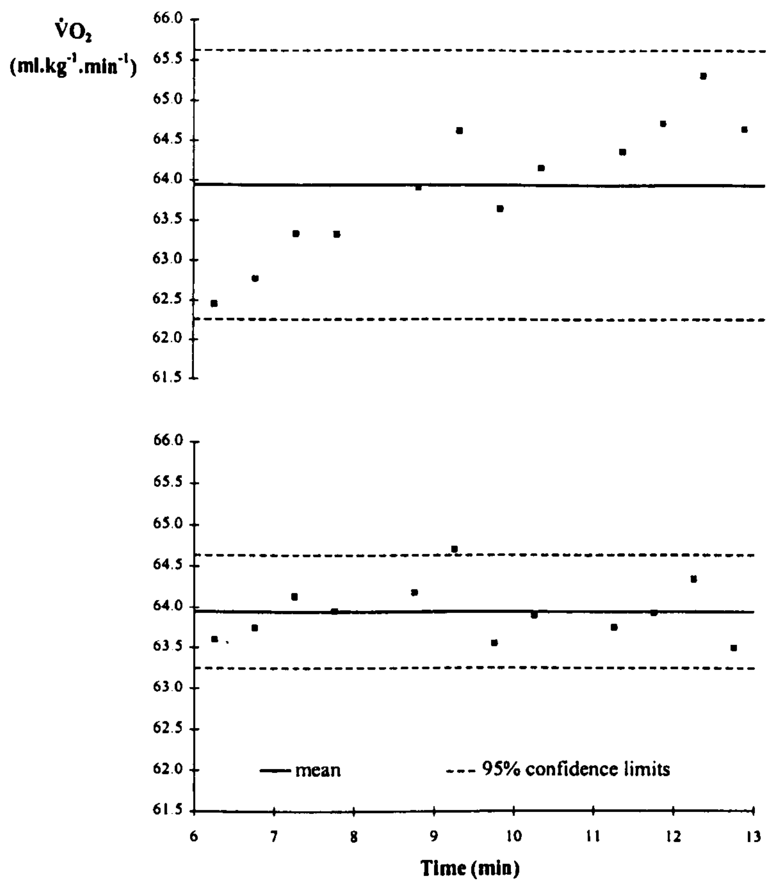

Figure 8.1. Data from a representative subject showing $\dot{V}O_2$ as a function of time for the HI run, before (upper panel) and after (lower panel) the data were corrected for the increase in $\dot{V}O_2$ that occurred over the course of the collection period.

Although it was not strictly necessary to correct the data for those runs in which $\dot{V}O_2$ reached a steady state within the first 6 min, the $\dot{V}O_2$ data were corrected for all runs, and the index of variability used in all subsequent analyses was the SD of the 12 corrected values. In those cases in which a steady state was reached, the slope of the regression line was very close to zero, and therefore the effect of this correction was negligible.

8.2.7 *Statistical analysis*

All tests were performed at an alpha level of 0.05, and all data are presented as mean ± SD (unless otherwise stated). Individual data can be found in Appendix 4, together with full results for each of the tests described below.

To ascertain whether the variability in $\dot{V}O_2$ was influenced by sampling period a one-way RM ANOVA was performed on the SD of the 12 samples across the 4 sampling periods (n = 8). A Newman-Keuls post hoc test was used to locate significant differences between the means.

To ascertain whether the variability in $\dot{V}O_2$ was influenced by exercise intensity, a paired t-test was performed on the SD of the twelve 30 s samples for the LI and the HI intensity run (n = 6).

Finally, a t-test (unpaired data) was used to compare the SD for the twelve 30 s samples taken during the HI run (n = 6) with that for the 60 s samples taken during the run at ~70% $\dot{V}O_{2peak}$ (n = 8).

8.3 Results

8.3.1 *Effect of sampling period*

Table 8.2 (below) shows that, as expected, F_EO_2 and F_ECO_2 remained unchanged while V_E increased as the sampling period increased. For $\dot{V}O_2$, the mean value was not affected by sampling period, but the SD was ($p = 0.007$). Post hoc tests revealed that this SD decreased when the sampling period increased from 30 to 60 s. A further decrease was observed when the sampling period was increased from 60 to 90 s (table 8.2), but this decrease was not significant ($p > 0.05$).

Table 8.2. Mean values for F_EO_2, F_ECO_2, V_E, $\dot{V}O_2$, and the SD for $\dot{V}O_2$, for the 4 sampling periods (n=8).

Sampling period	Mean F_EO_2	Mean F_ECO_2	Mean V_E [L (ATPS)]	Mean $\dot{V}O_2$ (% $\dot{V}O_{2peak}$)	SD for $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$)
30 s	16.3 ± 0.3%	4.3 ± 0.2%	38 ± 6	70.7 ± 1.4	1.29 ± 0.66
60 s	16.3 ± 0.4%	4.3 ± 0.3%	77 ± 14	70.3 ± 1.2	0.57 ± 0.22*
90 s	16.5 ± 0.4%	4.2 ± 0.3%	120 ± 22	70.9 ± 1.3	0.41 ± 0.13*
120 s	16.4 ± 0.2%	4.3 ± 0.2%	155 ± 22	69.9 ± 1.5	0.36 ± 0.10*

*$p<0.05$ vs. 30 s samples.

The influence of sampling period on the variability in $\dot{V}O_2$ is illustrated in figure 8.2 (below). Data are presented for a representative subject showing how the variability in $\dot{V}O_2$ decreased as the sampling period increased from 30 to 120 s.

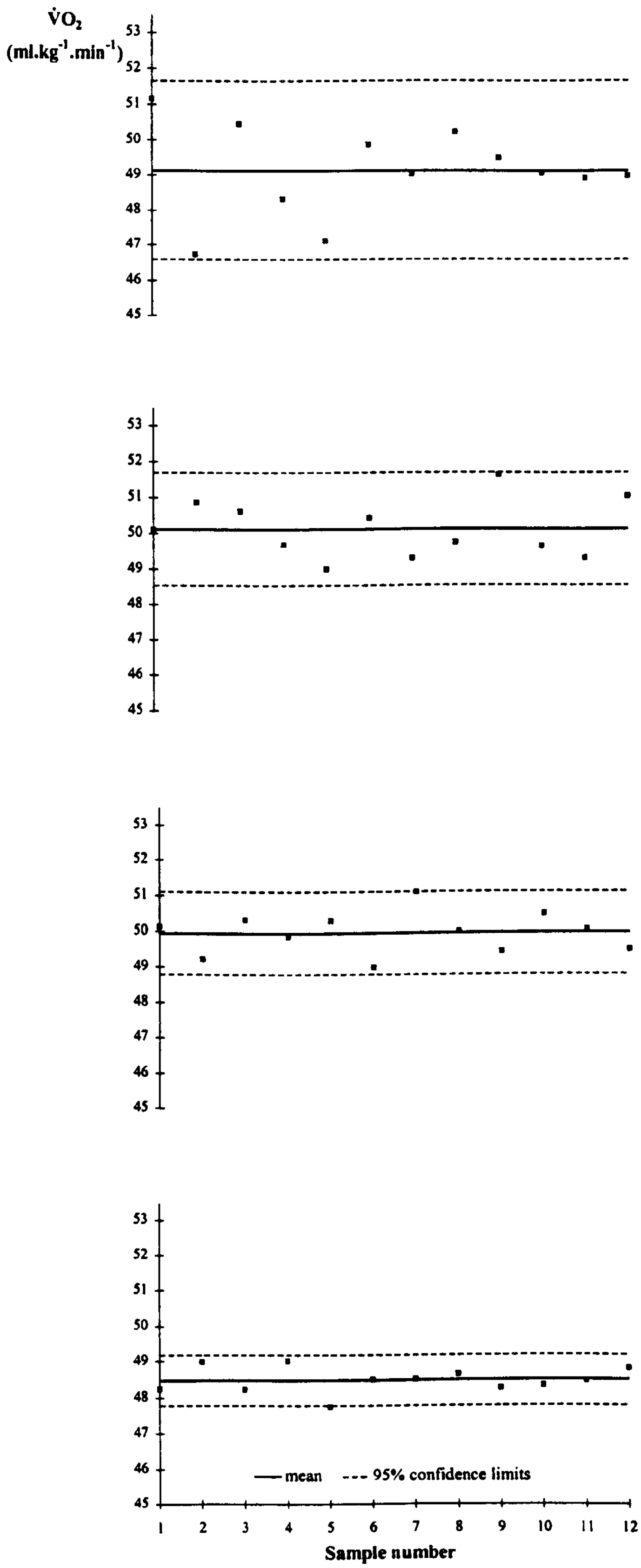

Figure 8.2. Data from a representative subject showing the variability in $\dot{V}O_2$ for sampling periods from 30 s (top panel) to 120 s (bottom panel).

8.3.2 *Effect of exercise intensity*

As exercise intensity increased, F_EO_2 and V_E (for a 30 s collection) increased, while F_ECO_2 decreased (table 8.3). For $\dot{V}O_2$, the SD was lower for the HI than for the LI run ($p = 0.005$).

Table 8.3. Mean values for F_EO_2, F_ECO_2, V_E, $\dot{V}O_2$, and the SD for $\dot{V}O_2$, for the LI and the HI run (n=6).

Exercise intensity	Mean F_EO_2	Mean F_ECO_2	Mean V_E [L (ATPS)]	Mean $\dot{V}O_2$ (% $\dot{V}O_{2peak}$)	SD for $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$)
low	16.1 ± 0.5%	4.4 ± 0.4%	36 ± 7	69.6 ± 2.1	1.05 ± 0.18
high	17.2 ± 0.2%	3.8 ± 0.2%	64 ± 6	95.6 ± 2.8	0.57 ± 0.25

The influence of exercise intensity on the variability in $\dot{V}O_2$ is illustrated in figure 8.3 (below). Data are presented for a representative subject showing the variability in $\dot{V}O_2$ for both the LI and the HI run.

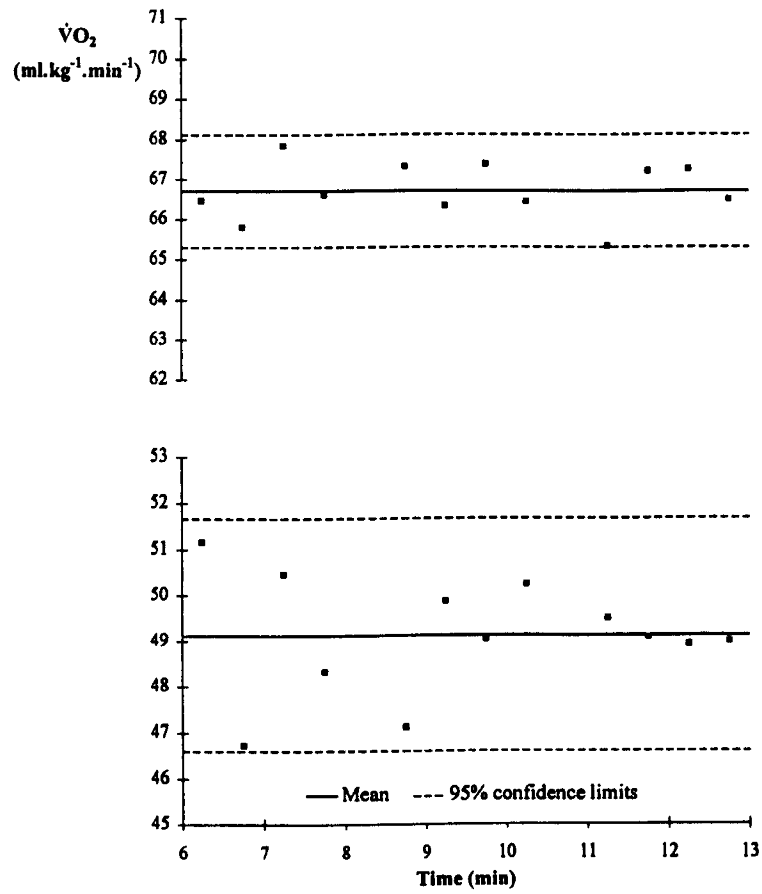

Figure 8.3. Data from a representative subject showing the variability in $\dot{V}O_2$ for the LI (lower panel) and the HI (upper panel) run.

8.3.3 *Effect of sampling period and exercise intensity combined*

The SD for the 30 s samples taken during the HI run (~96% $\dot{V}O_{2peak}$) was the same as that for the 60 s samples taken during running at ~70% $\dot{V}O_{2peak}$ (0.57 ± 0.25 vs. 0.57 ± 0.22 ml.kg^{-1}.min^{-1}; $p = 0.96$).

8.4 Discussion

8.4.1 *Effect of sampling period*

The results of the present study show that when the equipment and procedures outlined in Chapter 5 are used in the determination of $\dot{V}O_2$, the variability in $\dot{V}O_2$ decreases as the sampling period increases. Myers et al. (1990) report that the SD for repeated determinations of $\dot{V}O_2$ averaged 1.4 ml.kg^{-1}.min^{-1} for 30 and 0.8 ml.kg^{-1}.min^{-1} for 60 s samples. In the present study, the corresponding SDs were 1.3 and 0.6 $ml.kg^{-1}.min^{-1}$. However, Myers et al.'s data were obtained during cycle ergometer exercise at ~50% $\dot{V}O_{2peak}$, whilst in the present study subjects ran on a treadmill at ~70% $\dot{V}O_{2peak}$. James and Doust (1997) report a coefficient of variation (CV) of 1.4% for repeat determinations of $\dot{V}O_2$ in one subject (60 s samples). Their data were obtained during a run at ~75% $\dot{V}O_{2peak}$, and the CV of 1.4% was obtained by dividing the SD (0.61 $ml.kg^{-1}.min^{-1}$) by the mean $\dot{V}O_2$ (45.1 $ml.kg^{-1}.min^{-1}$) (James, personal communication). It might be expected that the agreement between these data and those obtained in the present study (SD = 0.6 $ml.kg^{-1}.min^{-1}$ for 60 s samples) would be good, given that James and Doust used the Douglas bag method and that their procedures were very similar to those that were employed in the present study. However, there is also good agreement between the data obtained in the present study and those obtained by Myers et al. (1990). This is noteworthy, given that Myers et al. determined $\dot{V}O_2$ breath-by-breath (and then averaged the breath-by-breath data over 30 or 60 s). It would appear that, for a given sampling period, the variability in $\dot{V}O_2$ is similar for both on-line and off-line data, but that, for both types of data, the variability in $\dot{V}O_2$ decreases as the sampling period increases.

To determine the extent to which technical factors might account for the decrease in variability that occurred when sampling period was increased in the present study, the data presented in table 8.2 were used, in conjunction with the data presented in section 5.5, to estimate the random error that would be incurred in the calculated $\dot{V}O_2$ for sampling periods of 30, 60, 90, and 120 s. The calculations that were outlined in section 5.6 were used to obtain four sets of confidence limits for the random error in $\dot{V}O_2$ (1 set for each sampling period). Theoretical values for the SD for repeat determinations of $\dot{V}O_2$ were then derived from these limits (95% confidence limits = $\pm 1.96 \times$ the SD). These SDs are theoretical in that they only account for technical factors (they take no account of biological variation). They are presented in table 8.4, together with mean values for the actual SDs that were determined from repeat determinations of $\dot{V}O_2$ (see table 8.2).

Table 8.4. Theoretical vs. actual SD for the 4 sampling periods.

Sampling period	Theoretical SD ($ml.kg^{-1}.min^{-1}$)	Actual SD ($ml.kg^{-1}.min^{-1}$)	Theoretical SD as a percentage of the actual SD
30 s	0.37	1.29	29%
60 s	0.19	0.57	33%
90 s	0.14	0.41	34%
120 s	0.12	0.36	33%

The above table shows that both the theoretical and the actual SD decrease as sampling period increases. The theoretical SD is, however, always smaller than the actual SD. Furthermore, in comparison to the actual SD, the theoretical SD decreases relatively little when sampling period increases. These data suggest that whilst factors associated with the determination of $\dot{V}O_2$ can account for part of the decrease in variability that was observed when sampling period was increased, biological factors must also be involved.

Myers et al. (1990) report that the SD for $\dot{V}O_2$ was 4.5 $ml.kg^{-1}.min^{-1}$ for breath-by-breath data as opposed to 0.8 $ml.kg^{-1}.min^{-1}$ for 60 s averages. Although technical factors must account for some of the variability in their breath-by-breath data, much of this variability is presumably biological. Averaging is used in many situations as a means of data smoothing. It is possible , therefore, that when $\dot{V}O_2$ is determined over a large number of breaths the variability in $\dot{V}O_2$ is low because the breath to breath fluctuations in $\dot{V}O_2$ are smoothed.

It is possible that the variability in $\dot{V}O_2$ decreased as sampling period increased because the number of breaths over which $\dot{V}O_2$ was determined, and therefore the extent to which the breath to breath fluctuations in $\dot{V}O_2$ were smoothed, increased. To investigate this possibility, several random, normally distributed data sets were generated. The aim was to generate data representative of breath-by-breath $\dot{V}O_2$ data, so only data sets for which the SD was ~4.5 ($4.45 \leq SD \leq 4.55$) (cf. Myers et al., 1990) were accepted. The runs during which sampling period was varied were performed at the same intensity as the LI run (~70% $\dot{V}O_{2peak}$). For this intensity, the mean breathing frequency was 32.9 breaths.min^{-1}, so sampling periods of 30, 60, 90, and 120 s would have included 16, 32, 49, and 65 breaths respectively. For each random data set, 12 average values were derived, and the SD of these average values was then determined. Averages were derived for intervals of 16, 32, 49, or 65 points. Thirty two data sets were evaluated (8 for each of the intervals), and 32 standard deviations were obtained (8 values for each interval).

The mean SD was 1.12, 0.84, 0.61, and 0.57 for averaging intervals of 16, 32, 49, and 65 points respectively. For averaging intervals of 32 points and above this SD is larger than the corresponding actual SD (tables 8.2 and 8.4). However, the data that were averaged were based on those of Myers et al. (1990), and whilst in the present study data on the effect of sampling period were obtained during running at ~70% $\dot{V}O_{2peak}$, in Myers et al.'s study these data were obtained during cycling at 50% $\dot{V}O_{2peak}$. It is likely, therefore, that the variability in $\dot{V}O_2$ would have been higher for Myers et al.'s data than for those obtained in Part 1 of the present study (see section 8.3.2).

The pattern of decrease in the SDs for the averaged data is similar to that observed for the actual data (tables 8.2 and 8.4), except that the decrease from 16 to 32 points is small. For the actual data, the SD decreased by 0.72 ml.kg^{-1}.min^{-1} (from 1.29 to 0.57) as sampling period increased from 30 s (16 breaths) to 60 s (32 breaths), whereas when the averaging interval was increased from 16 to 32 points the SD decreased by only 0.28 (from 1.12 to 0.84). It should be recognised though that the confidence interval for the actual SD was wide (see table 8.2). Indeed, although the LI run completed in part 2 of the study was identical to that from which 30 s samples were obtained in Part 1, the SD was lower for the subjects involved in Part 2 (1.05 ± 0.18 vs. 1.29 ± 0.66 ml.kg^{-1}.min^{-1}). The data in table 8.4 suggest that due to technical factors alone, the SD for $\dot{V}O_2$ should decrease markedly as sampling period increases from 30 to 60 s but little thereafter. It appears, therefore, that the effect of sampling period on the variability in $\dot{V}O_2$ can be adequately explained when the effects of both smoothing and technical factors are considered.

8.4.2 *Effect of exercise intensity*

The results of the present study show that the variability in $\dot{V}O_2$ decreases as exercise intensity increases from moderate to severe. This finding has not previously been reported. Indeed, Lamarra et al. (1987) found that the SD for $\dot{V}O_2$ was independent of exercise intensity, but these investigators did not study severe intensity exercise. No data are available on the variability in $\dot{V}O_2$ for severe intensity exercise such as that encountered in the HI run.

To determine the extent to which technical factors might account for the decrease in variability that occurred when exercise intensity was increased in the present study, the data presented in table 8.3 were used, in conjunction with the data presented in section 5.5, to estimate the random error that would be incurred in the calculated $\dot{V}O_2$ for the LI and the HI run. Theoretical values for the SD for repeat determinations of $\dot{V}O_2$ were derived for the LI and the HI run. These values are presented in table 8.5 (below), together with mean values for the actual SDs that were determined from repeat determinations of $\dot{V}O_2$ (see table 8.3).

Table 8.5. Theoretical vs. actual SD for the LI and the HI run.

Exercise intensity	**Theoretical SD ($ml.kg^{-1}.min^{-1}$)**	**Actual SD ($ml.kg^{-1}.min^{-1}$)**	**Theoretical SD as a percentage of the actual SD**
low	0.40	1.05	38%
high	0.32	0.57	56%

The above table shows that both the theoretical and the actual SD decrease as exercise intensity increases. The theoretical SD is, however, always smaller than the actual SD. Furthermore, in comparison to the actual SD, the theoretical SD decreases relatively little when exercise intensity increases. These data suggest that factors associated with the determination of $\dot{V}O_2$ can only account for a small part of the decrease in variability that occurred when exercise intensity was increased.

