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The measurement and interpretation of aerobic fitness in children: current issues

J R Welsman PhD N Armstrong PhD

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INTRODUCTION

Generation of energy from aerobic metabolism is largely dependent upon the ability of the pulmonary, cardiovascular, haematological and cellular systems to transport oxygen from the atmosphere to the contracting muscles and the ability of the tissues to use oxygen to catabolize fuels[1].

Maximal aerobic power or maximum oxygen uptake ($\dot{V}O_{2max}$) refers to the maximum rate of oxygen consumption during exercise with large muscle groups of increasing intensity continued to exhaustion. As $\dot{V}O_{2max}$ limits an individual's capacity for aerobic exercise it is widely accepted as the single best indicator of aerobic fitness[2].

Protocols for the measurement of $\dot{V}O_{2max}$ and its interpretation in the context of health or training status in adults are well established. Children, however, are not mini adults and the variability of physiological responses to maximal exercise observed during growth and maturation confound and complicate these processes. Interest has recently been focused on the determination of maximal effort in children and adolescents and whether the peak levels of oxygen uptake measured during incremental exercise truly represent a maximal index of aerobic fitness.

The interpretation of aerobic fitness in young people is confounded by the need to appropriately partition out body size differences from group comparisons, e.g. by age or sex. Renewed interest in the merits and pitfalls of various scaling techniques has produced some interesting findings which challenge conventional interpretation of changes in aerobic fitness with growth and maturation. This paper addresses some of these issues currently engaging the interest of paediatric exercise physiologists with an emphasis on the recent work of the Children's Health and Exercise Research Centre at the University of Exeter.

MEASUREMENT OF AEROBIC POWER

The response of oxygen uptake to progressive exercise is essentially linear until a point is reached where further increases in exercise intensity fail to elicit comparable increments in oxygen uptake which is seen to plateau. This relationship was first demonstrated by Hill and co-workers in a series of now classic experiments carried out in the early part of this century[3,4]. As subjects were able to continue exercising beyond the point at which $\dot{V}O_2$ levelled off, the conclusion was that additional energy requirements were being met by anaerobic sources with consequent lactate accumulation and inevitable fatigue. Although recent studies have raised issues concerning both the theoretical[5] and methodological[6] validity of the $\dot{V}O_2$ plateau, the demonstration of a plateau is invariably sought to establish maximal effort during an exercise test to exhaustion[1,2].

As an absolute levelling off in oxygen uptake during such a test is rarely observed, it is usual to apply one of the less stringent plateau criteria. These include: an increase of less than $150\,mL.min^{-1}$ or $2.1\,mL.kg^{-1}.min^{-1}$ for a 2.5% increase in speed[7]; a rise in $\dot{V}O_2$ of less than 2 standard deviations below that of the mean of changes between previous exercise intensities[8]; or a final increase in $\dot{V}O_2$ of less than 5%[13,14]. The criterion proposed by Shephard[9], of an increase in $\dot{V}O_2$ of no more than $2.0\,mL.kg^{-1}.min^{-1}$ for a 5–10% increase in exercise intensity has perhaps been most widely used by paediatric exercise physiologists[10–12].

Regardless of the definition used, it is accepted that many children will not attain a $\dot{V}O_2$ plateau during an incremental exercise test to exhaustion. Exact percentages vary, but in large samples of untrained children only 30–50% typically fulfil a plateau criterion[10,13,15,16], hence the preferential use of the term peak $\dot{V}O_2$ to denote the highest $\dot{V}O_2$ elicited during an incremental test to exhaustion rather than $\dot{V}O_{2max}$ which assumes the demonstration of a plateau[17].

In the absence of this apparently objective marker, the question arises as to whether a child has indeed given a truly maximal effort? Several studies have failed to identify significant differences in values of oxygen uptake obtained between groups of subjects who demonstrate plateaux and those who do not[18–21]. Others have actually noted significantly higher values for oxygen uptake in those subjects not attaining a plateau[16,22].

Furthermore, in groups of boys and girls aged 9–10 years we have found no significant increase in oxygen uptake during exhaustive runs at treadmill gradients 2.5% and 5% greater than the final gradient completed in the initial

Correspondence to: Dr Joanne Welsman, Children's Health and Exercise Research Centre, University of Exeter, Heavitree Road, Exeter EX1 2LU, England

test[23,24]. These data support previous indications[25] and confirm that a $\dot{V}O_2$ max plateau is not a prerequisite for defining maximal effort in children.

