

Review article

Can we confidently study $\dot{V}O_2$ kinetics in young people?

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Abstract

The study of $\dot{V}O_2$ kinetics offers the potential to non-invasively examine the cardiorespiratory and metabolic response to dynamic exercise and limitations to every day physical activity. Its non-invasive nature makes it hugely attractive for use with young people, both healthy and those with disease, and yet the literature, whilst growing with respect to adults, remains confined to a cluster of studies with these special populations. It is most likely that this is partly due to the methodological difficulties involved in studying $\dot{V}O_2$ kinetics in young people which are not present, or present to a lesser degree, with adults. This article reviews these methodological issues, and explains the main procedures that might be used to overcome them.

Key words: Children, oxygen kinetics, methodology.

Introduction

Since the original identification of the exponential nature of the oxygen uptake ($\dot{V}O_2$) response at the onset of exercise (Hill and Lupton, 1923) there has been substantial progress towards understanding the true nature of the $\dot{V}O_2$ kinetic response to exercise and, in the last 20 or 30 years, a plethora of attempts to manipulate this in order to explore underlying muscle and cardiorespiratory physiology. Currently, a simple search for the phrase 'oxygen uptake kinetics' in one of many appropriate search engines returns a diverse range of articles using $\dot{V}O_2$ kinetics to explore issues from the most basic rudimentary muscle physiology to the exercise response in clinical populations. Today, $\dot{V}O_2$ kinetics is wholeheartedly embraced by the exercise scientist.

The main attraction of exploring $\dot{V}O_2$ kinetics is that with correct application and interpretation, it non-invasively provides information pertaining to metabolic activity at the muscular level, and the integrated response of the ventilatory, cardiovascular and metabolic systems to an exercise stress. This 'non-invasive' nature is fundamental to its utility in exploring the response to exercise under numerous situations and exercise stresses, and no more so than when dealing with children. In this special population, where the use of invasive techniques has long been considered unethical, the opportunity to utilise $\dot{V}O_2$ kinetics to understand the nuances of developmental exercise physiology is extremely attractive.

It is maybe surprising then, that with such a growth in research dedicated to the $\dot{V}O_2$ kinetic response, there is such a dearth of data examining and interpreting this response in children.

Historically, standard laboratory based tests that are considered valid in adults, are, after some considered adaptation, adopted by the paediatric exercise physiologist. As a result, the literature is rich with data pertaining to steady state and exhaustive exercise bouts in children. However, although useful and informative, these exercise stresses are poor correlates of the every day cardiorespiratory needs of the active child, and more specifically, the needs of children in diseased states. For this, we need to be able to examine the dynamic response to exercise, and the analysis of the transient $\dot{V}O_2$ response to exercise provides us with this tool. Unfortunately though, it is this transient nature that is perhaps the very reason why data pertaining to children are so scarce.

The following brief review discusses some of the methodological nuances of evaluating the $\dot{V}O_2$ kinetic response with children, and subsequently aims to encourage readers to adopt this analytical tool with this population with confidence. It is not the purpose of this article to extensively describe the $\dot{V}O_2$ kinetic response to an exercise stress, discuss the theoretical control mechanisms, or what is currently known regards the kinetic response in children, and readers who are not familiar with the concept are directed to other detailed reviews (Fawkner and Armstrong, 2003, Gaesser and Poole, 1996, Jones and Poole, 2005, Tschakovsky and Hughson, 1999).