In the present study, breathing frequency was higher for the HI than for the LI run (46.7 vs. 32.9 breaths.min^{-1}). Consequently, the number of breaths over which $\dot{V}O_2$ was determined was higher for the HI than for the LI run (23 vs. 16 breaths for each 30 s sample). It is possible, therefore, that the variability in $\dot{V}O_2$ decreased as exercise intensity increased because the number of breaths over which $\dot{V}O_2$ was determined, and therefore the extent to which the breath to breath fluctuations in $\dot{V}O_2$ were smoothed, increased. To investigate this possibility, random, normally distributed data sets were generated (only data sets for which the SD was ~4.5 ($4.45 \leq SD \leq 4.55$) (cf. Myers et al., 1990) were accepted). For each data set, 12 average values were derived, and the SD of these average values was then determined. Averages were derived for intervals of 16 and 23 points only. Sixteen data sets were evaluated (8 for each of the intervals), and 16 standard deviations were obtained (8 values for each interval).

When the averaging interval was increased from 16 to 23 points, the SD decreased by 0.19 (from 1.12 to 0.93). However, the actual SD for the HI run (23 breaths per sample) was 0.48 ml.kg^{-1}.min^{-1} lower than that for the LI run (16 breaths per sample) (0.57 vs. 1.05 ml.kg^{-1}.min^{-1}). In addition, the data presented in table 8.5 suggest that technical factors account for only a small portion of the decrease in variability that occurred when exercise intensity was increased. The implication is that there was a marked decrease in biological variability. At present, the mechanism of this decrease is unknown.

8.4.3 *Effect of exercise intensity and sampling period combined*

The results of this study have important implications for the assessment of $\dot{V}O_{2max}$. Indeed, the fact that the variability in $\dot{V}O_2$ decreased when exercise intensity increased means that the confidence interval for $\Delta\dot{V}O_2$ obtained from sub-$\dot{V}O_{2peak}$ intensities will be wider than that which would be obtained at higher intensities. This in turn means that for studies such as Study 1 (Chapter 7), in which sub-$\dot{V}O_{2peak}$ intensities are used to determine the confidence interval for $\Delta\dot{V}O_2$, the incidence of a $\dot{V}O_2$-plateau will be artificially low. However, it is the finding that the SD was the same for the 60 s samples taken at 70% $\dot{V}O_{2peak}$ as for the 30 s samples taken at ~96% $\dot{V}O_{2peak}$ that arguably has the greatest practical significance. This finding confirms that the variability in $\dot{V}O_2$ will only be independent of exercise intensity if the sampling period is reduced as exercise intensity increases. The implication is that the only valid approach to defining a $\dot{V}O_2$-plateau is one which allows for the sampling period to decrease as exercise intensity increases. However, the $\dot{V}O_2$ response to a ramp test is a continuous function of time. This means that, were a confidence interval for $\Delta\dot{V}O_2$ to be derived from 60 s samples taken during the early stages of such a test, this interval would not be applicable to 30 s samples taken during severe intensity exercise because the mean $\Delta\dot{V}O_2$ would be lower for a 30 than for a 60 s sample. It is inappropriate, therefore, to use approaches such as that used in Study 1 where a criterion $\Delta\dot{V}O_2$ is derived from data collected during moderate intensity exercise. Instead, there is a need to develop an alternative approach to defining a $\dot{V}O_2$-plateau.

8.4.4 *Alternative approaches to identifying a $\dot{V}O_2$-plateau*

The confidence interval based approach used in Study 1 could be modified to incorporate a decreasing sampling period. A linear regression equation relating $\dot{V}O_2$ to WR could be derived for sub-$\dot{V}O_{2peak}$ intensities (the early stages of a ramp test for example), and the confidence limits for the predicted $\dot{V}O_2$ could be determined. This equation could then be used to calculate a predicted $\dot{V}O_2$ for the WR corresponding to the final sampling interval. A $\dot{V}O_2$-plateau would be defined as an actual $\dot{V}O_2$ for the final sample of less than the lower 95% confidence limit of the predicted $\dot{V}O_2$.

Such an approach has been described previously (Holthoer, 1996), although in that study the sampling period was constant throughout the test. To date, no studies have been published in which the sampling period has been reduced as exercise intensity increases. The regression approach described above can still be used when the samples taken towards the end are shorter than those taken early in the test. Indeed, provided WR increases as a continuous function of time (as it does in a ramp test), a $\dot{V}O_2$-WR regression can be used to calculate a predicted $\dot{V}O_2$ for any sampling period. However, this approach would be open to the same criticism (Howley et al., 1995) that has been directed at the confidence interval based approach used in Study 1. The problem with both these approaches is that they only identify the point where the $\dot{V}O_2$-WR relationship starts to plateau; they do not identify an asymptotic $\dot{V}O_2$.

Although there has been some debate over whether the $\dot{V}O_2$-running speed relationship plateaus at high speeds (see Chapter 4), it has never been suggested that the slope of this relationship increases as $\dot{V}O_2$ approaches $\dot{V}O_{2peak}$. There are essentially two rival models; the plateau model and the linear model. These models can be attributed to Hill's group and to Noakes respectively (see Chapter 4). Both assume that $\dot{V}O_2$ increases as a linear function of running speed in the early stages of a CGIS test. However, the plateau model assumes that a speed is eventually reached beyond which no further increase in $\dot{V}O_2$ is observed, whereas the linear model assumes that $\dot{V}O_2$ continues to increase as a linear function of running speed throughout the test. These models can be expressed mathematically. The linear model is defined by a single equation ($y = a_1x + b_1$), whilst the plateau model, which is a two segment model, is defined by two equations, an initial linear segment ($y = a_2x + b_2$) and a final horizontal segment ($y = c$). In study 3 (Chapter 9), this modelling approach was adopted for 3 different ramp tests. Regression techniques were used to derive the best fit plateau model and the best fit linear model for each set of data ($\dot{V}O_2$ vs. WR). The rationale for this study was that whether the data are better fit by the plateau or the linear model should provide an indication of whether or not the $\dot{V}O_2$-WR relationship typically plateaus during a treadmill ramp test.

CHAPTER 9: STUDY 3: EVALUATION OF THREE RAMP TESTS FOR THE ASSESSMENT OF $\dot{V}O_{2max}$ IN RUNNERS

9.1 Introduction

The finding that the peak $\dot{V}O_2$ was higher for the 5% ramp test than for the DCT (section 7.3.2.3) suggests that $\dot{V}O_{2max}$ is more likely to be elicited during a CT than during a DCT. Moreover, it can be argued, on both theoretical (section 7.4.2.2) and empirical (Whipp et al., 1981) grounds, that $\dot{V}O_{2max}$ is more likely to be elicited during a ramp than during an incremental test. However, for the 5% ramp test used in Study 1, a $\dot{V}O_2$-plateau was identified in only 20% of subjects when 30 s samples were used. The incidence of a plateau was higher when 60 s samples were used, but even then a plateau was observed in only 50% of subjects (section 7.3.3).

In study 1, confidence limits for $\Delta\dot{V}O_2$ were derived, for each test, from data collected in the early stages of the test, and a $\dot{V}O_2$-plateau was defined as a final $\Delta\dot{V}O_2$ of less that the lower 95% confidence limit. This approach can only be used when the sampling period is held constant, as it was for each of these tests. However, the findings of Study 2 (Chapter 8) suggest that the incidence of a $\dot{V}O_2$-plateau will be artificially low when such an approach is used. Indeed, it is possible that the true incidence of a $\dot{V}O_2$-plateau was underestimated in Study 1, and that were an approach to be adopted in which sampling period decreases as exercise intensity increases the observed incidence would more accurately reflect the true incidence.

Three different ramp tests were evaluated in the present study: two CGIS tests (one for which the treadmill grade was zero and another for which it was 5%) and one CSIG test. The sampling period was always shorter for the later collections (relative to the early collections), and the $\dot{V}O_2$ data were always modelled as described in section 8.4.4. For each subject, and for each test, standard errors of estimate were calculated for the linear model and the plateau model. The advantage of modelling the data in this way was that statistical analysis could be performed on these standard errors to ascertain, for each of the 3 tests, whether $\dot{V}O_2$ typically increased as a linear function of WR throughout the test or whether it typically reached a plateau at high WRs.

In agreement with the primary aim of this thesis, the focus of the present study was the question of whether the $\dot{V}O_2$-running speed relationship plateaus at high speeds. Findings from Study 1 (section 7.3.1) suggest that the incidence of a $\dot{V}O_2$-plateau might be higher for a CGIS test completed at a 5% grade than for a similar test completed on a level treadmill. However, these findings are by no means conclusive, and further study seems warranted. The present study afforded an opportunity to evaluate the impact of treadmill grade (5% vs. 0%) on the $\dot{V}O_2$-running speed relationship for the final minutes of a CGIS test. A CSIG test was also evaluated because such tests are commonly used for the assessment of $\dot{V}O_{2peak}$ (see section 3.2.1). The test used was a ramp test in which the treadmill grade was increased by 0.1% every 6 s (equivalent to 1% per min). This test is similar to that which has been used previously for the assessment of $\dot{V}O_{2peak}$ in runners. For instance, Jones and Doust (1996) describe an incremental CSIG test in which the treadmill grade was increased by 1% at the end of each min. In the present study, and in that of Jones and Doust, the belt speed was set for each individual so that the test duration was ~10 min.

Both the plateau model and the linear model assume that the $\dot{V}O_2$-WR relationship is linear for intensities below that at which $\dot{V}O_2$ might start to plateau. The $\dot{V}O_2$-running speed relationship was found to be linear for a CGIS test conducted on a level treadmill (section 7.3.2.4). However, it has not been established that the $\dot{V}O_2$-running speed relationship is linear for a CGIS test conducted at a 5% grade. Nor has it been established that the $\dot{V}O_2$-treadmill grade relationship is linear for a CSIG test. In the present study, the linearity of the $\dot{V}O_2$-running speed relationship was assessed for the 0% and the 5% test. In addition, the linearity of the $\dot{V}O_2$-treadmill grade relationship was assessed for the CSIG test.

9.2 Methods

9.2.1 *Subjects*

Twelve trained male runners volunteered to take part in the study. All were well habituated with laboratory procedures in general and with motorised treadmill running in particular. Seven were distance runners, 3 were middle-distance runners, and 2 were triathletes. All were in regular training for running at the time of the study.

Table 9.1. Physiological characteristics of the subjects (mean ± SD).

Age (years)	Height (m)	Mass (kg)	$\dot{V}O_{2peak}$ * ($ml.kg^{-1}.min^{-1}$)
26.7 ± 5.6	1.80 ± 0.07	70.9 ± 8.0	64.0 ± 4.7

*taken from the 5%T (see below).

9.2.2 *Preliminary tests*

Each subject completed a preliminary day of testing during which they performed each of the 3 ramp tests. Subjects rested for ~30 min between tests, and the 3 tests were completed in a random order. The purpose of this preliminary testing was to collect data that would allow an appropriate starting speed to be selected for each test. The aim was to ensure that, for each subject and for each test, exhaustion would be reached in ~10 min. For each of the preliminary tests, the starting speed was estimated on the basis of what was already known about the particular subject's capabilities as a runner. These speeds were then adjusted upwards or downwards, respectively, depending on whether the time to exhaustion was greater than or less than 10 min.

9.2.3 *Experimental design*

Each subject completed the following 3 tests:

1. a CGIS ramp test on a level treadmill (0%T)
2. a CGIS ramp test at a 5% grade (5%T)
3. a CSIG ramp test (IGT)

The order in which the tests were completed was randomised (6 sequences were available, so 2 subjects were allocated to each sequence). Subjects rested for at least 24 hours between tests.

9.2.4 *Test protocols*

Each test was preceded by a 5 min warm-up at 50% of the peak speed attained in the preliminary 0%T, which in turn was followed by a 5 min rest period. Towards the end of the rest period the belt speed was increased to the pre-determined starting speed. The test then started with the subject lowering themselves onto the moving belt.

For the 0%T and the 5%T, belt speed was increased by 0.1 $km.h^{-1}$ every 5 s (equivalent to 1.2 $km.h^{-1}$ per min), while the treadmill grade was held constant. For the IGT, the treadmill grade was increased by 0.1% every 6 s (equivalent to 1% per min) while the belt speed was held constant (at a level which varied depending on the capabilities of the subject).

A finger-prick capillary blood sample was drawn 1 min after the end of each test. This sample was subsequently analysed to determine [Bla].

9.2.5 *Sampling procedures*

Expired gases were collected throughout the test. Eight 60 s samples were taken over the first 8 min of the test. Following this, two 45 s collections were taken (8 to 8.75 and 8.75 to 9.5 min), and thereafter a 30 s sampling period was used. It was anticipated that, were a $\dot{V}O_2$-plateau to occur, it would typically occur within the last 2 minutes of the test. Hence it was important that a relatively short sampling period was used throughout this period. It was also important that a relatively long sampling period was used in the early stages of the test, and this is why 60 s samples were used for the first 8 minutes of the test.

The above sampling periods are in fact nominal periods. A whole number of breaths was always collected and the elapsed time was recorded (see section 5.5.1). In addition, sampling was only continuous within each 4 bag rack. Racks were changed at 4 and 8 min. Typically the final collection on the first rack was stopped ~5 s early and the first collection on the next rack was started ~5 s late [5 s is sufficient to ensure that the dead space volume of the new rack has been flushed with expirate before the first bag is opened (see section 5.5.1)]. The time over which no expirate was collected was therefore ~10 s. For bags that were not at the start or the end of the rack the actual sampling period was always within 2 s of the nominal sampling period. Respiratory data were not derived for the final collection if the duration of this collection was less than 20 s.

9.2.6 *Modelling the $\dot{V}O_2$-WR relationship*

Data from the first 2 min of each test were excluded from the analysis to account for the time lag in the $\dot{V}O_2$ response. The remaining data were fitted with two different models. One was a simple linear model ($y = a_1x + b_1$), and the other was a two segment plateau model. For the plateau model, the first segment was a simple linear function ($y = a_2x + b_2$), and the second was a horizontal line ($y = c$). These models are illustrated in figure 9.1 (below).

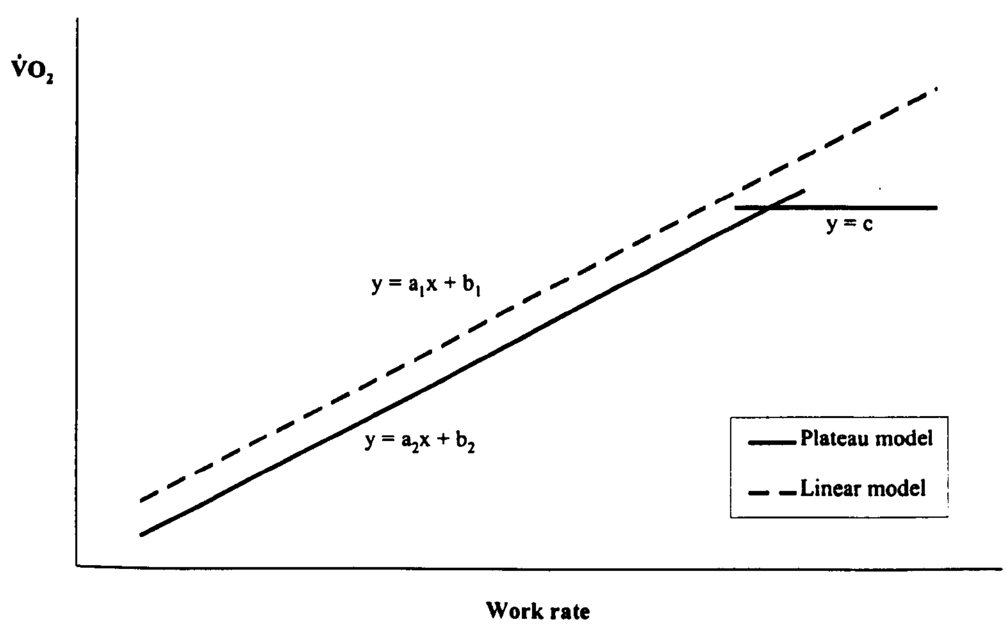

Figure 9.1. Schematic of the two models used to describe the $\dot{V}O_2$-WR relationship.

For the 0%T and the 5%T, the independent variable was running speed ($km.h^{-1}$), whilst for the IGT it was treadmill grade (%). In all cases, the dependent variable was $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$).

Model fitting was performed using standard least squares regression. For the plateau model, all possible groupings were evaluated. That is, initially the first 2 points were included in the first segment and the remainder were allocated to the second. Then the first 3 points were included in the first segment and the remainder were allocated to the second, and so on. This procedure continued until the last two points were allocated to the second segment. Each data point was included in either the first or the second segment; no data points were common to both. The residual sum of squares (RSS) was calculated for each grouping, and for a particular data set the grouping which yielded the lowest RSS was selected. The values for a_2, b_2, and c obtained for this grouping were used to describe that data set.

Goodness of fit was evaluated by means of the standard error of estimate (SEE). This was calculated according to the following equation

$$SEE = \sqrt{RSS/df}$$

where df (degrees of freedom) is equal to the total number of data points minus the number of parameters. For the linear model, there were 2 parameters (a_1 and b_1), whereas for the plateau model there were 3 (a_2, b_2, and c).

9.2.7 *Determining the duration of the $\dot{V}O_2$ plateau*

In those cases in which the SEE was lower for the plateau model, the time over which a $\dot{V}O_2$-plateau was sustained was determined by calculating the time between the WR at which the two segments intercepted and the end of the test. Solving the two equations ($y = a_2x + b_2$ and $y = c$) yielded a set of coordinates (WR, $\dot{V}O_2$) for the intercept. The x-coordinate for this point was in either $km.h^{-1}$ (0%T and 5%T) or % grade (IGT), but since there was a direct relationship between either belt speed (0.1 $km.h^{-1}$ per 5 s) or treadmill grade (0.1% per 6 s) and time, this coordinate could easily be converted to a time. The time at which the test was terminated was always recorded, and the duration of the $\dot{V}O_2$-plateau was determined by subtracting the time at which the two segments intercepted from this final time.

9.2.8 *Assessing the linearity of the $\dot{V}O_2$-WR relationship*

For each subject, and for each test, 2 linear $\dot{V}O_2$-WR relationships were derived. (WR was expressed as % grade for the IGT, and as running speed for the 0%T and the 5%T). Each subject's data were plotted, and the first and the last 1-2 min of the test were excluded so that only the apparently linear portion remained. This portion was divided in half and a separate regression equation was derived for each half. There were always at least 6 data points, so each equation was based on at least 3 points. When an odd number of data points were available, the middle point was included in both regression lines.

9.2.9 *Statistical analysis*

All tests were performed at an alpha level of 0.05, and all data are presented as mean ± SD (unless otherwise stated). Individual data can be found in Appendix 5, together with full results for each of the tests described below.

To establish whether the goodness of fit was better for the linear or the plateau model, and whether the situation was different for different tests, a two-way (test × model) RM ANOVA was performed on the SEEs.

Data on the duration of the $\dot{V}O_2$-plateau were not normally distributed, so to ascertain whether this duration differed between the 3 tests, a (one-way) Friedman ANOVA by ranks was used. To locate significant differences between the means, a post-hoc test for ranked data (Siegal and Castellan, 1988) was used, and to establish whether the duration of a plateau for one individual in one test was related to that for the same individual in another test, Spearman's rank order correlation coefficients were calculated (one for each pair of tests).

To ascertain whether the peak values for $\dot{V}O_2$, RER, and [Bla] differed between the 3 tests, separate one-way RM ANOVAs were performed (one for each variable) on the peak values attained in the 3 tests. Newman-Keuls post hoc tests were performed to locate significant differences between the means.

Finally, to ascertain whether the $\dot{V}O_2$-WR relationship was linear for the major portion of the test, the $\dot{V}O_2$-WR relationship derived from the lower WRs was compared with that derived from the higher WRs. For a given test, two $\dot{V}O_2$-WR relationships were available for each subject, and for each test the slopes of these relationships were compared by means of a paired t test. The aim was to establish, for a given test, whether the slope of the $\dot{V}O_2$-WR relationship varied with WR (i.e. whether the $\dot{V}O_2$-WR relationship was non-linear).

9.3 Results

9.3.1 *Comparison of models*

Table 9.2 (below) gives data on the SEE and the incidence of a $\dot{V}O_2$-plateau, for each of the 3 tests and for each of the two models. In determining the incidence of a $\dot{V}O_2$-plateau, it was assumed that a plateau had occurred if the SEE was lower for the plateau than for the linear model.

Table 9.2. SEE for the linear and the plateau model and the incidence of a $\dot{V}O_2$-plateau for the 3 tests (n = 12).

Test	SEE for the linear model ($ml.kg^{-1}.min^{-1}$)	SEE for the plateau model ($ml.kg^{-1}.min^{-1}$)	Incidence of a $\dot{V}O_2$-plateau
0%T	1.09 ± 0.48	0.63 ± 0.17	92%
5%T	1.34 ± 0.47	0.68 ± 0.21	92%
IGT	1.04 ± 0.45	0.60 ± 0.29	100%

These data suggest that for each of the tests the SEE was lower for the plateau than for the linear model. The RM ANOVA revealed a significant main effect for model ($p < 0.0005$), but no interaction ($p = 0.203$) and no main effect for test ($p = 0.10$). Of the 36 tests, there were only 2 for which the SEE was lower for the linear than for the plateau model, and in one of these cases the difference was trivial (0.75 vs. 0.76 $ml.kg^{-1}.min^{-1}$). The responses of a representative subject are shown in figures 9.2 (0%T and 5%T) and 9.3 (IGT), and the group mean responses are shown in figures 9.4 and 9.5.