Whether or not there is a physiological explanation for children's inability to consistently demonstrate $\dot{V}O_{2max}$ plateaux during a standard incremental exercise test remains unclear. No significant differences in any peak physiologic or anthropometric measures between children demonstrating a plateau and those not demonstrating a plateau have been found[22,24,26]. The apparently obvious explanation is that children lack the necessary mechanisms to generate sufficient energy anaerobically to enable them to continue exercising beyond the limits of aerobic metabolism[27,28]. Although higher indications of anaerobic metabolism, such as increased respiratory exchange ratio (RER) and blood lactate, have been noted in children consistently demonstrating plateaux in repeated testing[19], other studies with prepubescent and adolescent subjects have failed to record significant differences in post-exercise lactates between plateau and no-plateau groups[15,22,26]. Furthermore, the significantly higher blood lactate, RER and ventilation observed in children during supramaximal exercise further confirm that children's capacity to exercise beyond peak $\dot{V}O_2$ is not limited by an inability to exercise anaerobically[23,24].

The paediatric incremental exercise test is usually terminated by the subject's voluntary exhaustion, i.e. where despite strong verbal encouragement, the child is unwilling or unable to continue[17]. Subjective signs of exhaustion towards the end of the test (unsteady gait, hyperpnea, sweating, facial flushing and grimacing) may, in fact, provide the most useful indication that the child has attained maximal effort—providing, that is, that the child has been appropriately habituated to the laboratory procedures[17]. In the absence of a $\dot{V}O_{2max}$ plateau it is conventional to seek confirmation of maximal effort through application of recommended secondary criteria[17,29] based upon final values for heart rate, RER and blood lactate. However, although objective, these criteria are not without problems. For example, a terminal heart rate of 200 beats.min^{-1} ($\pm 5\%$) and/or a respiratory exchange ratio at least 0.99 to 1.0 are most frequently sought. Maximal heart rates are, however, extremely variable in children and adolescents and may range from 180 to 220 beats.min^{-1}. RER is highly dependent upon test protocol and mode of exercise with cycle ergometry typically eliciting higher values[10,30,31]. However, in the presence of clear subjective indications of maximal effort, a levelling off in heart rate and high RER do provide valuable confirmatory markers[26].

The requirement for high post-exercise blood lactates[27,32,33] is particularly problematic with children and adolescents: In our laboratory post peak $\dot{V}O_2$ blood lactates range from less than 4.0 mmol.L^{-1} to more than 13 mmol.L^{-1}. Again, many methodological factors influence blood lactate determinations including the timing of post-exercise sampling and the blood preparation and assay procedures[34,35]. As the timing of, and mechanisms behind, the maturation of the blood lactate response remain to be clarified[35,36] the use of this measure to establish maximal effort is not recommended.

INTERPRETATION OF AEROBIC FITNESS DURING GROWTH

Armstrong and Welsman[17] recently summarized data representing over 10 000 cross-sectional and longitudinal peak $\dot{V}O_2$ determinations in 8 to 16-year-old 'untrained' children. These data show a progressive, linear increase in peak aerobic fitness in relation to chronological age during this period in both boys and girls with higher levels in boys apparent from approximately 10 years of age. When expressed relative to body mass a different picture emerges. A remarkably consistent level of mass-related peak $\dot{V}O_2$ is observed in boys over the adolescent period[10] with typical values of 49–50 mL.kg^{-1}.min^{-1}. In contrast, a marked tendency for mass-related aerobic fitness to decline is characteristic of female adolescence with peak $\dot{V}O_2$ falling from around 45 to 39 mL.kg^{-1}.min^{-1}.

Concerns raised by Tanner[37] with the validity of normalizing peak $\dot{V}O_2$ data by its expression in ratio with body mass are again topical[17,38,39]. Despite some interest in the seventies[40,41] there has been no widespread investigation of alternative normalization techniques and ratio standards have continued to be applied widely and, in the most part, uncritically to the interpretation of children's and adolescents' peak $\dot{V}O_2$.

Tanner[37] demonstrated the caveats associated with ratio standards showing that their use was only appropriate to normalize data when the following statistical condition was satisfied; $V_x/V_y = r\ x,y$, where V_x and V_y represent the coefficients of variation for the body size and performance variable, respectively, and r is the Pearson product moment correlation coefficient. If this condition is not satisfied, application of ratio standards will distort data with the size of the distortion increasing as the discrepancy between the two sides of the equation increases. The effect of this distortion is to advantage individuals of low body mass and, conversely, penalise those of high mass.

An alternative means of partitioning out body size differences based upon linear regression was proposed by Tanner. Here, the relationship between body mass and peak $\dot{V}O_2$ is not described by $Y = ax$ (the line of the ratio standard) but by the regression equation: $Y = a+bx$. Regression lines describing different groups, e.g. by age, sex or maturity, may be compared using analysis of covariance. Using this procedure, adjusted means are produced, which although expressed in absolute terms (L.min^{-1}) reflect values for peak $\dot{V}O_2$ from which the influence of body mass has been removed[38].