Overview of the $\dot{V}O_2$ kinetic response to exercise

With adults, and to an extent children, the nature of the kinetic response has been identified to depend upon the relative exercise intensity set. At the onset of moderate intensity exercise (below the anaerobic threshold (T_{AN} , (Wasserman et al, 1994)), a cardiodynamic phase (phase 1) which is independent of oxygen uptake at the muscle (\dot{Q}_{O_2}) is followed by an observable exponential rise in $\dot{V}O_2$ (phase 2) towards a steady state (phase 3), and an oxygen (O_2) cost relative to work rate in adults (and probably children) of approximately $10\text{mL}O_2\cdot\text{min}^{-1}\cdot\text{W}^{-1}$. When the exercise intensity is above T_{AN} and below critical power (CP, (Moritani, 1981)), in the heavy intensity domain, the steady-state in $\dot{V}O_2$ is delayed, and an additional slow component of $\dot{V}O_2$ causes an eventual and elevated steady-state, and an elevation in the oxygen cost of exercise (Poole et al, 1988). Above CP, in the very heavy intensity domain, $\dot{V}O_2$ continues to rise almost linearly, and the slow component causes the eventual attainment of peak $\dot{V}O_2$. In severe intensity exercise,

Table 1. Methodologies for assessing the $\dot{V}O_2$ kinetic response to moderate intensity exercise in children.

Author	Sex	N	Age (y)	Step change	Sampling interval	Quantification method	No of transitions	Confidence interval	Time constant (τ , s)
Freedson et al. (1981)	M	28	10.2 (2.3)	BL – 49W	20s	$t_{1/2}$	1		34.8 (12.7)
Sady et al. (1983)	M	21	10.2 (1.3)	BL – 42% $\dot{V}O_{2\max}$	15s	$t_{1/2}$	1		18.5 (.75)
Cooper et al. (1984)	M	37	10 (2)	Ramp protocol	BB	MRT from ramp protocol	1		43 (15)
	M	21	16 (1)						
	F	24	9 (2)						
	F	27	15 (2)						
Cooper et al. (1985)	M	5	8 (1)	Rest – 75% T_{vent}	BB	Model 1, $t > 20s$	6		26.5 (3.0)
	F	5	9 (1)						26.5 (4.0)*
Springer et al. (1991)	M+F	9	8.2 (1.4)	Rest – 80% T_{vent}	BB	Model 2, $t > 15s$	5		23.9 (4.6)
Zanconato et al. (1991)	M+F	10	9.0 (1.3)	BL – 80% T_{vent}	BB	1min $t_{1/2}$	1		23.0 (5.3)
Armon et al. (1991)	M+F	6	6 – 12	BL – 80% T_{vent}	BB	Model 1, $t > 0s$	1		26 (8)*
Hamar et al. (1991)		18	14.1 (.6)	Rest – 65% peak	BB	Model 2, $t > \text{phase1}$	1		20.2 (5.9)
Hebestreit et al. (1998)	M	9	11.1 (1.2)	20W-50% peak $\dot{V}O_2$	BB	Model 2, $t > \text{phase1}$	4		22.8 (5.1)
Obert et al. (2000)	M+F	23	10-13	BL – 80% TLac	BB	Model 4, $t > \text{phase 1}$	1		24.9 (6.6)
Williams et al. (2001)	M	8	12.2 (.2)	Rest – 80% - TLac	BB	Model 5	4		10.2 (1.0)
Fawkner and Armstrong (2002b)	M	11	11.6 (.3)	BL – 80% T_{vent}	BB	Model 1, $t > 0s$	4-10	$\tau < \pm 5s$	29.5 (3.9)**
	F	12	11.7 (.4)						30.9 (4.5)*
Fawkner and Armstrong (2002b)	M	11	11.6 (.3)	BL – 80% T_{vent}	BB	Model 1, $t > 15s$	4-10	$\tau < \pm 5s$	29.0 (3.9)**
	F	12	11.7 (.4)						30.5 (3.9)*
Fawkner and Armstrong (2002b)	M	11	11.6 (.3)	BL – 80% T_{vent}	BB	Model 2, $t > 0s$	4-10	$\tau < \pm 5s$	25.9 (3.3)**
	F	12	11.7 (.4)						27.8 (4.2)*
Fawkner and Armstrong (2002b)	M	11	11.6 (.3)	BL – 80% T_{vent}	BB	Model 2, $t > 15s$	4-10	$\tau < \pm 5s$	19.0 \pm 2.0**
	F	12	11.7 (.4)						21.0 \pm 5.5*

Abbreviations: BL = baseline pedalling; T_{vent} = ventilatory threshold; TLac = lactate threshold ; τ = time constant

where the projected $\dot{V}O_2$ is greater than peak, the response is truncated with the rapid attainment of peak $\dot{V}O_2$ within minutes (Whipp and Mahler, 1980).