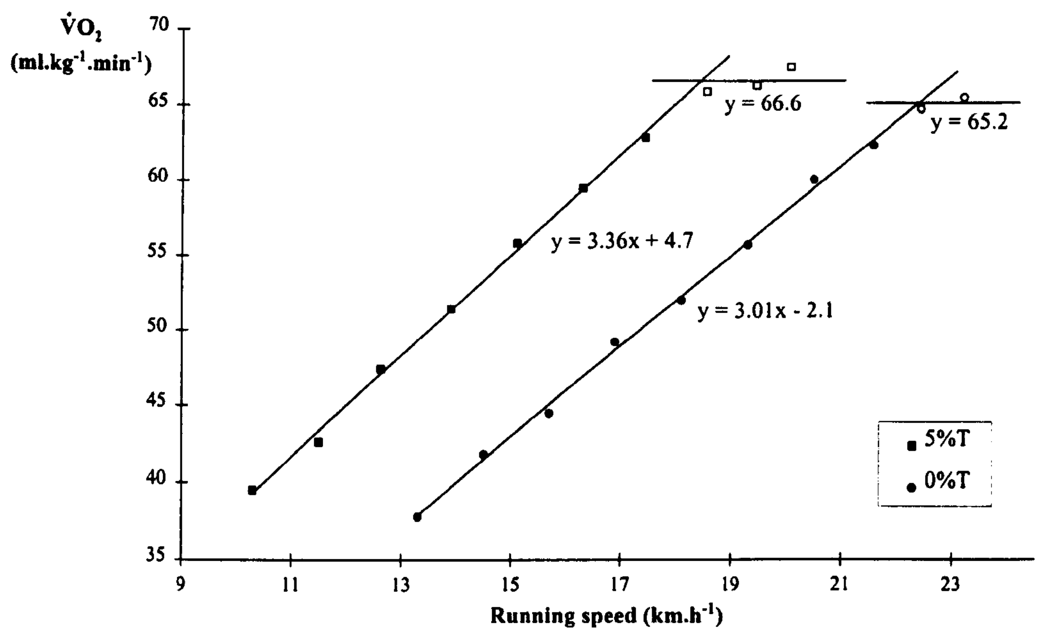

Figure 9.2. Data from a representative subject showing $\dot{V}O_2$ as a function of running speed for the 0%T and the 5%T.

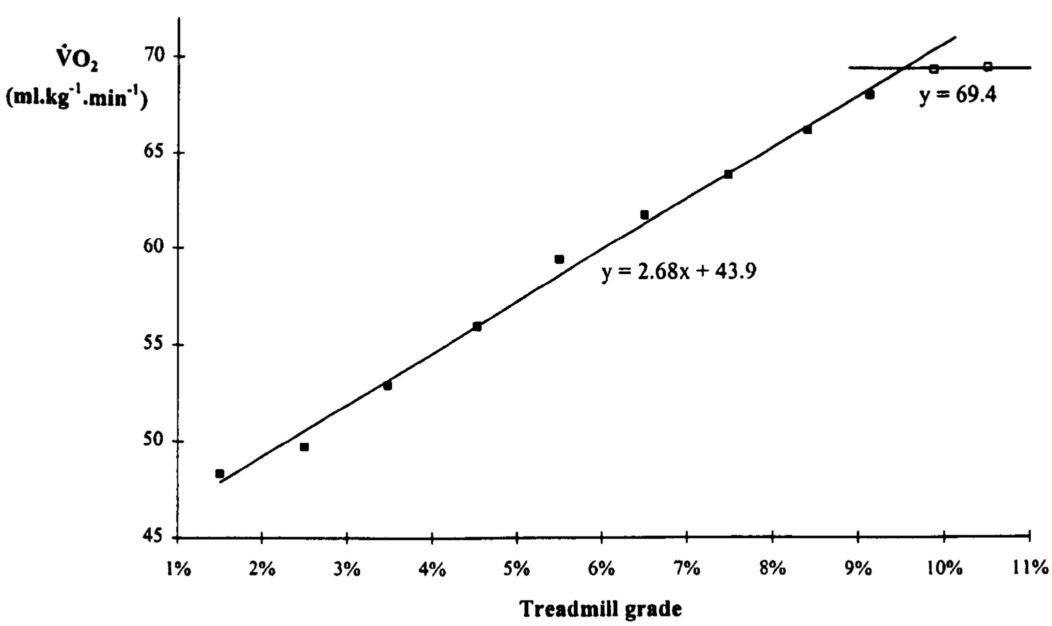

Figure 9.3. Data from a representative subject showing $\dot{V}O_2$ as a function of treadmill grade for the IGT.

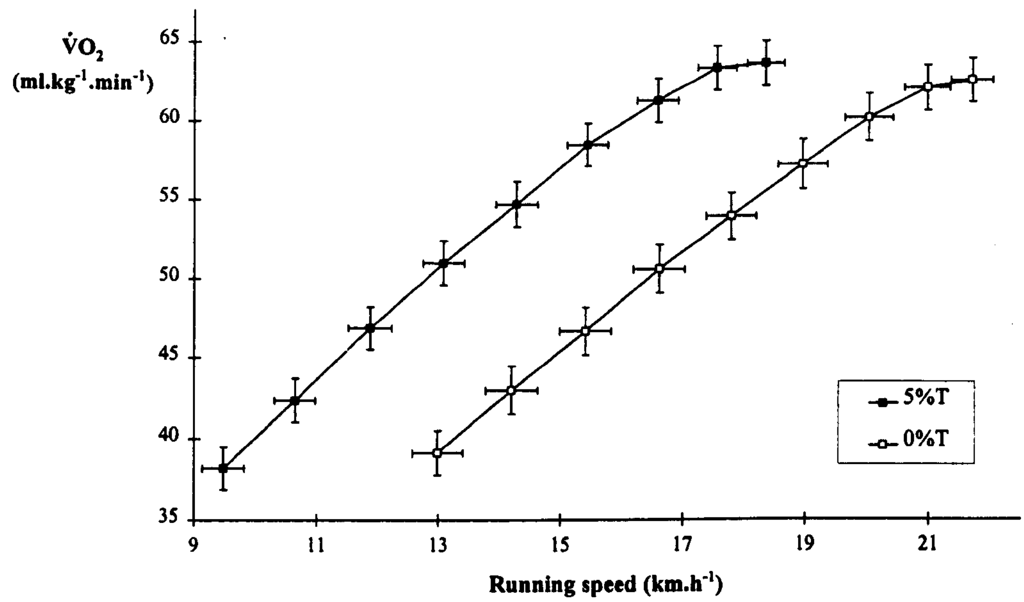

Figure 9.4. Group data (mean ± SEM; n = 12) showing $\dot{V}O_2$ as a function of running speed for the 0%T and the 5%T.

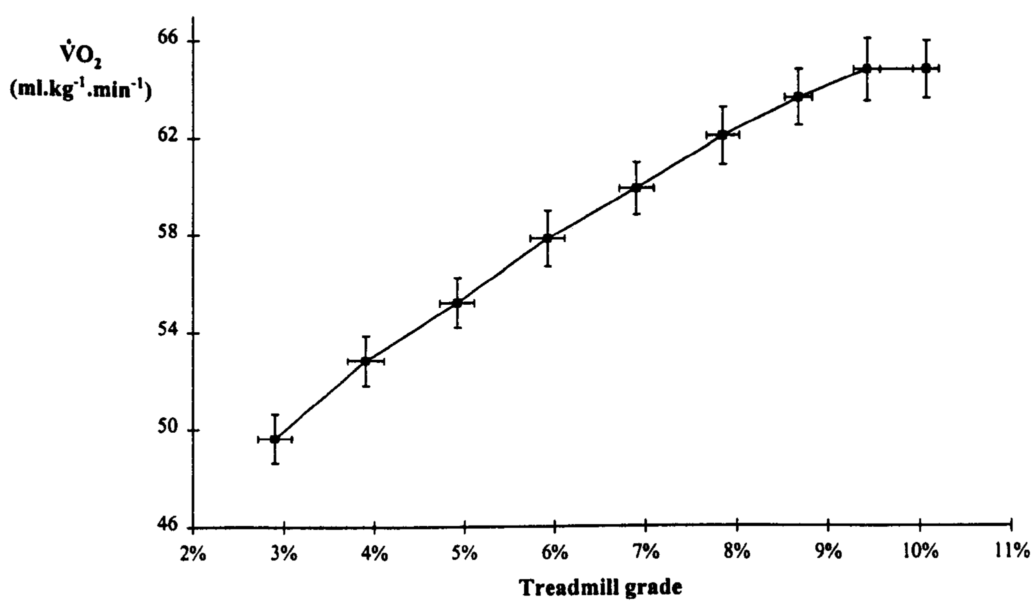

Figure 9.5. Group data (mean ± SEM; n = 12) showing $\dot{V}O_2$ as a function of treadmill grade for the IGT.

9.3.2 *Duration of the $\dot{V}O_2$-plateau*

The data presented in this section were derived from 11 of the 12 subjects. There were in fact only 10 subjects in whom the SEE was always lowest for the plateau model. However, for each of the remaining subjects the linear model was a better fit for just 1 of the 3 tests. Furthermore, whilst the difference in SEE between the linear and the plateau model for the relevant test was substantial in one of these subjects, it was trivial in the other (section 9.3.1). The group data presented below include data from the latter subject only.

Non-parametric data have been presented, and non-parametric statistical tests were used, because for each of the tests the data were positively skewed [skewness/$SE_{skewness} > 2$ (Vincent, 1995)]. The time over which a plateau was sustained [median (interquartile range)] differed between the tests ($p = 0.013$), being lower for the 0%T [68 (23) s] than for the 5%T [81 (12) s] or the IGT [84 (44) s]. The duration of a plateau for a given test did not correlate with that for either of the other tests ($p > 0.05$ for all correlation coefficients).

9.3.3 *Peak physiological responses for the 3 tests*

For each individual and for each test, the highest $\dot{V}O_2$ observed was taken as the peak $\dot{V}O_2$, provided the sample from which it was derived was collected over ≥ 20 s. This $\dot{V}O_2$ differed between tests ($p < 0.0005$), being higher for the 5%T than for the 0%T, and higher still for the IGT. The peak RER also differed ($p < 0.0005$), being higher for the 0%T than for the IGT, and higher still for the 5%T. However, no differences were observed for the peak [Bla] ($p = 0.785$) (see table 9.3, below).

Table 9.3. Peak values for $\dot{V}O_2$, RER, and [Bla] for the 3 tests (n = 12).

Test	Peak $\dot{V}O_2$[a] (ml.kg^{-1}.min^{-1})	Peak RER	Peak [Bla] (mmol.L^{-1})
0%T	62.6 ± 4.6#	1.19 ± 0.04#	7.85 ± 1.78
5%T	64.0 ± 4.7*	1.21 ± 0.05*	7.67 ± 1.69
IGT	65.1 ± 4.3*#	1.17 ± 0.04*#	7.83 ± 1.47

#p < 0.05 vs. the 5%T; *p < 0.05 vs. the 0%T.

9.3.4 *Linearity of the $\dot{V}O_2$-WR relationship for the 3 tests*

For the portion of the test before the point at which $\dot{V}O_2$ started to plateau, the $\dot{V}O_2$-running speed relationship was linear for both the 0%T and the 5%T. However, for the equivalent portion of the IGT, the relationship between $\dot{V}O_2$ and treadmill grade was non-linear. Table 9.4 (below) shows that whilst the slope of the $\dot{V}O_2$-running speed relationship was the same for the first and the second half of both the 0%T and the 5%T, the slope of the relationship between $\dot{V}O_2$ and treadmill grade was lower for the second than for the first half of the IGT (see also figures 9.4 and 9.5).

Table 9.4. Slope of the $\dot{V}O_2$-WR relationship for the first and the second half of the 0%T, the 5%T, and the IGT (n = 12).

Test	Start speed/grade for 1st half[a]	Start speed/grade for 2nd half[a]	Slope for 1st half[b]	Slope for 2nd half[b]	p value (2nd vs. 1st)
0%T	12.0 ± 1.1	15.6 ± 1.1	2.98 ± 0.22	2.91 ± 0.53	0.677
5%T	8.8 ± 1.0	12.4 ± 1.1	3.36 ± 0.43	3.33 ± 0.39	0.792
IGT	1.7 ± 0.4	4.8 ± 0.5	2.77 ± 0.32	2.38 ± 0.32	0.007

[a]Running speed is expressed in km.h^{-1} and treadmill grade is expressed as %grade.
[b]The units for slope are ml.kg^{-1}.min^{-1} per km.h^{-1} or ml.kg^{-1}.min^{-1} per % grade.

9.4 Discussion

9.4.1 *Comparison of models*

The results of the present study suggest that, in general, the $\dot{V}O_2$-WR relationship does plateau over the closing stages of a treadmill ramp test. This appears to be the case regardless of whether a CGIS or a CSIG test is used, and regardless of whether the CGIS test is completed on a level treadmill or at a 5% grade. The plateau model was a better fit in all subjects for the IGT and in 92% of subjects for the 0%T and the 5%T (table 9.2).

The approach to defining a plateau that was adopted in the present study was a novel one. Conceptually it is straight forward. It assumes that $\dot{V}O_2$ either increases as a linear function of WR throughout the test or increases as a linear function initially and then plateaus in the closing stages. However, whereas previous approaches to defining a $\dot{V}O_2$-plateau have tended to focus on identifying whether or not a plateau has occurred in a particular individual, in the present study the primary aim was to determine, for the group as a whole, whether $\dot{V}O_2$ typically plateaued or whether it continued to increase in the closing stages of a particular test.

The approach used in Study 1 was modelled on that of Taylor et al. (1955). Confidence limits were derived for the sub-$\dot{V}O_{2peak}$ $\Delta\dot{V}O_2$, and a plateau was defined as a final $\Delta\dot{V}O_2$ of less than the lower 95% confidence limit. The probability that such a final $\Delta\dot{V}O_2$ would be observed if $\dot{V}O_2$ continued to increase as a linear function of WR throughout the closing stages of the test is 2.5%. That is, with such an approach there is a 2.5% chance of concluding that $\dot{V}O_2$ has plateaued in a given individual for a particular test when in fact it has continued to increase throughout the test. For the approach used in the present study it is impossible to quantify the probability of such a spurious plateau being identified in a particular individual. However, when the $\dot{V}O_2$ data were modelled, at least 8 data points were typically included in the model. Were the $\dot{V}O_2$-WR relationship linear, each of these data points would vary randomly around a straight line. The goodness of fit would only be better for the plateau model if the final few data points varied in such a way that they were generally lower than would be predicted from a linear $\dot{V}O_2$-WR relationship. For example, the plateau model would be the best fit model for a set of data in which all data points except the last fit a straight line, provided the final data point falls well below this line. The chance of this occurring at random when 8 or more data points are available and the $\dot{V}O_2$-WR relationship is linear is, however, very small.

In the present study, a plateau was deemed to have occurred whenever the SEE was lower for the plateau than for the linear model. If it is accepted that the chance of a spurious plateau being identified when this approach is adopted is small, the incidence of a plateau for Study 3 can be compared with that for Study 1. In the present study, the incidence of a $\dot{V}O_2$-plateau was >90% for each of the tests, whereas in Study 1, the incidence of a $\dot{V}O_2$-plateau was found to be between 20 and 50% for a CGIS ramp test.

The present study differed from Study 1 not only in the sampling procedures used and the approach taken to defining a $\dot{V}O_2$-plateau, but also in the way in which the problem of contaminated expirate was dealt with (see sections 5.5.5.9 and 5.5.5.10).

In Study 1, the measured values for F_EO_2 and F_ECO_2 were not corrected to account for the effect of contamination. Instead, an attempt was made to ensure that the effect of this contamination on the measured gas fractions was small. This entailed flushing all Douglas bags with expirate prior to use (see section 5.5.5.9). However, since this expirate was collected during moderate intensity exercise the measured gas fractions would have been artificially low (and therefore $\dot{V}O_2$ would have been artificially high), especially for intensities close to that at which $\dot{V}O_{2peak}$ was attained. As a result, the true incidence of a $\dot{V}O_2$-plateau might have been underestimated in Study 1. In the present study, all Douglas bags were flushed with room air prior to use and the measured concentrations of O_2 and CO_2 were corrected to account for the effect of contamination (section 5.5.5.10). The important point about this strategy is that it would have ensured that all $\dot{V}O_2$ data were unbiased. The implication is that the observed incidence of a $\dot{V}O_2$-plateau should be closer to the true incidence for the present study than for Study 1.

The sampling procedures used should have ensured that the density of data was sufficiently high for the final 2-3 min of the test to allow a plateau to be detected even when it occurred within the last minute of the test. They should also have ensured that the variability in $\dot{V}O_2$ was relatively low, even in the early stages of the test. The typical data presented in figures 9.2 and 9.3 suggest that the variability in $\dot{V}O_2$ was indeed low throughout the test (the spread around the regression line is small). The fact that a plateau was identified in >90% of subjects for each test (table 9.2) suggests that the variability was low enough, and the density of data was high enough, for a $\dot{V}O_2$-plateau to be identified whenever one was present.

The way in which the data were modelled was based on the premise that $\dot{V}O_2$ either continues to increase as a linear function of WR or plateaus in the closing stages of a ramp test. It is in fact conceivable that the slope of the $\dot{V}O_2$-WR relationship might increase in the closing stages of such a test. Were this the case, the goodness of fit would be better for the linear model than for the plateau model. But for the group as a whole, and for at least 11 of the 12 subjects, the SEE was lower for the plateau than for the linear model for each test. Hence it is reasonable to conclude that in trained runners $\dot{V}O_2$ typically plateaus in the closing stages of a ramp test, regardless of whether this test is a CGIS test completed on a level treadmill, a CGIS test completed at a 5% grade, or a CSIG test. It should not be assumed, however, that the same results would be obtained were an elite group of specialist runners to be assessed. Several of the subjects in the present study were not specialist distance runners, and none were elite athletes (section 9.2.1).

9.4.2 *Duration of the $\dot{V}O_2$-plateau*

For the 33 tests that were analysed, the duration of the $\dot{V}O_2$-plateau ranged from 59 to 179 s. However the longest times were always observed in the same subject. When this subject's data are excluded, the range is 59 to 97, 65 to 128, and 67 to 132 s for the 0%T, the 5%T, and the IGT respectively. These data show that when a plateau occurs in a ramp test it generally occurs within the last 1-2 min of the test. At least two data points are needed to define a plateau, so a reasonable suggestion would be that a sampling period of 20-30 s should be used throughout the final 2 min of the test when a CT is used for the determination of $\dot{V}O_{2max}$. The results of the present study suggest that the peak $\dot{V}O_2$ attained from such a test is likely to be a maximal value. However, it could be argued that the $\dot{V}O_{2max}$ value derived from such a test would be more reliable were a longer sampling period to be used. Whilst it is certainly important to obtain a reliable value for $\dot{V}O_{2peak}$, it is also important to ensure that the peak value obtained is a valid measure of $\dot{V}O_{2max}$. The results of Study 2 (Chapter 8) suggest that the variability in $\dot{V}O_2$ is low for 30 s samples, provided the intensity of the exercise during which they are taken is close to that at which $\dot{V}O_{2peak}$ is reached. Were a very high level of reliability required, a possible solution would be to use a short sampling period (e.g. 20 s) and define $\dot{V}O_{2max}$ as the highest $\dot{V}O_2$ where $\dot{V}O_2$ is averaged over 2 consecutive samples. Using 20 s samples should ensure that the density of data is sufficient for a $\dot{V}O_2$-plateau to be identified whenever one is present, and averaging data from 2 samples should ensure that the $\dot{V}O_{2max}$ value obtained is sufficiently reliable. Alternatively the data could be modelled as in the present study and $\dot{V}O_{2max}$ could be defined by the horizontal line (y = c) that defines the upper portion of the plateau model. Either of these approaches could also be adopted for breath-by-breath data.

The finding (section 9.3.2) that the time over which a $\dot{V}O_2$-plateau was sustained was lower for the 0%T than for either the 5%T or the IGT suggests that it might be more difficult to detect a plateau for a CGIS completed on a level treadmill than for a similar test conducted at a moderate grade or a CSIG test. For the 0%T, the duration of the plateau generally varied between 1 and 1.5 min (see above). Hence it is especially important that a suitable sampling procedure is adopted when a CT is used to determine $\dot{V}O_{2max}$ for level treadmill running. In the present study, the incidence of a $\dot{V}O_2$-

plateau was similar for the 3 tests. It is possible, however, that previous studies which have found the incidence of a $\dot{V}O_2$-plateau to be low for a CGIS (0% grade) test (Åstrand, 1952; Mayhew and Gross, 1975; see also section 7.3.1) have not given enough consideration to sampling procedures.