Recent research evidence has demonstrated how conclusions regarding the interpretation of performance have altered considerably from conventional interpretation when linear regression rather than ratio normalization procedures have been employed. In adults, Winter *et al.*[42] identified differences in maximal anaerobic performance between men and women that were obscured by a ratio-based comparison. Similarly child–adult differences in submaximal running economy were shown to disappear when comparisons were based upon linear regression[43]. Our initial investigations of changes in peak $\dot{V}O_2$ with age and maturity in boys using a linear regression model[44] revealed significant increases in peak $\dot{V}O_2$ during this period in contrast to the usual finding of no significant change with values expressed in relation to body mass. A subsequent developing of this study to include males and females from prepuberty to adulthood[45] confirmed these findings in the male group with significant increases in peak $\dot{V}O_2$ across this maturational range. The results for females also differed from the conventional interpretation as adjusted peak $\dot{V}O_2$ was observed to increase into puberty and then remain constant. Although these and other studies[39,46,47] have demonstrated the utility of linear scaling techniques to account for body size differences, several statistical difficulties associated with their use signal caution with their widespread application to the interpretation of performance data.

The frequent finding of positive intercepts, suggesting that a physiological response exists for zero body mass, is obviously a concern which remains even if care is taken not to extrapolate beyond actual data points[38]. Of perhaps greater significance are the problems associated with the regression model's assumption of an additive error term[17,39,45]. Linear scaling methods are only appropriate where performance scores diverge at a constant rate with increasing body size. This is rarely the case with performance data where an increasing spread around the regression line is observed as body size increases[39]. Where this is the case, allometric scaling may be more suitable. Allometry is widely used in the biological sciences to describe and understand structure–function relationships[48] but has seen relatively minimal application within the exercise sciences. The allometric equation takes the general form, $Y = a\,x^b$. The parameters a and b may be conveniently derived by fitting a least-squares linear regression line to the log-transformed data

$$\ln y = \ln a + b \ln x$$

This transformation also permits group comparisons using ANCOVA exactly as described for the linear regression scaling. Alternatively, having identified the value of the mass exponent (b) power function ratios, Y/x^b, can be computed. This still accurately controls for differences in body mass but group comparisons are simplified as simple t-test or analysis of variance statistical tests may be used[39]. Studies using allometric principles to interpret performance data have consistently shown these models to represent a better statistical fit than either ratio or linear models[35,39,49] despite leading to essentially the same conclusions regarding sex or maturational differences in peak $\dot{V}O_2$ as described following application of the linear models.

Linked with the application of allometry to the interpretation of performance data in children is the much-debated question as to the numerical value of the mass exponent which best describes the relationship between peak $\dot{V}O_2$ and body mass during growth. The findings, in several studies, of mass exponents close to 1.0[18,50,51] have inevitably provided support to perpetuate the use of simple ratio standards. However, evidence is accumulating which, first, explains the high exponents previously observed and, secondly, indicates that a mass exponent of 0.67 as predicted by surface law or the theory of geometric similarity[2,48] appropriately normalizes peak $\dot{V}O_2$ data in children and adolescents. To summarize this evidence briefly, Nevill[49] has argued that in heterogeneous subject groups, for example where body size varies widely, failure to incorporate body size (height) as well as mass into the allometric equation will inflate the mass exponent. The explanation for this effect lies in the increase in the proportion of muscle mass in relation to overall body mass apparent with increasing size in larger mammals[55]. A similar relationship has been confirmed in adolescent males with leg volume proportional to mass[1,11,56]. With body size controlled for by including height as a continuous covariate in the allometric analysis, mass exponents not significantly different from 0.67 have been identified in children, adolescents and adults[45,49]. In what appears to be the only study to have modelled peak $\dot{V}O_2$ in a large ($n = 164$) well-defined (prepubertal) group of boys and girls where differences in body size are not extreme a mass exponent of 0.67 was identified for peak $\dot{V}O_2$[57] confirming findings from appropriately modelled adult data[2,39].

In summary, the assessment and interpretation of peak aerobic fitness in children and adolescents is fraught with problems. The wide variability in children's physiological responses to incremental exercise preclude the recommendation of fixed criteria for defining maximal effort. Subjective signs of exertion may, in fact, be most valuable supported by a plateau in heart rate and high RER. There is now sufficient evidence to seriously question the uncritical acceptance of ratio standards to partition out body size differences from the interpretation of growth and maturational changes in peak $\dot{V}O_2$. If alternative scaling techniques identify significant differences between groups previously obscured then physiological explanations to account for them must be sought[44]. Further investigations of the validity of these techniques are required to elucidate these issues.

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