The rise in $\dot{V}O_2$ during phase 2 is thought to be a linear function of exercise intensity, certainly within the moderate domain. That is, the magnitude of the response is proportional to the stimulus, but the rate change is constant across exercise intensities. It is the rate of this change that is of considerable interest, since the more rapid is the rise

to steady state, the smaller is the O_2 deficit, and the less is the drain on exhaustible sources. The mechanism(s) controlling this response have been an issue of some contention, although the literature suggests that it is primarily governed by the muscles' potential for O_2 utilisation, with a number of additional contributory factors involved (Tschakovsky and Hughson, 1999). With exercise intensities above T_{AN} , although the exponential nature of phase 2 is maintained, the influence of exercise intensity upon the rate change within the heavy and very heavy domains is not confirmed. Although there

Table 2. Methodologies for assessing the $\dot{V}O_2$ kinetic response to heavy and severe intensity exercise in children.

Author	Sex	N	Age (y)	Step change	Sampling interval	Quantification method	No of transitions	Confidence interval
Robinson (1938)	M	8	6.0	Treadmill to exhaustion	30s	% of peak $\dot{V}O_2$ after 30s	1	
	M	10	10.5					
Mácek and Vavra (1977)	M	10	10	Treadmill to exhaustion	30s	% of peak $\dot{V}O_2$ after 30s	1	
	M	14	12					
	M	23	15					
M	6	17						
Mácek and Vávra (1980)	M	10	10-11	Cycle to exhaustion	30s	% of peak $\dot{V}O_2$ after 30s	1	
Sady (1981)	M	21	10.2 (.3)	Cycle - 110% $\dot{V}O_{2max}$	15s	t ½	1	
Zanconato et al. (1991)	M+F	10	9.0 (1.3)	BL - 50% Δ	BB	1min t½	1	
				BL - 100% peak $\dot{V}O_2$				
Armon et al. (1991)	M+F	6	6 - 12	BL - 125% peak $\dot{V}O_2$	BB	Model 4, $\delta_1 = \delta_2$, t > 0s	1	
				BL - 25% Δ				
				BL - 50% Δ				
BL - 75% Δ								
Obert et al. (2000)	M+F	23	10-13	BL - 90% max power	BB	Model 4, t > phase 1	1	
Williams et al (2001)	M	8	12 (.2)	Rest - 50% Δ	BB	Model 5, t > 0s	2	
Hebestreit et al (1998)	M	9	11.1 (1.2)	20W-100% peak $\dot{V}O_2$	BB	Model 2, t > phase1	2	
				20W - 130% peak $\dot{V}O_2$				
Fawkner and Armstrong (2004c)	M	13	10.6 (.3)	BL - 40% T_{Vent}	BB	Model 2, phase 1 < t < onset of SC	3-4	$\tau < \pm 5s$
	F	9	10.9 (.2)					A1 < $\pm 5\%$
Fawkner and Armstrong (2004a)	M	25	10.6 (.3)	BL - 40% T_{Vent}	BB	Model 2, phase 1 < t < onset of SC	3-4	Mean τ , 4.3 \pm 1.3s
	F	23	10.7 (.7)					Mean A1, 3.0 \pm 1.3 %

Abbreviations: BL = baseline pedalling; Δ = difference between anaerobic threshold had peak $\dot{V}O_2$; T_{Vent} = ventilatory threshold; τ = time constant; A1 = primary amplitude; for model details see text.

is conflicting evidence (Burnley et al, 2000, Tschakovsky and Hughson, 1999) it is possible that at these higher exercise intensities, O_2 delivery may play a greater contributory role in the adaptation of $\dot{V}O_2$ (Grassi et al, 2000). The source of the additional O_2 cost of exercise in phase 3 at intensities above T_{AN} (i.e. the slow component) remains equivocal, but has clear implications regarding efficiency. Current consensus refutes a causative link with lactate production (Poole et al, 1991, Womack et al, 1995), and favours a dependence upon fibre type distribution and recruitment (Barstow et al, 1996, Gaesser and Poole, 1996, Poole et al, 1994) with a range of possible contributory factors (Gaesser and Poole, 1996).