9.4.3 *Peak physiological responses*

The key finding here is that $\dot{V}O_{2peak}$ differed between the 3 tests. In itself this finding is not new. Indeed, Study 1 found that the peak $\dot{V}O_2$ was higher for a CGIS test completed at a 5% grade than for a similar test completed on a level treadmill (section 7.3.1), and various groups have reported that $\dot{V}O_{2peak}$ is higher for a CSIG test than for a CGIS (0% grade) test (see section 4.3.3). However, the present study is important because it is the first to show that $\dot{V}O_2$ can plateau at different values, depending on the test protocol. According to Wagner (1996), the value at which $\dot{V}O_2$ plateaus should vary as the rate at which O_2 can be supplied varies. Assuming his argument is applicable in the present situation, the obvious question is why might an individual be able to supply O_2 at a higher rate during uphill than during level running.

An important consideration here is that the active muscle mass is greater for uphill than for level running (Sloniger et al., 1997b). Any increase in the active muscle mass would presumably be accompanied by an increase in the available capillary volume, and any increase in the available capillary volume would potentially be accompanied by a drop in total peripheral resistance. Thus afterload might decrease as the active muscle mass increases and, provided venous return is adequate, $\dot{Q}_c$ might increase as a result. In fact, increasing the active muscle mass should increase the effectiveness of the muscle pump, thus facilitating an enhanced venous return, so the potential for $\dot{Q}_c$ to increase in response to an increase in the active muscle mass is considerable. No comparative data are available for $\dot{Q}_c$, total peripheral resistance, and mean arterial pressure during level and uphill running. However, Hermansen (1973) compared "maximal" uphill running with "maximal" cycling and found that total peripheral resistance and mean arterial pressure were lower, while $\dot{Q}_c$ was higher, for running as compared with cycling.

These results can be explained if it is assumed that the active muscle mass (and thus the available capillary volume) is higher for uphill running than for cycling. Strictly speaking the effect of treadmill grade *per se* can only be evaluated by comparing the 0%T with the 5%T. However, the final grade reached in the IGT averaged 10.4% (range = 9.3 to 10.9%). Therefore, the 3 tests can almost be considered equivalent to CGIS tests conducted at grades of 0, 5, and 10%. Although $\dot{V}O_{2peak}$ was lowest for the 0%T, higher in the 5%T, and highest in the IGT, it increased slightly more between the 0%T and the 5%T than between the 5%T and the IGT (table 9.3). This may reflect the fact that in the IGT subjects typically spent <0.5 min at a grade of 10% whereas in the 5%T they spent the entire test (~10 min) at a grade of 5%.

An increase in the active muscle mass might also influence O_2 transport by influencing the diffusion of O_2 from the red blood cells to the mitochondria. Wagner and colleagues (Hogan et al., 1989; Roca et al., 1989; Wagner, 1992, 1995, 1996) have stressed the importance of diffusive conductance at the muscle level as a determinant of O_2 transport to muscle mitochondria. These authors have stressed that, for a given rate of convective O_2 delivery, the $\dot{V}O_2$ of a particular muscle is a function of its overall O_2 conductance (Wagner, 1996). Although at present it is not possible to identify the most important determinants of muscle O_2 conductance (Wagner, 1996), the transit time for red blood cells is thought to be an important factor (Gayeski et al., 1988), and, intuitively at least, the available capillary surface area should also be an important determinant of O_2 conductance. Increasing the active muscle mass would presumably increase the available capillary surface area. It would also increase the red cell transit time provided the increase in the available capillary volume exceeded the increase in muscle blood flow. There are therefore 3 possible explanations for the increase in $\dot{V}O_{2max}$ that was observed when the treadmill grade was increased:

1) $\dot{Q}_c$ (and $\dot{Q}_{legs}$) increased but O_2 extraction was unchanged;
2) $\dot{Q}_c$ (and $\dot{Q}_{legs}$) remained unchanged but O_2 extraction at the muscle increased;
3) $\dot{Q}_c$ (and $\dot{Q}_{legs}$) increased slightly, as did O_2 extraction.

Muscle O_2 extraction may have increased in response to an increase in the active muscle mass as described above. However, changes in the extent to which particular muscle groups are recruited might also affect muscle O_2 extraction. Compared with level running, uphill running requires greater activation of the vastus group and the soleus, and less activation of the rectus femoris, gracilis, and semitendinosus muscles (Sloniger et al., 1997c). For a given individual, factors which influence O_2 conductance (e.g. capillary density) might vary between muscle groups. Similarly, for a given muscle group, O_2 conductance might vary between individuals. It is possible, therefore, that differences in $\dot{V}O_{2max}$ between level and uphill running might reflect differences in O_2 extraction which are related to differences in the extent to which certain key muscle groups are activated. Inter-individual variation in this difference in $\dot{V}O_2$ might reflect either variation in the way in which muscle recruitment is affected by treadmill grade or variation in the relative diffusing capacity for O_2 of the various muscle groups.

Regardless of the mechanism underpinning the differences, the finding that $\dot{V}O_{2peak}$ differed among the 3 tests has important practical implications. Given that the plateau model was a better fit than the linear model for each of the tests, it seems reasonable to conclude that in each case the peak $\dot{V}O_2$ was a maximal $\dot{V}O_2$ for that particular test. That is, it seems reasonable to conclude that $\dot{V}O_{2max}$ for level running differs from that for uphill running. The implication is that physiologists should consider the context in which the $\dot{V}O_{2max}$ obtained from a particular test will be applied. In particular, CSIG tests should not be used indiscriminately because it is unlikely that the $\dot{V}O_{2max}$ value obtained from such a test will ever be attained during level running.

The results obtained for RER and [Bla] are difficult to explain. Whilst the peak RER was lowest for the IGT, higher for the 0%T, and higher still for the 5%T, the peak [Bla] did not differ between the tests (table 9.3). Tests similar to the 0%T and the 5%T were performed in Study 1, but different result were obtained (table 7.3). The differences in RER are less pronounced for the subjects of the present study, as are the differences in [Bla], and indeed the difference in $\dot{V}O_{2peak}$ was also less pronounced for the present study. These differences may reflect differences in the characteristics of the subjects.

The subjects in Study 1 were mostly games players (section 7.2.1) whereas the subjects in the present study were trained runners (section 9.2.1). Most of these runners were used to training at speeds at or above that which they reached in the 0%T, and they may therefore have been more skilled at running at high speed than the subjects of Study 1. It should be mentioned, however, that the peak speed reached was higher for the subjects of the present study [21.4 ± 1.1 vs. 18.2 ± 1.0 $km.h^{-1}$ (average for the final minute)].

The above explanation is speculative. However, it does highlight an important point which is that the responses to a given test protocol may be population specific. For a middle-distance runner who needs to be able to run at speeds above that which would be reached in a test such as the 0%T, a CGIS test on a level treadmill may be most appropriate for the assessment of $\dot{V}O_{2max}$. However, for a distance runner who will never race at such high speeds, a CGIS test conducted at a moderate grade (e.g. 5%) might be more appropriate.

9.4.4 *Linearity of the $\dot{V}O_2$-WR relationship*

The data presented in table 9.4 suggest that a CGIS ramp test is valid for the assessment of $\dot{V}O_{2max}$, regardless of whether the test is completed on a level treadmill or at a moderate grade. The same cannot be said for the IGT though. For this test, the slope of the $\dot{V}O_2$-treadmill grade relationship decreased with increasing grade. Such an effect has not previously been documented. For instance, Pugh (1971) presented data on $\dot{V}O_2$ as a function of treadmill grade for one subject running at each of 4 speeds, but in each case the $\dot{V}O_2$-treadmill grade relationship appears to be linear. However it may be related to a change in running mechanics. Specifically, compared with running at a low grade, running at a high grade appeared to be associated with a more pronounced forward lean of the trunk and a less pronounced vertical oscillation of the head. No biomechanical analysis was performed, so it is impossible to quantify these changes. Nevertheless, it has been shown for level treadmill running that good economy tends to be associated with a pronounced forward lean of the trunk (Williams and Cavanagh, 1987) and with relatively small oscillations of the centre of mass (Cavanagh et al., 1977;

Williams and Cavanagh, 1987). Further research is needed to clarify the effect of treadmill grade on the delta efficiency for running.

In the present study, the $\dot{V}O_2$-treadmill grade relationship was modelled for the entire test. It is unlikely therefore that a spurious plateau would have been identified because provided the $\dot{V}O_2$-treadmill grade did not plateau the best fit model would always have been the linear one. However, many previous studies have been conducted in which a CSIG test has been used and a confidence interval for $\Delta\dot{V}O_2$ has been derived from the early stages of the test (i.e. from relatively low grades). If the $\dot{V}O_2$-treadmill grade relationship is non-linear, the mean $\Delta\dot{V}O_2$ derived from low grades will be greater than that which would be derived from higher grades, and the cut-off value used to define a $\dot{V}O_2$-plateau for such a test will be too lenient. The result would be that spurious plateaus would be detected. Once again, the implication is that a CSIG test should not be adopted as the test of choice for the assessment of $\dot{V}O_{2max}$.

PART V

GENERAL DISCUSSION AND CONCLUDING REMARKS

CHAPTER 10: GENERAL DISCUSSION

10.1 Problems with discontinuous tests

Study 1 was a large study which attempted to address many issues. Nevertheless, the finding (table 7.4) that the peak $\dot{V}O_2$ was higher for the 5%RT than for the DCT is of particular importance. It is difficult to reconcile this finding with the observation that a $\dot{V}O_2$-plateau could be identified in 80% of subjects for the DCT. It would appear that although the $\dot{V}O_2$-running speed relationship plateaued in the majority of subjects during the DCT, it did so at a sub maximal $\dot{V}O_2$.

Discontinuous tests are too time consuming to be suitable for the routine assessment of $\dot{V}O_{2max}$. However, it is of interest to investigate the $\dot{V}O_2$ response to such a test because a DCT was used in each of the studies which found the incidence of a $\dot{V}O_2$-plateau to be >80% (Taylor et al., 1955; Krahenbuhl et al., 1979; Krahenbuhl and Pangrazi, 1983; Rivera-Brown et al., 1994). The results of these studies have been taken as evidence that an upper limit for $\dot{V}O_2$ is reached during progressive exercise. However, the finding that the peak $\dot{V}O_2$ attained in a DCT can be exceeded in a ramp test suggests that such a limit is not in fact reached in a DCT.

It is unclear at present why $\dot{V}O_2$ plateaued at a sub maximal level during the DCT. There was no indication that the kinetics of the $\dot{V}O_2$-response got progressively slower over the last few stages of the test (see section 7.3.2.1). In fact, the rate of increase in $\dot{V}O_2$ (as estimated from the $\Delta\dot{V}O_2$ between the 1st and the 2nd sampling interval) tended to be fastest for the final stage of the test (figure 7.3). There was, however, a positive correlation between the $\dot{V}O_2$ that was attained in the DCT (expressed relative to the peak $\dot{V}O_2$ from the 5%RT) and the speed that was reached in the DCT (expressed relative to $v\dot{V}O_{2peak}$). A possible interpretation of this finding is that only those subjects whose anaerobic capabilities were sufficient were able to match their peak $\dot{V}O_2$ from the ramp test in the DCT (see section 7.4.2.2).

Spencer et al. (1996) determined the $\dot{V}O_2$ response to race pace treadmill running for a group of sprinters (200/400 m runners) and a group of middle-distance (800/1500 m) runners. All runs were completed on a motorised treadmill, and all were exhaustive (square wave) runs. The sprinters ran at 400 m race pace, whilst the middle-distance runners completed both an 800 and a 1500 m pace run. For the 1500 m pace run, $\dot{V}O_2$ plateaued at ~94% $\dot{V}O_{2peak}$ after ~195 s, and for the 800 m pace run, it plateaued at ~90% $\dot{V}O_{2peak}$ after ~90 s. It might be expected, therefore, that had these runners completed a run at 400 m race pace, $\dot{V}O_2$ would have plateaued at <90% $\dot{V}O_{2peak}$. However, in the sprinters, $\dot{V}O_2$ plateaued at ~98% $\dot{V}O_{2peak}$ after ~35 s of the 400 m pace run.

Spencer et al. referenced the $\dot{V}O_2$ response for these runs to the peak $\dot{V}O_2$ from a CSIG test. However, given that all of these runs were completed on a level treadmill, this was inappropriate. For the subjects on whom data were presented in table 9.3, $\dot{V}O_{2max}$ for the IGT (a CSIG test similar to the test which Spencer et al. used) was 2.5 $ml.kg^{-1}min^{-1}$ (4%) higher than that for the 0%T. An estimate of the peak $\dot{V}O_2$ that Spencer et al.'s subjects would have been able to attain during level running can therefore be obtained by subtracting 4% from the reported values for $\dot{V}O_{2peak}$. Corrected accordingly, Spencer et al.'s data indicate that $\dot{V}O_2$ plateaued at ~94, ~98, and ~102% of $\dot{V}O_{2peak}$, respectively, in the 1500, 800, and 400 m pace runs. The time to exhaustion averaged 1.97 min for the 800 and 4.03 min for the 1500 m pace run, whereas for the DCT used in Study 1 the stage duration was 3 min. It is noteworthy, therefore, that the peak $\dot{V}O_2$ for this test averaged ~96% of that which was attained in the 5%RT (table 7.4).

Data were presented as 10 s averages for the race pace runs. However, for the CSIG test, the averaging period was 20 s and $\dot{V}O_{2peak}$ was defined as the highest $\dot{V}O_2$ sustained over 3 consecutive 20 s periods (Spencer, personal communication). For 10 s averages, the variability in $\dot{V}O_2$ would be large, and therefore $\dot{V}O_{2peak}$ would be high, relative to that for the CSIG test. In addition, as it is unlikely that $\dot{V}O_2$ would have plateaued over the final 60 s of the CSIG test in all subjects (see section 9.4.2), it is likely that by averaging over 60 s periods Spencer et al. would have underestimated the true $\dot{V}O_{2peak}$ for this test. It would seem, therefore, that rather than concluding that $\dot{V}O_2$ plateaued at 102% $\dot{V}O_{2peak}$, it might be more reasonable to conclude that $\dot{V}O_2$ plateaued at $\dot{V}O_{2peak}$ in the 400 m pace run. The middle-distance runners did not run at 400 m pace and the sprinters did not run at either 800 or 1500 m pace. Nevertheless, it seems likely that had both groups of runners completed a run at 400 m pace the $\dot{V}O_2$ response would have differed between the two groups. Specifically, whilst the sprinters attained $\dot{V}O_{2peak}$, it would be predicted that the middle-distance runners would have attained <90% $\dot{V}O_{2peak}$ during a run at 400 m race pace.

It seems reasonable to assume that the anaerobic capabilities of the sprinters would have been superior to those of the middle-distance runners. However, the sprinters also had a much lower $\dot{V}O_{2peak}$ than the middle-distance runners [mean ± SEM: 53 ± 3 vs. 65 ± 2 $ml.kg^{-1}min^{-1}$ (Spencer et al., 1996)]. It is tempting to suggest that whether or not an individual can attain $\dot{V}O_{2max}$ in a short square wave run is determined by the balance between their aerobic and anaerobic capabilities. The results of Study 1 provide some support for this interpretation, and pertinent data can also be extracted from several published studies.

Margaria et al. (1965) studied square wave runs for which the time to exhaustion was between 0.5 and 3 min and found that the rate at which $\dot{V}O_2$ increased at the start of the run increased in proportion to the relative intensity of the exercise (relative to $\dot{V}O_{2peak}$). Williams et al. (1998) also studied high intensity treadmill running, and they also found that the rate at which $\dot{V}O_2$ increased at the start of exercise increased in proportion to exercise intensity. Spencer et al. estimated the relative intensity to be 170, 112, and 102% $\dot{V}O_{2peak}$ for the 400, 800, and 1500 m pace runs. These estimates were derived from a $\dot{V}O_2$ -running speed relationship which was determined for sub- $\dot{V}O_{2peak}$ speeds and extrapolated to the relevant race pace. Whilst there would certainly be problems associated with extrapolating such a relationship to 170% $\dot{V}O_{2max}$, it is clear that the relative intensity was much higher for the 400 than for either the 800 or the 1500 m pace run.

Greenhaff and Timmons (1998) suggest that interaction between aerobic and anaerobic metabolism is likely to be important in determining the time course of the $\dot{V}O_2$ response in the early stages of intense exercise. Studies in which the activation status of the pyruvate dehydrogenase complex has been manipulated (Timmons et al., 1996, 1997, 1998) have revealed that this complex may be an important site for such interaction. These studies are of interest because they suggest that factors unrelated to O_2 delivery might influence the way in which $\dot{V}O_2$ responds at the onset of exercise.

Connett and colleagues (Connett et al., 1985; Connett and Honig, 1989; Honig et al., 1992) have stressed the importance of the redox drive in allowing oxidative phosphorylation to proceed at a high rate when PO_2 is low. It is possible, for instance, that NADH derived from glycolysis is an important stimulus for the increase in the rate of mitochondrial respiration that occurs at the onset of exercise (Connett et al., 1985). The implication would be that an individual who is capable of generating a high flux through glycolysis at the onset of exercise would also be capable of accelerating mitochondrial respiration at a high rate. This is just one example of the way in which aerobic and anaerobic capabilities might interact. There are certainly others, and further research aimed at elucidating the mechanisms whereby aerobic and anaerobic metabolism are integrated is certainly warranted. It should be stressed, however, that whilst recent work has provided some insight into how aerobic metabolism might be controlled in the early stages of intense exercise, no explanation has yet been given for why $\dot{V}O_2$ might plateau below $\dot{V}O_{2max}$ during a short, exhaustive (square wave) exercise bout.

It is possible that researchers are unaware that such an effect occurs. Åstrand and Saltin (1961b) presented data on cycle ergometer exercise which showed that the peak $\dot{V}O_2$ was lower for an exhaustive exercise bout that lasted ~2 min than for one that lasted ~6 min. They mentioned this effect, but having claimed that the peak $\dot{V}O_2$ was only 2% higher for the longer bout, they dismissed it. Close inspection of the individual data reveals, however, that in 4 of the 5 subjects the difference between the highest and lowest values for peak $\dot{V}O_2$ was ~0.2 $L.min^{-1}$ (5%). (In the remaining subject, the difference was <0.1 $L.min^{-1}$.) The lowest peak $\dot{V}O_2$ was typically observed in the shortest bout (which lasted ~2 min) and the highest $\dot{V}O_2$ was typically observed in a bout which lasted 5-7 min, although this was not necessarily the longest bout.

The only other paper in which this effect has been documented is that of Spencer et al. (1996). In this study the effect was pronounced in the middle-distance runners, but it did not occur in the sprinters. Two recent papers (Williams et al., 1998; Hill and Ferguson, 1999) have claimed that $\dot{V}O_2$ reaches $\dot{V}O_{2peak}$ for a square wave run even when the duration of this run is ~2 min. However, Williams et al. presented no $\dot{V}O_2$ data (only an abstract of the study is available), and Hill and Ferguson's data show that $\dot{V}O_{2peak}$ was ~5% lower for a run which lasted ~2 min than for one which lasted ~5 min. In the latter study, $\dot{V}O_{2peak}$ was compared across 4 different square wave runs and one incremental test (ANOVA, $n = 12$), but no significant differences were found ($p > 0.05$).

The possibility that $\dot{V}O_2$ might plateau below $\dot{V}O_{2max}$ in an exhaustive square wave run has important implications, not only for the use of a DCT for the assessment of $\dot{V}O_{2max}$ but also for contemporary models of middle-distance running performance (see also section 10.6). Of particular interest is the possibility that the individuals in whom this effect is most likely to be observed are those athletes for whom aerobic capabilities are likely to be important determinants of performance (e.g. middle-distance runners). Further research is needed to clarify under what circumstances and in which individuals $\dot{V}O_2$ is likely to plateau below $\dot{V}O_{2max}$. In the meantime, it is suggested that discontinuous tests should not be used for the assessment of $\dot{V}O_{2max}$. Moreover, it is suggested that those studies which have found the incidence of a $\dot{V}O_2$-plateau to be high for a DCT should not be cited as evidence that a maximal $\dot{V}O_2$ is reached during progressive exercise.

10.2 Factors influencing the incidence of a $\dot{V}O_2$-plateau for a CT

10.2.1 *Ramp tests vs. incremental tests*

Ramp tests were used in Study 1, where the incidence of a $\dot{V}O_2$-plateau was ≤50%, and in Study 3, where the incidence was >90%. There were differences between these two studies but the factors that varied were the sampling techniques used, the way in which a plateau was defined, and, to a certain extent, the characteristics of the subjects. It would seem, therefore, that the incidence of a plateau is primarily determined by one or more of these factors. That is not to say that whether an incremental or a ramp test is used has no bearing on the incidence of a $\dot{V}O_2$-plateau. Indeed it is impossible to say whether this is the case because the procedures that were used in Study 3 have not been used to evaluate an incremental test. To ascertain whether the incidence of a $\dot{V}O_2$-plateau is in fact higher for a ramp than for an incremental test it would be necessary to use procedures such as these to evaluate both a ramp test and an incremental test.

Routine physiological testing of athletes could potentially play an important part in the prevention of the overtraining syndrome (Hooper and Mackinnon, 1995; Lehmann et al., 1993; Rowbottom et al., 1998). Studies of competitive cyclists (Jeukendrup et al., 1992; Snyder et al., 1995) have established that the peak values for WR, [Bla], and HR are all lower for a progressive cycle ergometer test performed after a period of short term overtraining (overreaching) than for a similar test performed after a period of normal training. In addition, Lehmann et al. (1991) found that the total distance covered in a progressive treadmill test decreased following a period of overreaching in runners.

In all of the above studies an incremental test was used. It could be argued, however, that it would have been preferable to use a ramp test. The important consideration here is that subjects tend to continue to the end of a stage rather than to the limit of tolerance when an incremental test is used (see section 7.4.2.2). In terms of routine physiological monitoring, the implication is that ramp tests should be used in preference to incremental tests because a more sensitive measure of peak WR can be obtained when a ramp test is used.

10.2.2 *Sampling period*

The rationale underpinning the choice of sampling procedures for Study 3 has already been presented (see section 9.1). No attempt was made to quantify the extent to which sampling procedures influence the incidence of a $\dot{V}O_2$-plateau in that study. However, the results of Study 1 indicate that the incidence of a $\dot{V}O_2$-plateau is sensitive to changes in the sampling period when a criterion $\Delta\dot{V}O_2$ is used to define a $\dot{V}O_2$-plateau (section 7.3.3). It would be of interest, for instance, to compare the incidence of a $\dot{V}O_2$-plateau for a test in which the sampling period is decreased from 60 to 30 s over the course of the test with that for a test in which the sampling period is maintained at 30 s throughout. However, this comparison would only be of interest if in both cases the data were modelled as described in section 9.2.6. It may be that when the data are modelled in this way the amount of variability that is present in the $\dot{V}O_2$ data for the early stages of the test is not an important determinant of whether a $\dot{V}O_2$-plateau is identified. At present it cannot be demonstrated that this is the case, and hence it is recommended that sampling procedures that allow the sampling period to decrease as exercise intensity increases are used whenever a CT is used for the assessment of $\dot{V}O_{2max}$. In addition, it is suggested that details of the sampling procedures should be included whenever data on $\dot{V}O_{2peak}$ are presented. At present this information is sometimes omitted, especially when on-line data are reported. However, breath-by-breath data are almost always averaged before $\dot{V}O_{2peak}$ is determined, and since the peak value obtained is likely to depend, at least to some extent, on the way in which this averaging is performed, details of the procedures involved should always be given.

10.2.3 *Approach taken to defining a $\dot{V}O_2$-plateau*

It is likely that one of the reasons why the incidence of a $\dot{V}O_2$-plateau was higher for Study 3 than for Study 1 was that the way in which a $\dot{V}O_2$-plateau was defined was different for the two studies. Whilst the approach adopted in Study 1 was considered to be the most defensible of the various procedures that had been adopted in previous studies, the novel approach adopted in Study 3 has several advantages.

One advantage is that inter-individual variation in the slope of the $\dot{V}O_2$-WR relationship has no influence on the definition of a $\dot{V}O_2$-plateau. This variation would affect the criterion $\Delta\dot{V}O_2$ for situations in which a confidence interval for $\Delta\dot{V}O_2$ is derived for a group of subjects (see section 7.4.3). In such situations, the incidence of a plateau might be artificially high for those individuals in whom the slope of the $\dot{V}O_2$-WR relationship is below average, and artificially low for those in whom this slope is above average. However, for the modelling approach adopted in Study 3, the slope of the $\dot{V}O_2$-WR relationship will have no bearing on whether the SEE is lower for the plateau than for the linear model in a particular indiviual.

A further advantage of this approach is that it allows for the sampling period to decrease as exercise intensity increases (see section 8.4.3). But what is most important is that it allows a statistical judgement to be made, for a particular group of subjects, as to whether the $\dot{V}O_2$-WR relationship is more likely to plateau or to continue to increase in the final minutes of a given test. This means that a given protocol can be evaluated in terms of its suitability for the assessment of $\dot{V}O_{2max}$ in a particular subject population. Previously, a statistical judgement has been made as to whether a $\dot{V}O_2$-plateau has occurred in a particular individual and a given protocol has been evaluated in terms of the incidence of such a plateau (see section 9.4.1). For Study 3, the conclusion is the same regardless of whether the tests are evaluated in terms of a statistical judgement for the group as a whole or in terms of the incidence of a $\dot{V}O_2$-plateau. However, in the former situation it is possible to fall back on a standard statistical criterion (e.g. an alpha level of 0.05), whereas in the latter it is necessary to make a judgement about whether the incidence of a plateau is sufficiently high.

The wider issue here is whether individual test performances should in fact be evaluated at all. Criteria defining a $\dot{V}O_2$-plateau are often given when guidelines for the assessment of $\dot{V}O_{2max}$ are issued (McConnell, 1988; Thoden, 1991; Bird and Davison, 1997), and the implication would appear to be that an individual's test results should be evaluated relative to these criteria. However, the important question of what should be done when these criteria are not met is rarely addressed. It has been suggested (Thoden, 1991) that the assessment of $\dot{V}O_{2max}$ should routinely be a 2 stage process, the 2 stages being a progressive CT and a square wave exercise bout at a WR above that which was reached in the CT. Thoden suggests that if $\dot{V}O_2$ increases by less than 2% between the progressive test and the square wave test $\dot{V}O_{2max}$ can be assumed to have been attained, but that if $\dot{V}O_2$ increases by more than 2% a further square wave bout should be performed at a higher WR, and so on, until a difference of less than 2% is observed. The results of Study 1 suggest, however, that the peak $\dot{V}O_2$ for a square wave run will often be lower than that for a CT, particularly when the duration of this square wave run is short. Thoden recommends a duration of 3-5 min for the square wave bout, but it is by no means certain that this is long enough for $\dot{V}O_{2max}$ to be attained in the majority of individuals (see figure 7.6).

Neither McConnell (1988) nor Bird and Davison (1997) give any recommendations for what should be done when the criteria are nor met. There would seem to be little point, however, in proposing criteria for the attainment of $\dot{V}O_{2max}$ that can be applied on an individual basis if in practice the way in which the data are interpreted is independent of whether or not these criteria are met. The problem is that it is difficult to know what should be done when the criteria are not met. For instance, if the primary criterion is a $\Delta\dot{V}O_2$ of <2 $ml.kg^{-1}min^{-1}$ and an individual completes a test for which the final $\Delta\dot{V}O_2$ is 3 $ml.kg^{-1}min^{-1}$, should they be told that their test results cannot be interpreted because it is uncertain that they attained $\dot{V}O_{2max}$ or should the data be interpreted as though a

$\dot{V}O_2$-plateau had been observed? It could be argued that the individual should be reassessed but in practice this may not be feasible. The alternative would be to accept that provided the protocol has been validated for use with the relevant population there is no need to scrutinise the data from individual tests. In terms of the modelling approach adopted in Study 3, validation would refer to demonstrating that, for a group of subjects drawn from the appropriate population, the $\dot{V}O_2$ data for a particular test can best be described by the plateau model. There may be individuals who consistently fail to demonstrate a $\dot{V}O_2$-plateau, and for these individuals there may be a need to investigate further to establish why this is the case. The decision to undertake such an investigation should not be made on the basis of data from a single test however.

10.2.4 *On-line vs. off-line data collection*

For each of the tests performed in Study 3, no respiratory data were determined for the final collection if the duration of this collection was <20 s (see section 9.2.5). It was necessary to define a lower limit for the period over which expirate would be collected in this study because the variability in $\dot{V}O_2$ increases as the sampling period decreases (table 8.2). The sampling period was ≥30 s for all collections other than the final one. However, it was necessary to control the length of the final collection because even though the $\dot{V}O_2$-WR typically reached a plateau the peak $\dot{V}O_2$ was frequently observed in the final collection interval. Were a very short sampling period to be used for the collection in which the peak $\dot{V}O_2$ was observed this peak $\dot{V}O_2$ would be a relatively unreliable estimate of $\dot{V}O_{2max}$.

It would appear that there is a conflict between the need to use a relatively short sampling period so that the density of data is high enough for a $\dot{V}O_2$-plateau to be identified even when it occurs very late in a CT and the need to use a relatively long sampling period so that a sufficiently reliable estimate of $\dot{V}O_{2max}$ is obtained (see section 9.4.2). This problem could possibly be overcome by using a short sampling period (e.g. 20 s) and calculating a rolling average over two sampling periods prior to determining the peak $\dot{V}O_2$. However, were such an approach to be adopted, data from the final collection would still have to be discarded whenever the duration of this collection was <20 s. The worst case scenario would be that $\dot{V}O_2$ was not determined over the final 19 s of the test. One possible consequence would be that $\dot{V}O_{2max}$ would be underestimated. The other would be that a $\dot{V}O_2$-plateau that occurred in the last 20-30 s of a CT would go undetected.

The above problem cannot be overcome when the Douglas bag method is used. However, when $\dot{V}O_2$ is determined on a breath-by-breath basis it is possible to select a sampling (averaging) period and work back from the end of the test. This means that $\dot{V}O_2$ can be averaged over the pre-determined sampling period in such a way that the end of the final period will always coincide with the end of the test (section 3.2.4). It would seem, therefore, that on-line (breath-by-breath) data collection might be preferable to off-line (Douglas bag) collection for the assessment of $\dot{V}O_{2max}$. For a given sampling period, the variability in $\dot{V}O_2$ is similar for on-line and off-line data (section 8.4.1). However, it should be stressed that on-line systems must be carefully calibrated. Special calibration devices have occasionally been used (Gore et al., 1997; Huszczuk et al., 1990), but typically these systems are calibrated against a Douglas bag system. This means that a Douglas bag system that allows $\dot{V}O_2$ to be determined with a high degree of accuracy and precision is an essential requirement for many laboratories. The issues that need to be considered before such a system can be developed were discussed in Chapter 5.

10.2.5 *Subject characteristics*

The incidence of a $\dot{V}O_2$-plateau was >90% $\dot{V}O_{2max}$ for each of the tests used in Study 3. The implication is that the vast majority of individuals are able to attain a maximal $\dot{V}O_2$ in a ramp test, even when the test is completed on a level treadmill. However, the possibility remains that had the same 3 tests been completed by a different group of subjects different results would have been obtained.

The subjects for Study 3 were all trained runners. Seven were classified as distance runners, but each of these included some high speed running in their training programme (as did the 2 triathletes), and 4 of them competed in both middle-distance and distance races. It is likely therefore that each of the runners studied would have been relatively skilled at running fast. It is also likely that there would have been a reasonable balance between aerobic and anaerobic capabilities in most of these runners. Were a group of specialist marathon or ultra-marathon runners to be tested the situation would be somewhat different. These runners would probably include little, if any, high speed running in their training. It is also likely that, relative to their anaerobic capabilities, these runners would have markedly superior aerobic capabilities.

The aerobic capabilities of these runners would presumably be such that they would be able to run at relatively fast speeds without attaining $\dot{V}O_{2max}$. However, they might lack the skill required to run at such fast speeds, and hence they might not reach the speeds that theoretically they should be able to reach were they to perform a CGIS on a level treadmill. The consequence would be that the incidence of a $\dot{V}O_2$-plateau would be low (relative to that for Study 3), as would the peak $\dot{V}O_2$ (relative to that for uphill running). In fact, the incidence of a $\dot{V}O_2$-plateau might be low even for a CSIG test in this group of runners because of their limited anaerobic capabilities. There is a need for the protocols evaluated in Study 3 to be evaluated in a similar way for a variety of populations.

10.3 Problems with CSIG tests

The results of Study 3 suggest that a ramp test is valid for the assessment of $\dot{V}O_{2max}$, provided it is a CGIS test. The problem with the IGT was that the $\dot{V}O_2$-treadmill grade relationship was non-linear (table 9.4). There is no obvious explanation for this (see section 9.4.4), but the implication is clear. It is that the incidence of a $\dot{V}O_2$-plateau may have been overestimated in those studies in which a CSIG test was used and a confidence interval for $\Delta\dot{V}O_2$ was derived from sub maximal grades.

A further problem with CSIG tests is that it is difficult to derive a simple measure of performance for such a test. Typically the speed at which a CSIG test is conducted is varied in proportion to the capabilities of the subject so that the test duration is consistent across subjects. This means that performance has to be described in terms of a grade and a speed, and it is difficult, therefore, to quantify inter-individual differences in performance for such a test. For instance, if one subject reached a grade of 10% at a speed of 14 $km.h^{-1}$ and another reached a grade of 9% at a speed of 15 $km.h^{-1}$ it would be difficult to decide which one had produced the better performance. The same considerations would apply to changes in performance that might occur longitudinally within an individual. Test duration is known to influence $\dot{V}O_{2peak}$ for a CT (Buchfuhrer et al., 1983), so the starting speed would need to be altered were the individual's capabilities to change markedly in response to a period of training or detraining. As a result, it might be hard to determine exactly how performance had changed.

This is an important point because a measure of performance for a progressive CT might be a useful marker of the onset of an overreached state (see section 10.2.1). The obvious solution would be to use a CGIS test instead. The results of Study 3 suggest, however, that the context in which the results of the test will be applied should be kept in mind when a decision is made about the grade at which a CGIS test should be conducted.

10.4 Implications for the concept of a maximal $\dot{V}O_2$

Study 3 showed that provided appropriate procedures are adopted a $\dot{V}O_2$-plateau can be identified in >90% of subjects for a CGIS or a CSIG test. This finding is important because it suggests that an upper limit for $\dot{V}O_2$ is typically reached in a progressive exercise test. The finding that a $\dot{V}O_2$-plateau was identified in >90% of subjects for both of the CGIS tests is of particular significance because it is consistent with Hill and Lupton's original concept of a maximal $\dot{V}O_2$. These investigators focused on running, suggesting that the $\dot{V}O_2$-running speed relationship would plateau at high speeds (see section 2.3). However, Hill et al. (1924b) were unable to demonstrate that such a plateau actually occurs (see section 2.3), and subsequent attempts by other groups have also failed. Indeed, other than Study 3, no study which has employed objective criteria to define a $\dot{V}O_2$-plateau has found the incidence of such a plateau to be >50% for a CGIS CT (see section 4.3.2).

In Study 3, a plateau in the $\dot{V}O_2$-running speed relationship occurred in >90% of individuals for the CGIS test, regardless of whether this test was completed on a level treadmill or at a 5% grade. However, the level at which $\dot{V}O_2$ plateaued was dependent on the conditions under which the test was conducted. It is essential, therefore, that any model that purports to be able to explain how $\dot{V}O_{2max}$ is attained incorporates the notion that $\dot{V}O_{2max}$ is only fixed for a given set of conditions.

Wagner and colleagues (Hogan et al., 1989; Roca et al., 1989; Wagner, 1992, 1995, 1996) have modelled $\dot{V}O_2$ as a function of (convective) O_2 delivery and (diffusive) O_2 conductance. A recurring theme throughout this work is that all of the diffusive and conductive steps in the O_2 transport pathway between the environment and the mitochondria interact to determine the rate at which O_2 is supplied to the mitochondria, and thus $\dot{V}O_{2max}$. The implication is that a given value for $\dot{V}O_{2max}$ will only be applicable to a given set of conditions. Indeed, as Wagner (1996, p. 25) notes, "plateauing of $\dot{V}O_2$ will occur at different absolute values of $\dot{V}O_2$ as O_2 supply is acutely manipulated."

Honig et al. (1992) reached a similar conclusion. They adopted a systems perspective, emphasising (p. 52) that $\dot{V}O_{2max}$ is a distributed property that depends "not only on individual parameters ... but also on the interaction of parameters as a system." Importantly, they argued (p. 51) that because it is determined by the characteristics of this system, $\dot{V}O_{2max}$ "does not have a unique value, not even for a particular muscle."

Wagner (1996) has shown how the model he describes can be useful in explaining why $\dot{V}O_2$ reaches an upper limit at a particular value in a given individual. The example he uses is that of a patient with chronic obstructive pulmonary disease. These patients, it appears, have $\dot{V}O_{2max}$ values which are lower than they would have were their muscle O_2 conductance similar to that of untrained healthy individuals. Wagner's analysis suggests that even a lung transplant that restored convective O_2 supply into the muscle circulation to normal would have a relatively minor impact on $\dot{V}O_{2max}$ as long as muscle O_2 conductance remained unchanged. It was suggested (Wagner, 1996) that these patients might benefit from training to induce muscle capillary growth.

A similar analysis could potentially be applied to data from an individual athlete were appropriate data available. This would necessitate the measurement of variables other than those respiratory variables ($\dot{V}O_2$, $\dot{V}_E$, RER) that are typically recorded when $\dot{V}O_{2max}$ is assessed in an athlete (McConnell, 1988; Thoden, 1991; Bird and Davison, 1997). For instance, in addition to [Hb], Wagner's model requires data on blood flow, arterial and venous O_2 saturation, and venous PO_2 for the muscles for which O_2 conductance is to be evaluated. Unless measures of this type are taken, it will always be impossible to identify those factors that, provided they could be altered by training, would exert the greatest influence on $\dot{V}O_{2max}$ for a particular individual. Indeed, it is important to recognise that when $\dot{V}O_{2max}$ is assessed and measures such as these are not taken, all that is available is "a fairly crude measure of whole-body activity which cannot guide us (exercise physiologists) towards the development of scientifically-based athlete-specific training programmes" (Bird and Davison, 1997, p.62).

It should be noted that whilst the model presented by Wagner (1996) assumes that $\dot{V}O_2$ plateaus because an upper limit for O_2 supply is reached, he does not present an explanation for how this might happen. Theoretically, a plateau in $\dot{V}O_{2legs}$ could be the result of: 1) a plateau in $\dot{Q}_{legs}$ which is not compensated by an increase in the a-v O_2 difference; 2) a decrease in the a-v O_2 difference that is sufficiently large to cause $\dot{V}O_2$ to plateau even when $\dot{Q}_{legs}$ continues to increase; or 3) a combination of the two.

Knight et al. (1992) studied (two-legged) cycle ergometer exercise and found that the relationship between $\dot{V}O_{2legs}$ and WR plateaued at high WRs because both $\dot{Q}_{legs}$ and the a-v O_2 difference plateaued. However, they studied only subjects in whom a plateau in whole body $\dot{V}O_2$ was consistently observed. Stringer et al. (1997) also studied cycle ergometer exercise. They didn't measure $\dot{Q}_{legs}$ but they did determine $\dot{Q}_C$ and the a-$\bar{v}$ O_2 difference. Their data show that $\dot{Q}_C$ plateaued in the closing stages of a progressive (ramp) test. Oxygen uptake did not plateau along with $\dot{Q}_C$, however, because a large increase in the a-v O_2 difference occurred after $\dot{Q}_C$ had plateaued. One study (Mitchell et al., 1958) has demonstrated that $\dot{Q}_C$ plateaus in the closing stages of a progressive treadmill test. However, the $\dot{V}O_2$ data presented by Mitchell et al. suggest that there may have been a problem with the way in which the WR was incremented in this study (see section 3.2.1).

There is a need for more studies investigating how $\dot{Q}_C$, $\dot{V}O_{2legs}$, and the a-v O_2 difference vary as a function of WR in the final minutes of a progressive test. The data of Knight et al. (1992) suggest that these variables do vary in a predictable way in the final minutes of a cycle ergometer test for those subjects in whom a $\dot{V}O_2$-plateau is observed. However, these data need to be substantiated, and there is a need to establish whether the situation is the same for other modes of exercise such as treadmill running. In addition, there is a need to investigate how $\dot{Q}_C$, $\dot{V}O_{2legs}$, and the a-v O_2 difference vary as a function of WR in the final minutes of a progressive test for those subjects in whom a plateau in $\dot{V}O_2$ is rarely observed. It is possible, for instance, that $\dot{V}O_{2legs}$ does plateau in these subjects but that the rate of O_2 uptake by the respiratory muscles is such that this plateau is not reflected in the whole body $\dot{V}O_2$. Respiratory muscle $\dot{V}O_2$ increases as a positive non-linear function of WR for WRs close to that at which $\dot{V}O_{2peak}$ is attained (Aaron et al., 1992a, b). Whole body $\dot{V}O_2$, which during severe exercise reflects primarily the $\dot{V}O_2$ of the respiratory muscles and that of the legs, might therefore continue to increase as a linear function of WR even if $\dot{V}O_{2legs}$ plateaus.

10.5 Implications for the assessment of $\dot{V}O_{2max}$

Published guidelines for the assessment of $\dot{V}O_{2max}$ (McConnell, 1988; Thoden, 1991; Bird and Davison, 1997) consistently recommend that a CSIG test is used. There are however several problems with this type of test (see sections 9.4.3, 9.4.4,and 10.3), and in light of these it could be argued that CSIG tests should not be used for the assessment of $\dot{V}O_{2max}$. In contrast, the results of Study 3 suggest that a CGIS ramp test is valid for the assessment of $\dot{V}O_{2max}$. One advantage of this type of test is that performance can easily be quantified in terms of the peak speed reached (provided the grade at which the test is performed is controlled). Furthermore, it may be possible, by systematically varying the grade at which the test is performed, to identify strengths and weaknesses for a particular individual.