Accurately quantifying the $\dot{V}O_2$ kinetic response

The aim of quantifying the $\dot{V}O_2$ kinetic response is to evaluate the speed and the magnitude of the response, which more often than not is to a square wave transition in exercise intensity during either cycle or treadmill ergometry. This may be achieved using non-linear regression and iterative fitting procedures, and fitting a specified model to the available data as best as possible by choosing the line of best fit that reduces the residual error (within the reimits of the specified model). In order to achieve this, the following is necessary; a) The relative exercise intensity must be known so that b) the basic pattern of the response may be predicted and an appropriate model may be applied to data that must c) have high temporal resolution in order to apply any given model with d) a signal-to-noise ratio which is sufficiently good to achieve confidence in response parameters. Each of these requirements will be discussed below.

a) Since the amplitude and pattern of the $\dot{V}O_2$ kinetic response differs according to the exercise intensity domain, making valid intra- and inter- study comparisons requires that subjects are exercising at the same exercise intensity relative to the domain demarcators T_{AN} (moderate intensity) and CP (heavy intensity). However, in order to study the response to moderate intensity exercise, a number of studies with children have set exercise intensities relative to peak $\dot{V}O_2$ alone or have enforced a single exercise intensity across individuals (see Table 1). This is problematic since T_{AN} has been shown in children to vary considerably as to the percentage of peak $\dot{V}O_2$ at which it occurs, not least due to the method by which T_{AN} is detected and the method's reproducibility, reliability and validity. More appropriately, setting the exercise intensity as a percentage of T_{AN} provides some assurance that subjects are at least within the same intensity domain, which due to the linearity of the response, is sufficient in order to make valid comparisons.

The kinetic response to exercise intensities above T_{AN} with children has rarely been studied within carefully defined exercise intensity domains. The majority of studies have assessed the response to maximal and supramaximal exercise intensities and few studies have attempted to assess the existence or magnitude of the slow component of $\dot{V}O_2$ with children (Table 2). This is most likely because the assessment of the threshold of heavy intensity exercise, CP, is especially demanding in terms of both subject effort and testing time and only once to the authors' knowledge has assessment been attempted and reported with children (Fawcner and Armstrong, 2002a). As a result, investigators intending to explore the response to heavy intensity exercise have set exercise intensities as a percentage of the difference between T_{AN} and peak $\dot{V}O_2$. With 12 year old children, 40% of the differences (40% Δ) is considered to lie below CP (Fawcner and Armstrong, 2002a) and fall within the heavy intensity domain.

b) A number of models have been proposed to represent the pattern of the kinetic response, both generically and within well-defined exercise intensity domains. Originally, it was considered that the speed of the response to any exercise intensity could be assessed by measuring the time it took to reach half of the peak exercise $\dot{V}O_2$ achieved during the exercise test (the $t_{1/2}$, see Table 1 and 2). This method however fails to observe the exponential nature of the response, and subsequently the time constant (τ), which represents the time taken to achieve 63% of the change in $\dot{V}O_2$ from baseline to steady state ($\Delta\dot{V}O_2$) has been used in its place and is solved using model 1 (see Appendix).

This model allows a monoexponential to be fit to data from the onset of exercise (i.e. when time = 0), and the time constant is usually referred to as the mean response time (MRT). However, as has been identified above, the phase 1 response that lasts 10-20 seconds is independent of $\dot{Q}O_2$, which only becomes evident at the

mouth after the muscle – lung transit delay. Therefore there is a delay in time before $\dot{V}O_2$ is representative of the exponential increase in $\dot{Q}O_2$. In order to account for this, a delay term may be included in the model (model 2, see Appendix), and phase 1 data eliminated from the modelling process. Although the MRT does not necessarily allow for the accurate determination of the $\dot{Q}O_2$ kinetics, it does provide a useful parameter with which to assess the O_2 deficit in the moderate intensity domain, which is the product of the increase in $\dot{V}O_2$ during the transition ($\Delta\dot{V}O_2$) and the MRT.