An important point that emerged from Study 3 is that $\dot{V}O_{2max}$ is highly specific to the conditions under which it is assessed. The implication is that runners should be tested under conditions which are similar to those that they will encounter in competition. For the subjects in Study 3, the peak speed reached in the 0%T (averaged over the final minute of the test) was equivalent to 800 m race pace for the group as a whole. However, this peak speed was close to 400 m pace in some subjects and close to 1500 m pace in others. It could be argued, therefore, that when a CGIS test is used to assess $\dot{V}O_{2max}$ in a runner who primarily competes over ≤1500 m the test should be performed on a level treadmill.

The peak speed for the 5%T was typically just above 5000 m race pace, so it could be argued that whenever a runner who competes over ≥5000 m is assessed the treadmill grade should be set at 5%. However, the $\dot{V}O_{2max}$ figure derived from such a test would presumably be above that which could be attained during level running (see section 9.4.3). For distance runners (i.e. those who compete over distances of ≥5000 m), there appears to be a conflict between the need to ensure that the peak speed reached in the test is not too far above that which will be encountered in competition and the need to derive a value for $\dot{V}O_{2max}$ that is applicable to level running. A reasonable compromise might be to test all distance runners at a 5% grade. Although the peak speed reached in such a test would typically be 2-3 $km.h^{-1}$ above marathon race pace, most marathon runners also compete over 10 km, and this peak speed would only be ~1 $km.h^{-1}$ above 10 km race pace. For the subjects in Study 3, the mean difference in $\dot{V}O_{2max}$ between the 5%T and the 0%T was 1.3 $ml.kg^{-1}.min^{-1}$ (2.2%), so the extent to which the $\dot{V}O_{2max}$ for level running would be overestimated in a typical distance runner would in fact be small. It might seem as though it should be possible to correct the $\dot{V}O_{2max}$ of a distance runner to make it applicable to level running by subtracting 1.3 $ml.kg^{-1}.min^{-1}$ from the actual value. However, it should be pointed out that the difference in $\dot{V}O_{2max}$ between the 5%T and the 0%T ranged from -1.4 to +3.6 $ml.kg^{-1}.min^{-1}$.

It might be possible to identify those individuals who lack the skill required to run at fast speeds by comparing their responses for two different CGIS tests. For such an individual, it might be expected that a $\dot{V}O_2$-plateau would be observed in a CGIS test when this test is completed at a moderate grade but not when it is completed on a level treadmill. It might also be the case that the difference in peak speed between the two tests would be relatively small in such an individual. Once such an individual had been identified, they could be advised to focus on distance running, or they could be encouraged to incorporate more skills training into their training programme. There might even be some mileage in conducting an assessment of their running mechanics. Thus it might be possible to identify particular aspects of their technique that should be targeted in training.

10.6 Implications for models of running performance

The finding (section 9.3.1) that the $\dot{V}O_2$-running speed relationship typically plateaus in the final minutes of a CGIS test suggests that one of the major assumptions on which contemporary models of running performance are based is valid. However, the finding (section 7.3.2.3) that $\dot{V}O_2$ plateaued below $\dot{V}O_{2max}$ in the DCT has potentially important implications for contemporary models of middle-distance running performance. These models (di Prampero, 1986; di Prampero et al., 1993; Péronnet and

Thibault, 1989) consider the determinants of performance to be $\dot{V}O_{2max}$, the rate at which $\dot{V}O_2$ increases towards $\dot{V}O_{2max}$ at the onset of exercise, the O_2 cost of running, and the O_2 equivalent of the anaerobic capacity. They do not acknowledge the possibility (section 10.1) that $\dot{V}O_2$ might plateau below $\dot{V}O_{2max}$ in a middle-distance race. Nor do they allow for any interaction between aerobic and anaerobic capabilities.

The data of Spencer et al. (1996) suggest that whilst $\dot{V}O_2$ is likely to plateau below $\dot{V}O_{2max}$ in a middle-distance race, the % $\dot{V}O_{2max}$ at which this plateau occurs is likely to vary with race distance. These data also raise the possibility that, for a given race distance, the % $\dot{V}O_{2max}$ at which this plateau occurs may vary between individuals. It is possible, therefore, that the % $\dot{V}O_{2max}$ that can be reached in a particular race might be an important determinant of performance in that race, and it is reasonable to expect this factor to be incorporated into any physiological model that attempts to explain performance in middle-distance running.

It would be difficult to quantify the extent to which anaerobic metabolism influences aerobic metabolism, and hence it would be difficult to account for this influence in a quantitative model similar to that which has been presented previously (di Prampero, 1986; di Prampero et al., 1993; Péronnet and Thibault, 1989). It is possible, however, that both the % $\dot{V}O_{2max}$ that can be reached in a particular race and the rate at which $\dot{V}O_2$ increases at the start of this race might increase in proportion to the anaerobic capabilities of the subject (see section 10.1). It is essential that physiologists acknowledge this possibility. Moreover, it is essential that an attempt is made to gain a better understanding of the way in which anaerobic metabolism might influence aerobic metabolism. Gaining such an understanding is a necessary first step towards establishing exactly how physiological factors determine performance in middle-distance running.

10.7 Recommendations for further research

At present, relatively little is known about the $\dot{V}O_2$ response to exercise at supra-$\dot{V}O_{2peak}$ intensities. In particular, little is known about the $\dot{V}O_2$ response to square wave running for these intensities. On the one hand, there is a need to characterise, for various groups, the $\dot{V}O_2$ response for square wave treadmill runs of varying intensity. But on the other, there is a need to establish whether the $\dot{V}O_2$ response is the same for overground (track) and treadmill running for the intensities typically encountered in middle-distance races. The available data suggest that $\dot{V}O_2$ typically plateaus below $\dot{V}O_{2max}$ when an 800 or a 1500 m runner completes a square wave treadmill run at race pace. It was assumed in section 10.6 that the $\dot{V}O_2$ response would be similar for an equivalent overground run, but this is an assumption that has never been tested.

There is a need for research aimed at elucidating the mechanisms whereby aerobic and anaerobic metabolism are integrated. Interaction between aerobic and anaerobic metabolism is likely to be important in determining the time course of the $\dot{V}O_2$ response in the early stages of intense exercise (Greenhaff and Timmons, 1998), and the time course of this response is likely to be an important determinant of middle-distance running performance, especially for the shorter events. It is important, therefore, that the mechanisms controlling this interaction are well understood.

Further research is also required to evaluate the effect of sampling procedures, subject characteristics, and test protocol on the peak $\dot{V}O_2$ and the incidence of a plateau for a CGIS CT. The modelling approach used in Study 3 could be very useful in this regard. This approach could be used to compare the incidence of a $\dot{V}O_2$-plateau for: 1) a ramp and an incremental test; 2) a test in which sampling period decreases as exercise intensity increases and one in which it remains constant throughout; 3) a test in which $\dot{V}O_2$ is determined breath-by-breath and one in which the Douglas bag method is used; 4) a test which is completed on a level treadmill and one which is completed at a moderate grade; and 5) two or more groups of subjects who differ in terms of a particular characteristic.

Finally, further research is required to determine how $\dot{Q}_C$, $\dot{Q}_{legs}$, the a-v O_2 difference, and $\dot{V}O_{2legs}$ vary in relation to WR for the final minutes of a progressive test. These measurements have been made during progressive cycle ergometer exercise (Knight et al., 1992), but not during treadmill running. Cannularisation of the femoral artery and vein would certainly be more difficult for treadmill exercise. However, were this to be possible, the data collected would potentially be very useful. Were such data available, it might be possible to establish exactly why $\dot{V}O_2$ plateaus in some individuals but not in others. Moreover, it might be possible to establish, for a given individual, which factor $\dot{V}O_{2max}$ is likely to be most sensitive to. Whilst some of these factors might be relatively untrainable, others might respond well, provided the right type of training is selected.

CHAPTER 11: SUMMARY AND CONCLUSIONS

11.1 Summary

The findings presented in the preceding chapters have important implications, both for the concept of a maximal $\dot{V}O_2$ and for the assessment of $\dot{V}O_{2max}$. The important findings have already been discussed, and the purpose of this section is not to repeat this discussion. Rather it is to provide a brief summary of these findings and to place them within the context of the aims of the thesis, which were outlined in Chapter 1. There were 4 aims, and each of them has been achieved, as the findings summarised in the next four paragraphs show.

First, the peak $\dot{V}O_2$ was found to be higher for a CGIS ramp test conducted at a 5% grade than for a DCT conducted at the same grade (table 7.4). The incidence of a $\dot{V}O_2$-plateau for this DCT was comparable to that which has been reported previously for such a test [>80% (Krahenbuhl and Pangrazi, 1983; Krahenbuhl et al., 1979; Rivera-Brown et al., 1994; Taylor et al., 1955)], so it seems reasonable to conclude that the plateau that occurs in a DCT is indeed an artefact of the test protocol. It seems likely, however, that $\dot{V}O_2$ actually reached a plateau below $\dot{V}O_{2max}$ in the final stage of the DCT, and if it did then Noakes' theoretical argument for why a plateau that occurs in a DCT might be an artefact of the test protocol (section 4.4.1) must be incorrect.

Second, the factors that appear to exert the greatest influence on the incidence of a $\dot{V}O_2$-plateau for a progressive test have been identified (section 10.2). Whether the test is continuous or discontinuous is one factor that is likely to influence the incidence of a plateau (see section 7.3.2.3). However, since the plateau that occurs in a DCT is likely to be an artefact of the test protocol, it is only worth considering those factors that influence the incidence of a $\dot{V}O_2$-plateau for a CT. Of these, the most important factors appear to be the sampling procedures adopted and the way in which a $\dot{V}O_2$-plateau is defined. It appears that a relatively short sampling period should be used for intensities close to that at which $\dot{V}O_{2peak}$ is attained, but that the sampling period should be relatively long for the lower intensities. It also appears that a modelling approach that allows individual differences in the slope of the $\dot{V}O_2$-running speed relationship to be accounted for and uses data from the majority of the test is preferable. Other factors that may influence the incidence of a $\dot{V}O_2$-plateau are the test type (the incidence of a plateau is likely to be higher for a ramp test), whether data are collected on- or off-line (theoretically, on-line data would be preferable), and the characteristics of the subjects (see section 10.5.5 for discussion).

Third, it was found that provided appropriate procedures were adopted a plateau could be identified in >90% of subjects for a CGIS test, regardless of whether the test was completed on a level treadmill or with the grade set at 5% (table 9.2). The value at which $\dot{V}O_2$ plateaued was higher for the 5% test, whereas the peak [Bla] did not differ between the tests. The peak RER was higher for the 5% test, but overall the differences in RER were difficult to interpret (see section 9.4.3). The important point that emerged was that $\dot{V}O_{2max}$ is highly specific to the conditions under which it is assessed.

Fourth, a continuous CGIS protocol was developed for which the incidence of a $\dot{V}O_2$-plateau was comparable to that which has been reported previously for a CSIG DCT (i.e. >80%). In fact, a plateau in the $\dot{V}O_2$-running speed relationship was observed for >90% of subjects in both of the CGIS tests evaluated in Study 3. It would seem, therefore, that one of the major assumptions on which contemporary models of running performance are based is valid. It should be emphasised though that different results might be attained in specialist distance or ultra-distance runners, or in runners who are more elite than those who were assessed in Study 3. It should also be stressed that contemporary models of running performance have not been shown to be valid in all respects. For example, models of middle-distance running performance may need revising to take account of the possibility that $\dot{V}O_2$ might plateau below $\dot{V}O_{2max}$ in a middle-distance race (see section 10.6).

11.2 Conclusions

Several conclusions can be drawn from the data presented in this thesis. For instance, it can be concluded that discontinuous tests are inappropriate for the assessment of $\dot{V}O_{2max}$, as are approaches in which a $\dot{V}O_2$-plateau is defined in terms of a criterion $\Delta\dot{V}O_2$ or treadmill tests in which the grade is increased while the speed is held constant. However, the most important conclusion is that $\dot{V}O_2$ is more likely to plateau than to continue to increase in the final minutes of a CGIS ramp test. This conclusion must be somewhat tentative because as yet this has only been shown to be the case for the runners that were assessed in Study 3. It should be emphasised however that the procedures that were outlined in section 9.2.6 could be used to determine whether $\dot{V}O_2$ is more likely to plateau or to continue to increase in the final minutes of a CGIS test for any group of subjects. Indeed, were similar procedures to be adopted for groups of subjects that differed in a particular characteristic, it would be possible to evaluate the importance of this characteristic in determining whether or not $\dot{V}O_2$ plateaus.

For the runners assessed in Study 3, $\dot{V}O_2$ typically plateaued in both the 0%T and the 5%T, but the value at which this plateau occurred was higher for the 5%T. The conclusion would be that $\dot{V}O_{2max}$ for running is specific to the conditions under which it is assessed. This has important implications for the assessment of $\dot{V}O_{2max}$ (see section 10.5). Indeed, it suggests that a runner's $\dot{V}O_{2max}$ should be assessed under conditions which are as close as possible to those that will be encountered in competition. However, there may be individuals or groups who are unable to demonstrate a plateau in $\dot{V}O_2$ for a CGIS when the test is completed on a level treadmill. Were procedures similar to those outlined in section 9.2.6 to be adopted for tests conducted at different grades, it would be possible to evaluate the importance of treadmill grade as a determinant of whether $\dot{V}O_2$ plateaus. Variation, either between individuals or between groups, in the way in which treadmill grade influences both $\dot{V}O_{2peak}$ and the incidence of a $\dot{V}O_2$-plateau may be of particular interest (see section 10.5).

Many questions have been left unanswered (see section 10.7). However, were the modelling approach that was used in Study 3 to be adopted, it would be possible to make an objective judgement, for a given test protocol and a given subject population, about whether a $\dot{V}O_2$-plateau has occurred. The finding that the incidence of a plateau was >90% for a CGIS test even when the test was completed on a level treadmill is testimony to the potential of this approach.

PART VI

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PART VII

APPENDICES

APPENDIX 1: ABSTRACTS OF CONFERENCE PAPERS RELATED TO THE THESIS

1) THE EFFECT OF TEST PROTOCOL ON $\dot{V}O_{2peak}$ AND THE INCIDENCE OF A $\dot{V}O_2$-PLATEAU

Steve Draper, Dan Wood, and Joanne Fallowfield

(paper presented at the annual conference of the British Association of Sport and Exercise Sciences, Worcester, UK, September 1998).

The most accepted criteria for the achievement of $\dot{V}O_{2max}$ is a plateau in $\dot{V}O_2$ with increasing work rate. Unlike earlier discontinuous protocols (Taylor *et al.*, 1955, *Journal of Applied Physiology*, **8**, 73-80), the ramp tests that are now commonly used for the assessment of $\dot{V}O_{2max}$ often fail to produce a $\dot{V}O_2$-plateau (Noakes, 1997, *Medicine and Science in Sports and Exercise*, **29**, 571-590). It is possible therefore that a true $\dot{V}O_{2max}$ is not achieved with these ramp protocols. This study examined the influence of test protocol on $\dot{V}O_{2peak}$ and the incidence of a $\dot{V}O_2$-plateau in treadmill exercise.

Ten male subjects (mean ± SD: age 26.8 ± 8.6 yrs; height 1.76 ± 0.06 m; mass 76.7 ± 12.4 kg) initially completed a progressive incremental test to establish a relationship between $\dot{V}O_2$ and running speed, and a speed ramped $\dot{V}O_{2max}$ test. Both tests were performed on a 5% gradient, and the data obtained were used to calculate the running speeds equivalent (on a 5% gradient) to $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$) and 105 %$\dot{V}O_{2max}$ (v105%). Subjects completed the following 6 protocols: 1) a discontinuous protocol using 3 min stages (each stage was run on a separate day); 2) a continuous version of this protocol using identical 3 min stages; 3) a speed ramped protocol (1.2 km.h^{-1} per min); 4) a speed ramped protocol using 30 sec expired gas collections; 5) a speed ramped protocol run on a zero gradient; and 6) a constant speed run (to exhaustion) at v105%. For both 3 min incremental tests, the initial speed was 2.4 km.h^{-1} below v$\dot{V}O_{2max}$, and speed was increased by 1.2 km.h^{-1} for each stage until the subject could no longer complete 3 min at the required speed. For both incremental tests, expired gases were collected (Douglas bag method) in the final min of each 3 min stage, and for all other tests expirate was collected continuously. Unless otherwise stated, each gas collection lasted 60 sec and each protocol was

performed with the treadmill at a 5% gradient. The order in which subjects completed the protocols was randomised.

Mean $\dot{V}O_{2peak}$ values and the incidence of a $\dot{V}O_2$-plateau for each protocol are contained in Table 1. The approach of Taylor *et al.* (1955) was used to develop criteria for the occurrence of a $\dot{V}O_2$-plateau; separate criteria were determined for each protocol.

Table 1. $\dot{V}O_{2peak}$ values (mean ± SD) and the incidence of a $\dot{V}O_2$-plateau for the six protocols.

Protocol	$\dot{V}O_{2peak}$ ($ml.kg^{-1}.min^{-1}$)	Incidence of a $\dot{V}O_2$-plateau (%)
Speed ramped	59.9 ± 7.9	50
Speed ramped (30 sec collections)	59.4 ± 7.2	20
3 min continuous	58.5 ± 8.9*	40
Constant speed at v105%	58.1 ± 6.8*	n/a
Speed ramped at zero gradient	57.8 ± 7.9*	20
3 min discontinuous	57.7 ± 8.1*	80

*$P < 0.1$ vs. speed ramped protocol.

These results show that $\dot{V}O_{2peak}$ is dependent on test protocol. The discontinuous test produced the highest incidence of a $\dot{V}O_2$-plateau yet a significantly lower $\dot{V}O_{2peak}$ than the speed ramped test, bringing into question the validity of using the criteria of Taylor *et al.* (1955) to determine if a true $\dot{V}O_{2max}$ has been achieved.

2) VARIABILITY IN $\dot{V}O_2$ DECREASES AS EXERCISE INTENSITY INCREASES: IMPLICATIONS FOR THE IDENTIFICATION OF A $\dot{V}O_2$-PLATEAU

Dan Wood, Steve Myers, and Joanne Fallowfield

(paper presented at the Third Annual Congress of the European College of Sports Science, Manchester, UK, July 1998).

The notion of a plateau in oxygen uptake ($\dot{V}O_2$) with increasing work rate is fundamental to the $\dot{V}O_{2max}$ concept (Noakes, 1988). However, to demonstrate the presence of a $\dot{V}O_2$-plateau it is first necessary to set criteria defining such a plateau. Taylor et al. (1955) were the first to develop such criteria and the approach taken by these authors is now adopted by many researchers. Taylor et al. used a progressive treadmill protocol in which the speed remained constant while the treadmill gradient increased in increments of 2.5% and, having determined the lower 95% confidence limit for the delta $\dot{V}O_2$ between two consecutive sub-maximal gradients to be 2.1 $ml.kg^{-1}.min^{-1}$, defined a $\dot{V}O_2$-plateau as an increase of less than 2.1 $ml.kg^{-1}.min^{-1}$ between two consecutive gradients. The assumptions inherent in this approach are that the mean delta-$\dot{V}O_2$ and the confidence limits of this delta-$\dot{V}O_2$ are independent of exercise intensity (until $\dot{V}O_2$ reaches a plateau at $\dot{V}O_{2max}$). The mean delta-$\dot{V}O_2$ will be independent of exercise intensity as long as the $\dot{V}O_2$-work rate relationship is linear, and it has been demonstrated for cycle ergometer exercise that this relationship is linear as long as the work rate is increased at an appropriate rate (Hansen et al., 1988). However, the effect of exercise intensity on the confidence limits of delta-$\dot{V}O_2$ is not known. These limits will partly reflect the random variation in the measured delta-$\dot{V}O_2$ about the true delta-$\dot{V}O_2$, and the effect of exercise intensity on this variation has not been studied.

To investigate the effect of exercise intensity on the variability in $\dot{V}O_2$, six active male subjects (mean ± SD: age 27.5 ± 3.5 yrs; height 1.81 ± 0.09 m; body mass 72.4 ± 10.5 kg; $\dot{V}O_{2max}$ 64.5 ± 5.0 $ml.kg^{-1}.min^{-1}$) initially completed a progressive incremental test to determine the relationship between running speed and $\dot{V}O_2$, and a ramp test to determine $\dot{V}O_{2max}$ during uphill treadmill running. Subjects then completed two 13 min treadmill runs, a low intensity run at a speed equivalent to 70 % $\dot{V}O_{2max}$, and a high intensity run at the highest speed that could be sustained for 13 min (~96 % $\dot{V}O_{2max}$ - estimated from the results of the incremental test). These runs were completed on separate days in a counterbalanced design, and for each run twelve 30s Douglas bag collections of expired gases were taken between 6 and 13 min. There was a tendency for $\dot{V}O_2$ to increase throughout this 7 min period, particularly for the high intensity run, so before variability was assessed the data were corrected (using linear regression) to ensure that the only variation in $\dot{V}O_2$ among the 12 collections was random variation. From these corrected data, the mean $\dot{V}O_2$ and the standard deviation around this mean $\dot{V}O_2$ (for the 12 gas collections) were calculated for each subject and for each run. This standard deviation was used as the index of the variability in $\dot{V}O_2$.