As is clearly identifiable from Table 1, a number of different models have been used to analyse the response to moderate intensity exercise with children, and the effect this has on response parameters is most evident when a number of the models are applied to the same data set (Fawcner and Armstrong, 2002b). This study, which addressed the use of different modelling techniques with children, confirmed that as with adults, the response to moderate intensity exercise is best described using a single exponential and delay term following phase 1 (model 2, see Appendix).

The situation becomes more complex when dealing with heavy intensity exercise. The true nature of the response, specifically the slow component, is not entirely understood. Despite this, some authors have chosen to model the slow component as an additional exponential (model 3, see Appendix) suggesting that it represents a delayed and slowly emerging component rather than one that emerges in synchrony with the initial phase 2 primary component. Thus the model includes two exponentials each with an independent delay term and two amplitudes which represent the amplitude of the primary and slow component. With this model, the secondary delay (δ_2) has been interpreted as the time of the onset of the slow component. Other authors have chosen to model the slow component as a linear term (model 4, see Appendix), which has some justification at exercise intensities above CP since at these intensities $\dot{V}O_2$ rises rapidly towards peak $\dot{V}O_2$.

Despite the wide spread use of these models (with adults and to an extent children), unlike the primary phase 2 component, modelling the slow component with either an exponential or a linear term does not have any confirmed physiological rationale. In fact, attempts to combine models of both the primary and slow component in the one model can negate the accuracy with which the primary time constant and amplitude are estimated (see below). This concern is paramount when a model is forced to fit a data set for which the basic pattern of response does not comply. In the case of fitting a double exponential, this is frequently the case if there is either no clear slow component, or its rise more closely resembles a linear function than an exponential one (see Table 3 and Figure 1, step change 3 for an example).

As a result, more recently, authors are adopting the process of attempting to objectively identify the onset of

Table 3. Model 3 response parameters for a series of step changes to heavy intensity exercise for an 11 year old child.

Step	Response parameters						Confidence intervals	
	A_1 (L·min ⁻¹)	δ_1 (s)	τ_1 (s)	A_2 (L·min ⁻¹)	δ_2 (s)	τ_2 (s)	τ_1 (s)	A_1 (%)
1	.96	16.2	11.3	.13	68.1	117.1	7.0	5.5
2	.94	14.3	15.7	.07	130.0	83.6	6.7	4.3
3	1.03	16.6	16.2	>1000.00	70.0	>1000.0	4.7	2.9
4	.92	18.8	9.1	.10	145.0	24.5	13.3	4.3
Steps averaged	.96	16.5	13.0	.08	144.0	41.3	2.7	2.1

A_1 , and A_2 , τ_1 and τ_2 and δ_1 and δ_2 , amplitudes, time constants and time delays of each exponential respectively.

the slow component, model the data of the primary component independently and report the amplitude of the slow component with respect to the end exercise $\dot{V}O_2$ (Fawkner and Armstrong, 2004a;c, Rossiter et al, 2002). Until a model with sound physiological basis with which to parameterise the slow component is identified, it is suggested that this is the model of choice (Fawkner and Armstrong, 2004b).

In severe intensity exercise the slow component of

$\dot{V}O_2$ does not have time to develop (although investigators must be assured that the exercise intensity is severe enough such that this is the case), and the mono-exponentiality of the response is therefore not distorted (Whipp and Özyener, 1998), and can be modelled as such (model 2, see Appendix). However, only a few early studies have attempted to investigate the kinetic response to severe intensity exercise with children, and they have adopted more simple methods (see Table 2) to

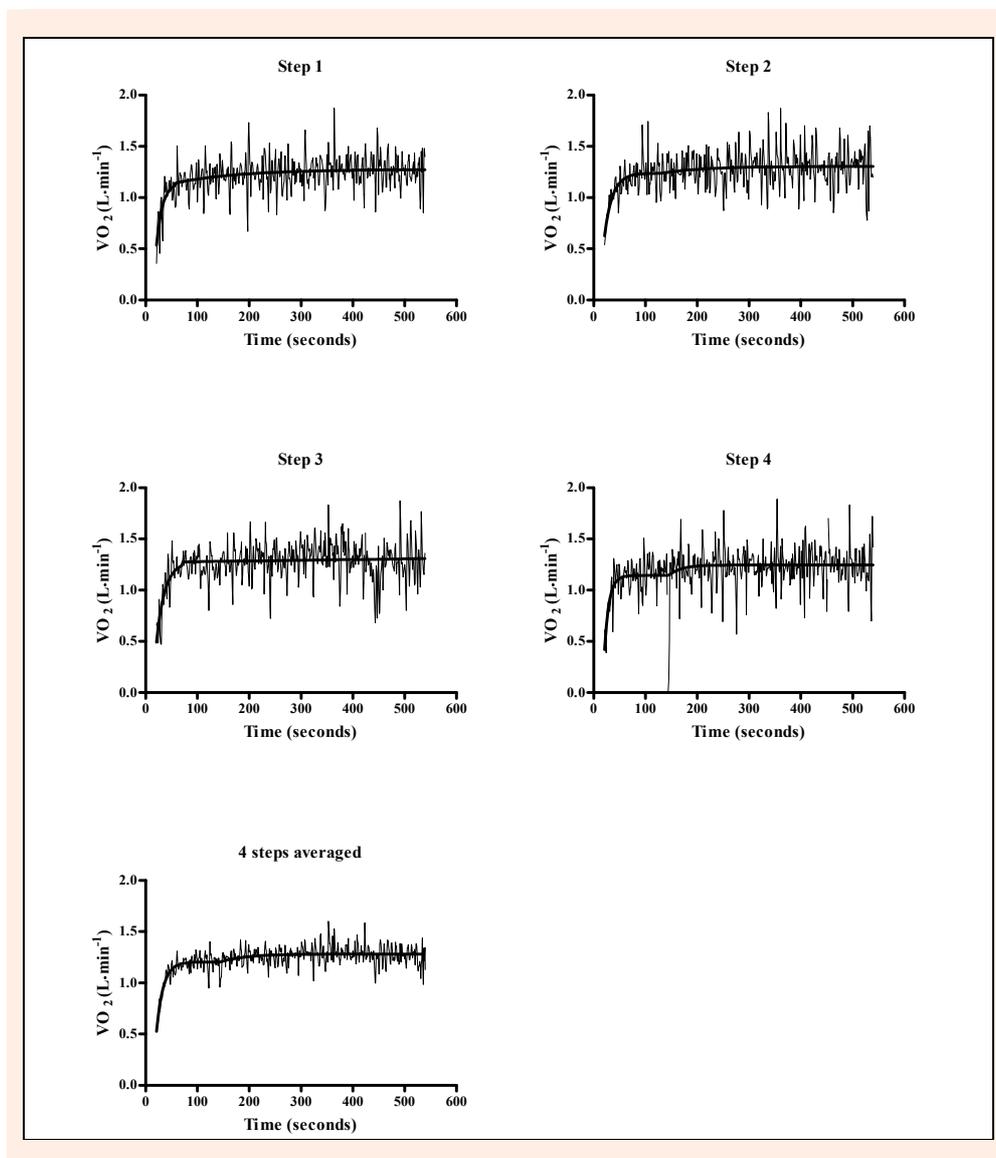


Figure 1. $\dot{V}O_2$ response to heavy intensity exercise for an 11 year old boy on four separate occasions, illustrating the interpolated breath-by-breath data and the best fit line using a double exponential model following phase 1 (model 3). The final graph illustrates the averaged data and the best fit line. The returned response parameters for each transition are reported in table 3.