Table 1. Mean and SD of twelve 30s gas collections for runs at ~70 and ~96 % $\dot{V}O_{2max}$ (n = 6).

Exercise intensity	Mean of 12 collections (% $\dot{V}O_{2max}$)	SD of 12 collections ($ml.kg^{-1}.min^{-1}$)
low	69.6 ± 2.1	1.05 ± 0.18
high	95.6 ± 2.8	0.57 ± 0.25*

*$p<0.01$ vs. low intensity run; data are mean ± SD.

The variability in $\dot{V}O_2$ decreased when the exercise intensity increased from ~70 to ~96 % $\dot{V}O_{2max}$ (Table 1). It cannot therefore be assumed that the confidence limits of delta-$\dot{V}O_2$ will be independent of exercise intensity. Confidence limits for delta-$\dot{V}O_2$ obtained from sub-maximal intensities will overestimate those that would be obtained at higher intensities. Thus the use of sub-maximal intensities to determine these confidence limits will artificially reduce the chance of detecting a $\dot{V}O_2$-plateau if a true plateau is present.

On the basis of these results, it is suggested that the approach of Taylor et al. (1955) to the determination of criteria for the identification of a $\dot{V}O_2$-plateau should not be adopted, and that alternative approaches should be investigated.

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3) COMPARISON OF THREE PROTOCOLS FOR THE ASSESSMENT OF MAXIMAL OXYGEN UPTAKE IN RUNNERS

Steve Draper, Dan Wood, and Joanne Fallowfield

(paper presented at the Third Annual Congress of the European College of Sports Science, Manchester, UK, July 1998).

The physiological assessment of middle-distance and distance runners typically includes a progressive test on a motorised treadmill for the determination of maximal oxygen uptake ($\dot{V}O_{2max}$). For such tests, exercise intensity may be increased by increasing treadmill speed, increasing treadmill gradient, or a combination of the two. Saltin and Astrand (1967) observed that subjects attained a higher peak $\dot{V}O_2$ on an ascending gradient (constant speed) protocol than on an increasing speed (zero gradient) protocol. A suggested explanation for this finding is that when gradient is maintained at zero, subjects are limited by the ability to reach a high cadence and are therefore unable to reach a true $\dot{V}O_{2max}$ (Noakes, 1997). As a consequence, it has been recommended that protocols where speed is held constant and the treadmill gradient is continuously increased are employed for the assessment of $\dot{V}O_{2max}$ in distance runners (McConnell, 1988). However, there are problems associated with the use of this type of protocol as different speeds must be used for runners of different ability to ensure that test duration is similar for all subjects. This means that a simple measure of performance (in terms of peak running speed) cannot be obtained, and it is difficult to apply standard criteria for the detection of a $\dot{V}O_2$-plateau (Taylor et al., 1955). It may be possible to overcome the problems associated with an increasing speed (zero gradient) protocol and those associated with an ascending gradient (constant speed) protocol by using a protocol where a moderate gradient is maintained throughout the test and speed is continuously increased.

Twelve male middle-distance and distance runners (mean ± SD: age 28.1 ± 5.1 yrs; height 1.79 ± 0.08 m; mass 70.9 ± 7.9 kg) completed a speed ramped protocol (1.2 km.h^{-1} per min) at 0% gradient, a gradient ramped protocol (1% per min) at a constant (individually determined) speed, and a speed ramped protocol (1.2 km.h^{-1} per min) at a 5% gradient. Each protocol was completed on a separate day, and the order in which the protocols were completed was randomised. Expired gases were collected in Douglas bags throughout each test, and the peak $\dot{V}O_2$ was defined as the highest $\dot{V}O_2$ sustained for any period of ≥20s. A linear $\dot{V}O_2$-work rate (running speed or treadmill gradient) regression was derived for each subject on each protocol (data from the first min and the final 2 min were excluded), and a predicted $\dot{V}O_2$ for the average work rate sustained over the duration of the final collection was calculated from this regression equation. A plateau in $\dot{V}O_2$ was considered to have occurred if, for this final gas collection, the actual $\dot{V}O_2$ was below the lower 95% confidence limit of the predicted $\dot{V}O_2$.

The peak $\dot{V}O_2$ was highest for the gradient ramped test and lowest for the speed ramped test at zero grade but the majority of subjects reached a plateau in $\dot{V}O_2$ on each of the three protocols. Final RER values were lowest for the gradient ramped test and highest for the speed ramped test at a 5% grade, but no differences were found in peak heart rate or final blood lactate concentration (Table 1).

Table 1. Peak physiological responses for the three protocols (mean ± SD; n=12)

Protocol	Incidence of a plateau	Peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$)	Peak RER	Peak HR ($b.min^{-1}$)	Peak lactate ($mmol.l^{-1}$)
Speed ramped at 0% grade	92%	62.6 ± 4.6	1.19 ± 0.04†	190 ± 9	7.9 ± 1.8
Speed ramped at 5% grade	100%	64.0 ± 4.8*	1.21 ± 0.05	188 ± 10	7.7 ± 1.7
Gradient ramped	100%	65.1 ± 4.3*†	1.17 ± 0.04*#	190 ± 8	7.8 ± 1.5

*p<0.01 vs. 0% grade; †p<0.05 vs. 5% grade; #p<0.01 vs. 5% grade.

The peak $\dot{V}O_2$ attained was lower for the speed ramped test at zero grade than for the speed ramped test at 5% grade or the gradient ramped test (peak gradient reached ~10%), but the finding that even on the test at zero grade the majority of subjects reached a plateau in $\dot{V}O_2$ with increasing work rate suggests that these subjects were not limited by cadence to the extent that they were unable to run fast enough to achieve a genuine $\dot{V}O_{2max}$ on a flat treadmill. A greater muscle mass is recruited during uphill running than during running on the flat (Sloniger et al, 1997), and recruiting a larger muscle mass would allow a higher $\dot{V}O_{2max}$ to be achieved, so it seems likely that the differences in $\dot{V}O_{2max}$ among the three protocols reflect differences in the muscle mass recruited.

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APPENDIX 2: SUPPORTING INFORMATION FOR CHAPTER 5

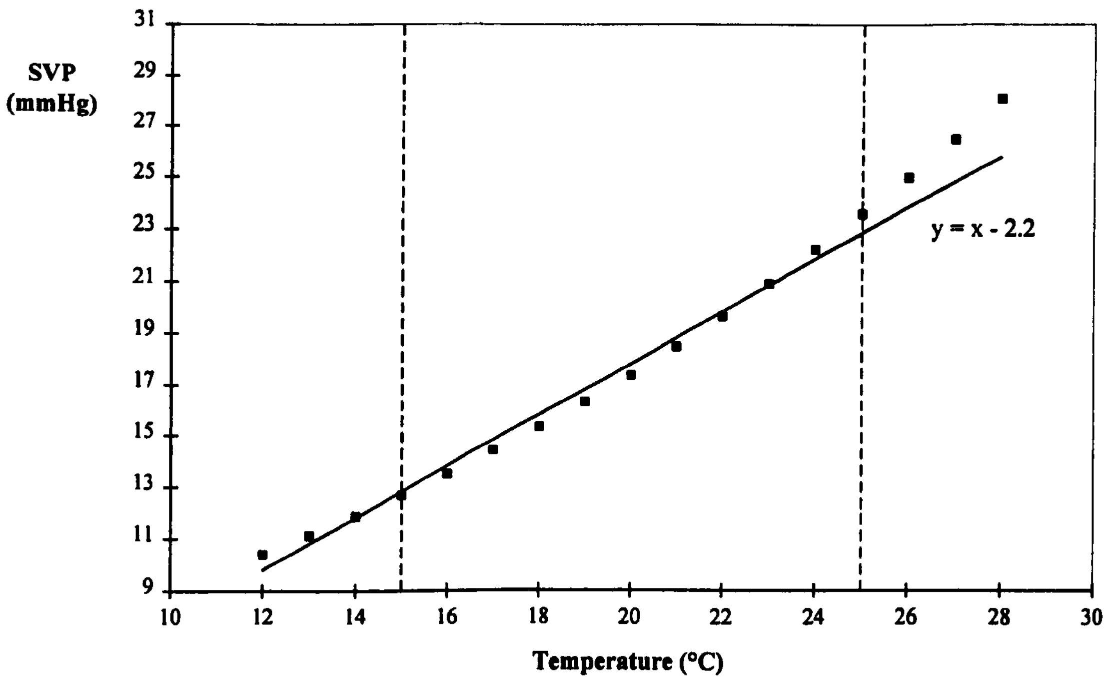

Figure A2.1. Relationship between saturated vapour pressure of water (SVP) and temperature for the range of temperatures likely to be encountered in the laboratory.

Note:

This figure shows that for temperatures between 15 and 25°C the relationship between saturated vapour pressure of water (SVP) and temperature can be reasonably well described by a linear function with a slope of 1 (see section 5.5.3).

Table A1.1. Ambient vapour pressure as a function of temperature and relative humidity.

		Temperature (°C)										
		0	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**
	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10%	0.5	0.6	0.7	0.9	1.0	1.3	1.5	1.8	2.2	2.6	3.2
	20%	0.9	1.1	1.4	1.7	2.1	2.5	3.1	3.7	4.4	5.3	6.3
	30%	1.4	1.7	2.1	2.6	3.1	3.8	4.6	5.5	6.6	7.9	9.5
Relative	**40%**	1.8	2.2	2.8	3.4	4.2	5.1	6.1	7.4	8.9	10.6	12.6
humidity	**50%**	2.3	2.8	3.5	4.3	5.2	6.3	7.7	9.2	11.1	13.2	15.8
	60%	2.7	3.4	4.2	5.1	6.2	7.6	9.2	11.1	13.3	15.9	18.9
	70%	3.2	3.9	4.9	6.0	7.3	8.9	10.7	12.9	15.5	18.5	22.1
	80%	3.6	4.5	5.5	6.8	8.3	10.1	12.3	14.8	17.7	21.2	25.2
	90%	4.1	5.1	6.2	7.7	9.4	11.4	13.8	16.6	19.9	23.8	28.4
	100%	4.5	5.6	6.9	8.5	10.4	12.7	15.3	18.5	22.2	26.5	31.5

Notes:
The shading highlights those combinations of temperature and relative humidity for which the vapour pressure is <6.5 mmHg. This is the SVP associated with a temperature of 5°C [the temperature to which gases were cooled prior to entry to the O_2 and CO_2 analysers (see section 5.5.5.4)].

APPENDIX 3: INDIVIDUAL DATA AND STATISTICAL OUTPUT (SPSS, VERSION 9.0.0) FOR STUDY 1

Table A3.1. Subject characteristics for Study 1 (individual data).

Subject	Age (years)	Height (m)	Mass (kg)	VO_{2peak} ($ml.kg^{-1}.min^{-1}$)
1	30	1.75	74.0	68.4
2	23	1.73	83.3	52.6
3	25	1.69	62.2	70.1
4	22	1.73	73.2	54.8
5	29	1.89	104.8	43.6
6	20	1.74	70.0	64.9
7	47	1.74	75.9	51.8
8	21	1.68	67.3	58.6
9	28	1.95	90.2	62.4
10	20	1.80	73.4	56.3
n	10	10	10	10
MEAN	**26.5**	**1.77**	**77.4**	**58.4**
SD	8.1	0.09	12.4	8.2

Notes: The mean data were originally presented in table 7.1. The value for $\dot{V}O_{2peak}$ was taken from the preliminary 5% ramp test (see section 7.2.2).

Table A3.2. Peak physiological responses for the 0% and the 5% ramp test (individual data).

Subject	Peak $\dot{V}O_2$ (ml.kg^{-1}.min^{-1})		Peak RER		Peak [Bla] (mmol.L^{-1})		$\dot{V}O_2$-plateau?	
	5%RT	0%RT	5%RT	0%RT	5%RT	0%RT	5%RT	0%RT
1	67.0	66.0	1.16	1.16	6.97	8.36	yes	yes
2	56.1	56.3	1.16	1.14	8.70	7.14	yes	no
3	73.3	72.4	1.14	1.12	7.31	6.91	no	no
4	58.9	55	1.19	1.17	9.34	9.78	no	no
5	45.2	44	1.25	1.17	9.36	7.78	yes	no
6	64.4	59.6	1.11	1.13	9.82	8.40	no	no
7	52.3	49.6	1.24	1.20	10.1	9.69	yes	yes
8	59.1	56.9	1.12	1.03	6.25	5.88	no	no
9	64.2	60.5	1.11	1.01	6.41	3.24	yes	no
10	58.4	57.8	1.22	1.12	9.32	8.54	no	yes
n	10	10	10	10	10	10	-	-
MEAN	**59.9**	**57.8**	**1.17**	**1.13**	**8.4**	**7.6**	-	-
SD	7.9	7.9	0.05	0.06	1.5	1.9	-	-

Note: The group data were originally presented in table 7.3.

Output A3.1. Paired t-tests comparing the peak physiological responses for the 5%T with those for the 0%T.

Paired Samples Test

	Paired Differences (5%T - 0%T)					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference: Lower	Upper			
Pair 1 - Peak VO2	2.08	1.65	.52	.90	3.26	3.99	9	.003
Pair 2 - Peak RER	4.33E-02	4.61E-02	.01	.01	.08	2.97	9	.016
Pair 3 - Peak [Bla]	.79	1.25	.39	-.11	1.68	1.99	9	.078

Output A3.2. Two-way RM ANOVA (stage × time) for the last four stages of the DCT

Mauchly's Test of Sphericity[b]

Measure: VO2

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon Greenhouse-Geisser	Epsilon Huynh-Feldt	Epsilon Lower-bound
STAGE	.398	7.11	5	.216	.700	.918	.333
TIME	1.00	.000	0	.	1.00	1.00	1.00
STAGE * TIME	.609	3.83	5	.576	.813	1.00	.333

b.

Design: Intercept
Within Subjects Design: STAGE+TIME+STAGE*TIME

Tests of Within-Subjects Effects

Measure: VO2

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
STAGE	Sphericity Assumed	387.3	3	129.1	38.1	.000	.809	114.2	1.00
	Greenhouse-Geisser	387.3	2.1	184.4	38.1	.000	.809	80.0	1.00
	Huynh-Feldt	387.3	2.8	140.6	38.1	.000	.809	104.9	1.00
Error(STAGE)	Sphericity Assumed	91.6	27	3.39					
	Greenhouse-Geisser	91.6	18.9	4.84					
	Huynh-Feldt	91.6	24.8	3.69					
TIME	Sphericity Assumed	36.9	1	36.9	71.5	.000	.888	71.5	1.00
	Greenhouse-Geisser	36.9	1.0	36.9	71.5	.000	.888	71.5	1.00
	Huynh-Feldt	36.9	1.0	36.9	71.5	.000	.888	71.5	1.00
Error(TIME)	Sphericity Assumed	4.64	9	.52					
	Greenhouse-Geisser	4.64	9.0	.52					
	Huynh-Feldt	4.64	9.0	.52					
STAGE * TIME	Sphericity Assumed	1.38	3	.46	2.27	.103	.201	6.8	.51
	Greenhouse-Geisser	1.38	2.4	.57	2.27	.118	.201	5.5	.45
	Huynh-Feldt	1.38	3.0	.46	2.27	.103	.201	6.8	.51
Error(STAGE*TIME)	Sphericity Assumed	5.46	27	.20					
	Greenhouse-Geisser	5.46	21.9	.25					
	Huynh-Feldt	5.46	27.0	.20					

a. Computed using alpha = .05

Table A3.3. Slope of the $\dot{V}O_2$-speed relationship for the first 3 stages of the DCT and the CT (individual data).

Subject	Slope of the $\dot{V}O_2$-speed relationship ($ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$)	
	DCT	**CT**
1	2.53	4.5
2	2.46	3.88
3	4.25	5.04
4	2.58	4.54
5	3.58	3.75
6	-	-
7	1.71	3.68
8	3.29	4.42
9	2.46	4.79
10	-	-
n	8	8
MEAN	**2.9**	**4.3**
SD	**0.8**	**0.5**

Note: Subjects 6 and 10 completed only 2 stages in the CT.

Output A3.3. Paired t-test comparing the slope of the $\dot{V}O_2$-speed relationship for the first 3 stages of the DCT and the CT.

Paired Samples Test

	Paired Differences (CT - DCT)					t	df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1 - slopes	1.47	.73	.26	.86	2.08	5.67	7	.0008

Table A3.4. Peak values for $\dot{V}O_2$ and RER for the 5% RT, the DCT, and the 105%T (individual data).

Subject	$\dot{V}O_{2peak}$ ($ml.kg^{-1}.min^{-1}$)			Peak RER		
	5%RT	**DCT**	**105%T**	**5%RT**	**DCT**	**105%T**
1	67.0	66.3	64.3	1.16	1.19	1.16
2	56.1	54.2	54.8	1.16	1.19	1.14
3	73.3	69.9	68.9	1.14	1.17	1.14
4	58.9	56.3	57.4	1.19	1.30	1.12
5	45.2	44.2	44.9	1.25	1.32	1.17
6	64.4	60	60.2	1.11	1.18	1.19
7	52.3	46.4	52.0	1.24	1.30	1.12
8	59.1	62.6	60	1.12	1.31	1.06
9	64.2	61.5	63	1.11	1.14	1.10
10	58.4	56.1	55.5	1.22	1.25	1.16
n	10	10	10	10	10	10
MEAN	**59.9**	**57.8**	**58.1**	**1.17**	**1.24**	**1.14**
SD	7.9	8.1	6.8	0.05	0.07	0.04

Note: The group data were originally presented in table 7.4.

Output A3.4a. RM ANOVA comparing peak values for $\dot{V}O_2$ for the 5%RT60, the DCT, and the 105%T.

Mauchly's Test of Sphericity[b]

Measure: VO2

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
TEST	.840	1.40	2	.495	.862	1.00	.500

b.
Design: Intercept
Within Subjects Design: TEST

Tests of Within-Subjects Effects

Measure: VO2

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
TEST	Sphericity Assumed	26.4	2	13.2	5.46	.014	.378	10.9	.781
	Greenhouse-Geisser	26.4	1.7	15.3	5.46	.019	.378	9.4	.731
	Huynh-Feldt	26.4	2.0	13.2	5.46	.014	.378	10.9	.781
Error(TEST)	Sphericity Assumed	43.4	18	2.41					
	Greenhouse-Geisser	43.4	15.5	2.80					
	Huynh-Feldt	43.4	18.0	2.41					

a. Computed using alpha = .05

Output A3.4b. RM ANOVA comparing peak values for RER for the 5%RT60, the DCT, and the 105%T.

Mauchly's Test of Sphericity[b]

Measure: RER

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
TEST	.573	4.45	2	.106	.701	.791	.500

b.
Design: Intercept
Within Subjects Design: TEST

Tests of Within-Subjects Effects

Measure: RER

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
TEST	Sphericity Assumed	5.22E-02	2	2.611E-02	12.16	.000	.575	24.3	.987
	Greenhouse-Geisser	5.22E-02	1.4	3.724E-02	12.16	.002	.575	17.0	.947
	Huynh-Feldt	5.22E-02	1.6	3.301E-02	12.16	.001	.575	19.2	.965
Error(TEST)	Sphericity Assumed	3.87E-02	18	2.147E-03					
	Greenhouse-Geisser	3.87E-02	12.6	3.064E-03					
	Huynh-Feldt	3.87E-02	14.2	2.715E-03					

a. Computed using alpha = .05

Table A3.5. Individual data on the $\dot{V}O_2$-running speed relationship for the first and the second half of the 0%RT.

	Slope (ml.kg^{-1}.min^{-1} per km.h^{-1})		Start speed (km.h^{-1})		End speed (km.h^{-1})	
Subject	**1st half**	**2nd half**	**1st half**	**2nd half**	**1st half**	**2nd half**
1	3.00	3.21	10.8	15.6	15.6	20.4
2	2.70	2.78	7.8	12.7	13.8	18.6
3	3.37	3.42	11.8	16.6	16.6	21.4
4	2.40	2.49	8.8	13.6	13.6	18.4
5	2.96	2.82	8.2	10.6	10.6	13
6	3.13	2.83	9.8	13.4	14.6	18.2
7	2.51	2.30	8.3	11.9	13.1	16.7
8	2.52	2.97	8.3	13.1	13.1	17.9
9	3.53	2.50	11.8	15.4	15.4	19
10	2.67	2.91	8.8	13.6	13.6	18.4
n	10	10	10	10	10	10
MEAN	**2.88**	**2.82**	**9.4**	**13.7**	**14.0**	**18.2**
SD	0.38	0.34	1.5	1.8	1.7	2.2

Note: The group data were presented in table 7.5.

Output A3.5. Paired t-test comparing the slope of the $\dot{V}O_2$-speed relationship for the first and the second half of the 0%T.

Paired Samples Test

	Paired Differences (2nd half - 1st half)							
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1 - slopes	-5.66E-02	.41	.13	-.35	.23	-.439	9	.671

Table A3.6. Peak physiological responses for the 5%RT60 and the 5%RT30 (individual data).