characterise the response. This is possibly due to the poor temporal resolution of the data collected which would have prevented more complex model parameterisation (see below).

c) Early studies with children examining the $\dot{V}O_2$ kinetic response to exercise relied on traditional mixing chamber systems, where by measures of mixed expired samples were drawn off mixing chambers with measurement intervals of typically 15 to 30s (Tables 1 and 2). However, in order to be able to accurately capture the dynamic response of $\dot{V}O_2$ to the onset of exercise, gas and respiratory data must be collected with a much higher temporal resolution, i.e. on a breath-by-breath basis. Online metabolic carts have come a long way since the pioneering work of Beaver et al. (1973), and although the combination of mass spectrometry and turbine flow meters is possibly still the ultimate tool for assessing true 'breath-by-breath' responses at the mouth, most commercially available metabolic carts with rapidly responding O_2 and carbon dioxide analysers now have the facility to generate breath-by-breath data. Despite this, as is clear from tables 1 and 2, there are still few studies that have employed these techniques with children.

d) One of the disadvantages of assessing gas and ventilatory variables on a breath-by-breath basis is that the response data reflect not only the true physiological signal of interest, but also breath-by-breath fluctuations in breathing patterns. Unfortunately for the paediatric exercise physiologist, the magnitude of these fluctuations (the noise) seems to be larger during exercise than it is with adults (Potter et al, 1999). Since the signal ($\dot{V}O_2$ amplitude in this case) is also smaller for children, the resulting signal-to-noise ratio is often so poor that fitting complex mathematical models requires serious consideration if the investigator is to be at all confident that the model fit is a true reflection of the physiological signal. This is particularly so when models involve a number of parameters, all of which are interdependent (such as models 3 – 5, see Table 3 and Figure 1, and see Appendix). It is also a serious issue when dealing with clinical populations, whose tolerance of exercise stresses may be restricted such that the stimulus must be low and thus the response signal is disproportionately small.

There are two main procedures that the investigator might carry out to improve confidence in their reported response parameters; reducing the signal-to-noise ratio and reporting the 95% confidence intervals of the response parameters.

The latter of these procedures is now relatively simple to achieve, as many iterative fitting programmes also return the 95% confidence intervals for the response parameters. Ideally, a confidence interval of no more than $\pm 5s$ for the primary τ , and $\pm 5\%$ for the primary amplitude should be achieved. Reducing the signal-to-noise ratio to achieve this can however place a substantial practical demand upon the study design. By carrying out a number of repeat transitions, time aligning and averaging the responses, the magnitude of the noise may be reduced, whilst theoretically the signal remains unaltered (see Lamara et al, 1987) for an in depth explanation of

this). So, whilst a single transition does not allow suitable confidence in estimating response parameters, averaging a series of data sets may do so (see table 3 and figure 1 for an example). The number of transitions that are required to achieve suitable confidence is directly proportional to the amount of data being fit, the variability of the data and the magnitude of the signal, and thus will vary from one individual to another. With children's data which are inherently noisy, as many as 10 transitions at moderate intensity might be required. At heavier intensities, fewer transitions are required because the signal is greater.

For practical purposes, if the investigator is interested in modelling the response to a step change at moderate intensity, s/he may estimate the number of repeat transitions required to achieve a given 95% confidence interval using the following equation (Lamarra et al, 1987). For this, only the amplitude and standard deviation of the steady state $\dot{V}O_2$ following a single transition are required (equation 1)

$$n = \left[\frac{\hat{L} \cdot \dot{V}O_2 \text{ (sd)}}{K_n \cdot \Delta \dot{V}O_2 \text{ (ss)}} \right]^2 \quad \text{Equation 1}$$

where n is the number of transitions required; \hat{L} is a constant dependent upon the underlying time constant, and the amount of data available for fitting; $\dot{V}O_2 \text{ (sd)}$ is the standard deviation of breath-by-breath fluctuations in $\dot{V}O_2$; $\Delta \dot{V}O_2 \text{ (ss)}$ is the steady-state amplitude of $\dot{V}O_2$ above the baseline; and K_n is the confidence interval.

This technique has proved useful when investigating the $\dot{V}O_2$ kinetic response in children (Fawkner et al, 2002) but might be especially effective when dealing with young children with cardiorespiratory or metabolic disorders. In these instances, a number of repeat bouts of exercise might be particularly demanding and practically difficult to achieve, yet may also be meaningless if the responses are still too noisy after averaging for use (Potter and Unnithan, 2005). For example, a recent study examining $\dot{V}O_2$ kinetics in cystic fibrosis patients (mean age 15.8 ± 6.1 years) had to exclude six of the 24 patients due to noise magnitude, despite averaging up to four transitions (Hebestreit et al, 2005).

Unfortunately, few investigators to date have incorporated either of these procedures, and where they may have averaged a number of transitions together in order to reduce the signal-to-noise ratio, this is relatively meaningless unless confidence intervals are also provided (Tables 1 and 2).

Conclusion

With the currently available technology and comprehension of the response to dynamic exercise, it is possible to study the $\dot{V}O_2$ kinetics of children with confidence. This is only possible if the investigator is able to take appropriate steps to insure that the data are modelled correctly and that response variables are returned with reported confidence intervals. To date, studies that have achieved this are so few and far between, that there is still a great deal

to be learnt regards the $\dot{V}O_2$ kinetic response in both healthy and diseased children.

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Key points

- The $\dot{V}O_2$ kinetic response to exercise represents the combined efficiency of the cardiovascular, pulmonary and metabolic systems, and an accurate assessment of the response potentially provides a great deal of useful information via non-invasive methodology.
- An accurate assessment of the $\dot{V}O_2$ kinetic response is however inherently difficult with children and especially those with reduced exercise tolerance, due primarily to the apparent breath-by-breath noise which masks the true underlying physiological response, and the small amplitudes of the response signal.
- Despite this, it is possible to assess and quantify the $\dot{V}O_2$ kinetic response with children if appropriate steps are taken to apply carefully selected methodologies and report response variables with confidence intervals. In this way, both the researcher and the reader can be confident that the data reported is meaningful.

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APPENDIX

$$\Delta \dot{V}O_2(t) = \Delta \dot{V}O_2(ss) \cdot \left(1 - e^{-t/\tau}\right) \quad [\text{model 1, MRT}]$$

$$\Delta \dot{V}O_2(t) = \Delta \dot{V}O_2(ss) \cdot \left(1 - e^{-(t-\delta)/\tau}\right) \quad [\text{model 2}]$$

$$\Delta \dot{V}O_2(t) = A_1 \cdot \left(1 - e^{-(t-\delta_1)/\tau_1}\right) + A_2 \cdot \left(1 - e^{-(t-\delta_2)/\tau_2}\right) \quad [\text{model 3}]$$

$$\Delta \dot{V}O_2(t) = A_1 \cdot \left(1 - e^{-(t-\delta_1)/\tau_1}\right) + S(t-\delta_2) \quad [\text{model 4}]$$

$$\Delta \dot{V}O_2(t) = A_1 \cdot \left(1 - e^{-(t-\delta_1)/\tau_1}\right) + A_2 \cdot \left(1 - e^{-(t-\delta_2)/\tau_2}\right) + A_3 \cdot \left(1 - e^{-(t-\delta_3)/\tau}\right) \quad [\text{model 5}]$$

Where: MRT, mean response time; t, time in seconds; $\Delta \dot{V}O_2(t)$, increase in $\dot{V}O_2$ at time t above the prior control level; $\Delta \dot{V}O_2(ss)$, steady-state increment in $\dot{V}O_2$; τ , time constant which is time to achieve 63% of the $\Delta \dot{V}O_2(ss)$; A_1 , A_2 and A_3 , τ_1 , τ_2 and τ_3 and δ_1 , δ_2 , δ_3 , amplitudes, time constants and time delays of each exponential respectively.