Subject	$\dot{V}O_{2peak}$ (ml.kg^{-1}.min^{-1})		Peak RER		Peak [Bla] (mmol.L^{-1})		$\dot{V}O_2$-plateau?	
	RT60	RT30	RT60	RT30	RT60	RT30	RT60	RT30
1	67.0	66.5	1.16	1.16	6.97	7.89	yes	yes
2	56.1	55.8	1.16	1.16	8.70	8.52	yes	yes
3	73.3	71.3	1.14	1.19	7.31	7.51	no	no
4	58.9	57.2	1.19	1.21	9.34	9.47	no	no
5	45.2	45.5	1.25	1.21	9.36	8.89	yes	no
6	64.4	63	1.11	1.15	9.82	8.83	no	no
7	52.3	53.7	1.24	1.22	10.1	9.65	yes	no
8	59.1	60.6	1.12	1.12	6.25	7.03	no	no
9	64.2	62.5	1.11	1.11	6.41	5.19	yes	no
10	58.4	58.2	1.22	1.18	9.32	9.19	no	no
n	10	10	10	10	10	10	-	-
MEAN	**59.9**	**59.4**	**1.17**	**1.17**	**8.4**	**8.2**	-	-
SD	7.9	7.2	0.05	0.04	1.5	1.4	-	-

Notes: RT60 and RT30 refer to the 5%RT60 and the 5%RT30, respectively. The group data were presented in table 7.6.

Output A3.6. Paired t-tests comparing the peak physiological responses for the 5%CT30 and the 5%CT60.

Paired Samples Test

	Paired Differences (5%RT60 - 5%RT30)					t	df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1 - Peak VO2	.46	1.26	.40	-.44	1.36	1.16	9	.276
Pair 2 - Peak RER	-2.24E-03	3.02E-02	9.54E-03	-2.38E-02	1.93E-02	-.235	9	.819
Pair 3 - Peak [Bla]	.14	.69	.22	-.35	.63	.649	9	.533

APPENDIX 4: INDIVIDUAL DATA AND STATISTICAL OUTPUT FOR STUDY 2

Table A4.1. Subject characteristics for Study 2 (individual data).

Part 1 (effect of sampling period)					Part 2 (effect of exercise intensity)				
Subj.	**Age (years)**	**Ht. (m)**	**Mass (kg)**	**$\dot{V}O_{2peak}$ (ml.kg^{-1}.min^{-1})**	**Subj.**	**Age (years)**	**Ht. (m)**	**Mass (kg)**	**$\dot{V}O_{2peak}$ (ml.kg^{-1}.min^{-1})**
1	29	1.95	90.5	58.2	1	29	1.95	90.5	58.2
2	30	1.73	74.6	65.3	2	22	1.82	65.5	69.7
3	27	1.83	77.5	58.8	3	26	1.79	72.6	62.0
4	26	1.79	72.6	58.4	4	31	1.75	78	68.1
5	31	1.75	78	68.1	5	31	1.84	63.7	60.1
6	32	1.82	82.6	61.7	6	26	1.69	64	68.9
7	31	1.84	63.7	56.5	-	-	-	-	-
8	26	1.69	64	68.9	-	-	-	-	-
n	8	8	8	8	6	6	6	6	6
Mean	**29**	**1.80**	**75.4**	**62.0**	-	**27.5**	**1.81**	**72.4**	**64.5**
SD	2.4	0.08	9.0	4.8	-	3.5	0.09	10.5	5.0

Note: The group data were presented in table 8.1.

Table A4.2. Individual data on the mean and SD of the 12 values for $\dot{V}O_2$ for the 4 sampling periods.

Subject	Mean for 12 samples (% $\dot{V}O_{2max}$)				SD for 12 samples ($ml.kg^{-1}.min^{-1}$)			
	30 s	60 s	90 s	120 s	30 s	60 s	90 s	120 s
1	68.8	69.9	70.6	70.1	2.42	0.47	0.35	0.36
2	69.0	68.5	68.8	69.8	0.67	0.60	0.25	0.57
3	72.4	70.6	71.0	70.3	1.55	0.69	0.49	0.25
4	69.9	69.9	71.9	68.1	1.00	0.92	0.54	0.42
5	70.3	69.3	70.2	69.0	1.05	0.24	0.32	0.30
6	72.3	70.8	72.4	73.0	0.42	0.46	0.25	0.26
7	71.2	70.3	70.0	68.3	1.95	0.40	0.47	0.33
8	71.3	72.7	72.5	70.3	1.29	0.80	0.59	0.36
n	8	8	8	8	8	8	8	8
MEAN	**70.7**	**70.3**	**70.9**	**69.9**	**1.29**	**0.57**	**0.41**	**0.36**
SD	1.4	1.2	1.3	1.5	0.66	0.22	0.13	0.10

Output A4.1. RM ANOVA comparing the SD for $\dot{V}O_2$ for the 4 sampling periods.

Mauchly's Test of Sphericity[b]

Measure: SD

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon: Greenhouse-Geisser	Epsilon: Huynh-Feldt	Epsilon: Lower-bound
S. PERIOD	.031	19.8	5	.002	.392	.424	.333

b.

Design: Intercept
Within Subjects Design: PERIOD

Tests of Within-Subjects Effects

Measure: SD

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
S. PERIOD	Sphericity Assumed	4.54	3	1.51	12.18	.000	.635	36.5	.998
	Greenhouse-Geisser	4.54	1.2	3.86	12.18	.007	.635	14.3	.894
	Huynh-Feldt	4.54	1.3	3.56	12.18	.005	.635	15.5	.913
Error(S. PERIOD)	Sphericity Assumed	2.61	21	.124					
	Greenhouse-Geisser	2.61	8.2	.317					
	Huynh-Feldt	2.61	8.9	.293					

a. Computed using alpha = .05

Table A4.3. Individual data on the mean of the 12 values for F_EO_2, F_ECO_2, and V_E for the 4 sampling periods.

Subj.	Mean F_EO_2 (%)				Mean F_ECO_2 (%)				Mean V_E (L, ATPS)			
	30 s	60 s	90 s	120 s	30 s	60 s	90 s	120 s	30 s	60 s	90 s	120 s
1	16.48	16.38	16.27	16.46	4.29	4.32	4.31	4.27	45.0	89.8	132.0	181.4
2	16.20	16.15	16.30	16.23	4.28	4.51	4.46	4.36	37.0	73.7	114.9	154.5
3	16.60	16.96	16.91	16.84	4.03	3.79	3.92	3.95	41.1	86.8	127.9	168.4
4	16.01	16.03	16.84	16.31	4.46	4.51	3.86	4.45	32.5	64.0	120.2	134.9
5	16.17	16.12	16.08	16.21	4.39	4.51	4.52	4.45	41.0	80.8	122.2	163.0
6	16.59	17.00	17.15	16.45	4.13	3.84	3.71	4.26	45.3	99.0	157.3	179.1
7	16.34	16.24	16.11	16.42	4.27	4.34	4.43	4.22	29.9	56.8	82.0	119.3
8	15.95	15.83	15.94	16.08	4.50	4.77	4.62	4.37	34.3	67.9	102.9	139.2
n	8	8	8	8	8	8	8	8	8	8	8	8
Mean	**16.3**	**16.3**	**16.4**	**16.4**	**4.3**	**4.3**	**4.2**	**4.3**	**38.2**	**77.3**	**119.9**	**155.0**
SD	0.3	0.4	0.5	0.2	0.2	0.3	0.3	0.2	5.7	14.3	21.9	22.2

Note: The group data for F_EO_2, F_ECO_2, V_E, and the mean and SD for $\dot{V}O_2$ were presented in table 8.2

Table A4.4. Mean values for F_EO_2, F_ECO_2, V_E, $\dot{V}O_2$, and the SD for $\dot{V}O_2$, for the LI and the HI run (individual data).

Subj.	Mean F_EO_2 (%)		Mean F_ECO_2 (%)		Mean V_E (L, ATPS)		Mean $\dot{V}O_2$ (% $\dot{V}O_{2max}$)		SD for $\dot{V}O_2$ (ml.kg^{-1}.min^{-1})	
	LI	HI	LI	HI	LI	HI	LI	HI	LI	HI
1	16.26	17.27	4.47	3.74	40.8	75.5	68.5	97.9	0.98	0.67
2	16.95	17.34	3.79	3.63	42.7	62.2	71.7	91.7	0.77	0.35
3	16.01	17.26	4.46	3.79	32.5	65.2	65.9	98.8	1.00	0.29
4	16.17	16.88	4.39	4.04	41.0	65.2	70.3	92.8	1.05	0.94
5	15.32	17.51	5.06	3.56	24.6	59.9	69.8	95.7	1.19	0.43
6	15.95	17.03	4.50	4.03	34.3	58.7	71.3	96.8	1.29	0.72
n	6	6	6	6	6	6	6	6	6	6
Mean	**16.1**	**17.2**	**4.4**	**3.8**	**36**	**64**	**69.6**	**95.6**	**1.05**	**0.57**
SD	0.5	0.2	0.4	0.2	7	6	2.1	2.8	0.18	0.25

Notes: The group data were presented in table 8.3. HI and LI refer to the HI run and the LI run, respectively.

Output A4.2. Paired t-test comparing the SD for $\dot{V}O_2$ for the LI and the HI run.

Paired Samples Test

	Paired Differences (LI run - HI run)					t	df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1 - LI vs. HI run	.48	.25	.10	.22	.74	4.69	5	.005

Output A4.3. Unpaired t-test comparing the SD for the 30 s samples taken during the HI run with that for the 60 s samples taken during running at 70% $\dot{V}O_{2peak}$.

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
SD for VO2	Equal variances assumed	.267	.615	.046	12	.964	5.92E-03	.13	-.27	.28
	Equal variances not assumed			.046	10.2	.964	5.92E-03	.13	-.28	.29

APPENDIX 5: INDIVIUAL DATA AND STATISTICAL OUTPUT FOR STUDY 3

Table A5.1. Subject characteristics for Study 3 (individual data).

Subject	Age (years)	Height (m)	Mass (kg)	$\dot{V}O_{2peak}$ (ml.kg^{-1}.min^{-1})
1	20	1.74	68	72.7
2	24	1.77	71	65.3
3	17	1.78	64.8	67.9
4	29	1.95	90.5	58.2
5	23	1.76	69.5	64.0
6	23	1.9	67.5	63.5
7	26	1.79	72	58.4
8	32	1.82	83	61.7
9	35	1.78	68	64.0
10	31	1.84	64	56.5
11	34	1.72	68	66.3
12	26	1.69	64.5	68.9
n	12	12	12	12
MEAN	**26.7**	**1.80**	**70.9**	**64.0**
SD	5.6	0.07	8.0	4.7

Notes: Group data were presented in Table 9.1. Values for $\dot{V}O_{2peak}$ were taken from the 5%T.

Table A5.2. SEE for the linear and the plateau model, and the duration of the $\dot{V}O_2$-plateau, for the three tests (individual data).

Subject	SEE for linear model ($ml.kg^{-1}.min^{-1}$)			SEE for plateau model ($ml.kg^{-1}.min^{-1}$)			Duration of the plateau (s)		
	0%T	5%T	IGT	0%T	5%T	IGT	0%T	5%T	IGT
1	0.81	1.13	0.88	0.50	0.47	0.58	59	65	74
2	0.87	0.75	1.32	0.55	0.76	0.78	65	80	114
3	2.13	1.61	0.77	0.68	1.04	0.67	68	128	84
4	1.26	0.94	0.79	0.88	0.47	0.78	84	90	70
5	0.68	1.07	0.70	0.56	0.44	0.20	69	78	67
6	0.92	1.13	0.92	0.58	0.38	0.39	61	81	89
7	1.42	2.58	1.76	0.70	0.89	0.61	127	178	179
8	1.03	1.17	0.97	0.28	0.68	0.29	66	81	106
9	1.14	1.47	0.74	0.82	0.86	0.54	69	91	70
10	0.43	1.24	0.62	0.84	0.73	0.56	-	-	-
11	0.71	1.31	0.96	0.47	0.59	0.50	60	92	74
12	1.70	1.68	2.05	0.68	0.83	1.32	97	80	132
n	12	12	12	12	12	12	-	-	-
MEAN	**1.09**	**1.34**	**1.04**	**0.63**	**0.68**	**0.60**	-	-	-
SD	0.48	0.47	0.45	0.17	0.21	0.29	-	-	-

Notes: The group data were presented in table 9.2 (SEE data) and section 9.3.2 (data on the duration of the plateau). Mean data have not been presented for the duration of the plateau because these data were not normally distributed (see section 9.3.2).

Output A5.1. Two-way RM ANOVA (model × test) comparing the SEE for the linear and the plateau model across the 3 tests.

Mauchly's Test of Sphericity[b]

Measure: SEE

					Epsilon		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse -Geisser	Huynh-Feldt	Lower-bound
TEST	.923	.799	2	.670	.929	1.00	.500
MODEL	1.00	.000	0	.	1.00	1.00	1.00
TEST * MODEL	.716	3.34	2	.186	.779	.884	.500

b.

Design: Intercept
Within Subjects Design: TEST+MODEL+TEST*MODEL

Tests of Within-Subjects Effects

Measure: SEE

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
TEST	Sphericity Assumed	.472	2	.236	2.56	.100	.189	5.1	.457
	Greenhouse-Geisser	.472	1.9	.254	2.56	.105	.189	4.8	.438
	Huynh-Feldt	.472	2.0	.236	2.56	.100	.189	5.1	.457
Error(TEST)	Sphericity Assumed	2.03	22	9.21E-02					
	Greenhouse-Geisser	2.03	20.4	9.92E-02					
	Huynh-Feldt	2.03	22.0	9.21E-02					
		2.03	11.0	.184					
MODEL	Sphericity Assumed	4.90	1	4.90	36.7	.000	.769	36.7	1.00
	Greenhouse-Geisser	4.90	1.0	4.90	36.7	.000	.769	36.7	1.00
	Huynh-Feldt	4.90	1.0	4.90	36.7	.000	.769	36.7	1.00
Error(MODEL)	Sphericity Assumed	1.47	11	.134					
	Greenhouse-Geisser	1.47	11.0	.134					
	Huynh-Feldt	1.47	11.0	.134					
TEST * MODEL	Sphericity Assumed	.186	2	9.28E-02	1.74	.198	.137	3.5	.326
	Greenhouse-Geisser	.186	1.6	.119	1.74	.207	.137	2.7	.284
	Huynh-Feldt	.186	1.8	.105	1.74	.203	.137	3.1	.304
Error(TEST*MODEL)	Sphericity Assumed	1.17	22	5.32E-02					
	Greenhouse-Geisser	1.17	17.1	6.83E-02					
	Huynh-Feldt	1.17	19.4	6.02E-02					

a. Computed using alpha = .05

Output A5.2. Friedman's ANOVA comparing the duration of the $\dot{V}O_2$-plateau for the 3 tests.

Ranks

	Mean Rank
0%T	1.27
5%T	2.36
IGT	2.36

Test Statistics[a]

N	11
Chi-Square	8.727
df	2
Asymp. Sig.	.013

a. Friedman Test

Table A5.3. Peak values for $\dot{V}O_2$, RER, and [Bla] for the 3 tests (individual data).

Subject	Peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$)			Peak RER			Peak [Bla] ($mmol.L^{-1}$)		
	0%T	5%T	IGT	0%T	5%T	IGT	0%T	5%T	IGT
1	72.3	72.7	72.2	1.17	1.22	1.17	-	-	-
2	63.2	65.3	67.3	1.26	1.23	1.18	8.7	8.9	9.0
3	66.5	67.9	66.0	1.18	1.25	1.21	9.0	8.3	9.7
4	57.5	58.2	61.0	1.15	1.19	1.16	6.5	6.7	6.4
5	60.4	64.0	64.9	1.21	1.21	1.18	9.0	8.6	8.8
6	62.3	63.5	65.5	1.15	1.19	1.14	5.3	5.8	5.9
7	57.5	58.4	57.3	1.18	1.19	1.11	8.5	8.3	6.6
8	58.5	61.7	62.4	1.13	1.11	1.11	4.8	4.4	5.9
9	63.1	64.0	65.9	1.27	1.29	1.21	10.2	10.1	9.8
10	57.9	56.5	60.1	1.24	1.30	1.23	6.7	6.2	7.6
11	65.5	66.3	69.4	1.18	1.20	1.16	8.0	9.3	7.9
12	66.6	68.9	68.7	1.21	1.20	1.14	9.6	7.8	8.5
n	12	12	12	12	12	12	11	11	11
MEAN	**62.6**	**64.0**	**65.1**	**1.19**	**1.21**	**1.17**	**7.85**	**7.67**	**7.83**
SD	4.6	4.7	4.3	0.04	0.05	0.04	1.78	1.69	1.47

Notes: The group data were presented in table 9.3. Lactate data were not available for all 3 tests in subject 1, so this subject's data were excluded.

Output A5.3a. One way RM ANOVA comparing the peak $\dot{V}O_2$ for the 3 tests.

Mauchly's Test of Sphericity[b]

Measure: VO2

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
TEST	.890	1.16	2	.557	.901	1.00	.500

b.
Design: Intercept
Within Subjects Design: TEST

Tests of Within-Subjects Effects

Measure: VO2

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
TEST	Sphericity Assumed	36.3	2	18.2	13.6	.000	.553	27.3	.995
	Greenhouse-Geisser	36.3	1.8	20.1	13.6	.000	.553	24.6	.991
	Huynh-Feldt	36.3	2.0	18.2	13.6	.000	.553	27.3	.995
Error(TEST)	Sphericity Assumed	29.3	22	1.33					
	Greenhouse-Geisser	29.3	19.8	1.48					
	Huynh-Feldt	29.3	22.0	1.33					

a. Computed using alpha = .05

Output A5.3b. One way RM ANOVA comparing the peak RER for the 3 tests.

Mauchly's Test of Sphericity[b]

Measure: RER

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
TEST	.792	2.33	2	.310	.828	.956	.500

b.
Design: Intercept
Within Subjects Design: TEST

Tests of Within-Subjects Effects

Measure: RER

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
TEST	Sphericity Assumed	1.41E-02	2	7.05E-03	15.2	.000	.580	30.3	.998
	Greenhouse-Geisser	1.41E-02	1.7	8.52E-03	15.2	.000	.580	25.1	.993
	Huynh-Feldt	1.41E-02	1.9	7.37E-03	15.2	.000	.580	29.0	.997
Error(TEST)	Sphericity Assumed	1.02E-02	22	4.65E-04					
	Greenhouse-Geisser	1.02E-02	18.2	5.61E-04					
	Huynh-Feldt	1.02E-02	21.0	4.86E-04					

a. Computed using alpha = .05

Output A5.3c. One way RM ANOVA comparing the peak [Bla] for the 3 tests.

Mauchly's Test of Sphericity[b]

Measure: LACTATE

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
TEST	.884	1.11	2	.571	.896	1.00	.500

b.

Design: Intercept
Within Subjects Design: TEST

Tests of Within-Subjects Effects

Measure: LACTATE

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared	Noncent. Parameter	Observed Power[a]
TEST	Sphericity Assumed	.202	2	.101	.244	.785	.024	.489	.083
	Greenhouse-Geisser	.202	1.8	.113	.244	.762	.024	.438	.081
	Huynh-Feldt	.202	2.0	.101	.244	.785	.024	.489	.083
Error(TEST)	Sphericity Assumed	8.27	20	.413					
	Greenhouse-Geisser	8.27	17.9	.461					
	Huynh-Feldt	8.27	20.0	.413					

a. Computed using alpha = .05

Table A5.4. Slope of the $\dot{V}O_2$-WR relationship for the first and second halves of the 0%T, the 5%T, and the IGT (individual data).

Subject	Slope for the 0%T ($ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$)		Slope for the 5%T ($ml.kg^{-1}.min^{-1}$ per $km.h^{-1}$)		Slope for the IGT ($ml.kg^{-1}.min^{-1}$ per %grade)	
	1st half	2nd half	1st half	2nd half	1st half	2nd half
1	3.26	3.60	3.19	3.56	2.90	2.58
2	3.07	2.23	2.52	2.87	3.29	2.42
3	2.89	2.66	3.19	3.32	2.70	2.01
4	3.09	2.04	3.21	3.23	2.04	2.28
5	2.67	3.52	3.79	3.65	2.76	3.08
6	2.99	3.67	3.37	3.53	2.84	2.64
7	3.27	2.66	3.97	3.09	3.26	2.36
8	2.82	2.80	3.89	3.95	2.74	2.61
9	2.57	2.61	3.47	2.80	2.67	2.27
10	3.14	2.77	2.75	2.83	2.62	1.85
11	3.09	3.02	3.39	3.36	2.60	2.31
12	2.97	3.39	3.63	3.84	2.85	2.14
n	12	12	12	12	12	12
MEAN	**2.98**	**2.91**	**3.36**	**3.33**	**2.77**	**2.38**
SD	0.22	0.53	0.43	0.39	0.32	0.32

Note: Group data were presented in table 9.4.

Output A5.4. Paired t-tests comparing the slope of $\dot{V}O_2$-WR relationship for the first and second halves of the 0%T, the 5%T, and the IGT.

Paired Samples Test

	Paired Differences (1st half - 2nd half)					t	df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1 0%T	7.22E-02	.58	.17	-.30	.44	.428	11	.677
Pair 2 5%T	2.97E-02	.38	.11	-.21	.27	.271	11	.792
Pair 3 IGT	.39	.41	.12	.13	.65	3.32	11	.007