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Ventilatory variables in normal children during rest and exercise

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ABSTRACT: The aim of this study was to provide a complete description of normal ventilation at rest and exercise in children and to determine how best to correct for body size.

One-hundred and six children aged 8–17 years (55 male) underwent incremental bicycle exercise testing from rest to exhaustion in 3 min, 15 W·m^{-2} steps and thence through 9 min recovery. All variables were calculated using helium dilution mixed expired gas analysis together with measures of alveolar gas concentrations from continuous measurement at the mouth, all *via* an AMIS 2000 quadrupole mass spectrometer.

Surface area was the best single measure to correct for body size but always explained <37% of the variance. Thus for example, surface area corrected oxygen consumption at rest in males was greater than females. Data is presented at rest, each work load and at "maximum" exercise. When presented per watt of work at each work load, this permits comparison of adaptability to exercise between sexes and age groups. Exercise appears to terminate when respiration reaches 45 and 40 breaths·min^{-1} in males and females respectively and when alveolar oxygen concentrations rise.

This simple protocol and near complete data set ought to permit accurate comparison with disease groups.

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It is nearly 30 yrs since a semicomplete set of ventilatory variables was published by GODFREY *et al.* [1] in normal UK children. These results were given as linear equations based on three points: rest, one-third and two-thirds of a previous estimate of maximum work for each child. Although linear equations were given which appear adequate, they were based on only three data points and cardiac output on two. The method used to calculate the regression equations is presently regarded as flawed [2]. It is thus difficult to compare a diseased subject with this data under identical conditions. Some ventilatory variables, for example carbon dioxide production, were not measured.

Since then there have been a large number of studies on various aspects of ventilation, in particular, maximum oxygen consumption. Many of these are summarized in review papers [3, 4]. There are few, if any studies which simultaneously measure all or near all ventilatory variables and none discovered that measure them simultaneously or near simultaneously with cardiac variables, gathered either invasively or noninvasively.

Many controversies still exist in the collection and presentation of such ventilatory data. For example, weight has been frequently used as a denominator for oxygen consumption although surface area may be better [5]; thus it is unclear how the effects of differing body size, sex, age and pubertal stage should be allowed for. The measurement of values at "maximum" exercise only, may represent a value at a psychological rather than a physiological maximum although much effort has been expended trying to define this state in children [3]. Although standards for paediatric exercise testing have been proposed [6], many different protocols are still used.

To overcome most, but not all the problems described above, this study describes the noninvasive collection of nearly all possible ventilatory variables using respiratory mass spectometry during rest, and a simple incremental bicycle exercise protocol that allows accurate comparison between healthy and disease study groups. The haemodynamic data collected near-simultaneously from this study has already been published [7]. A subsidiary aim was to determine how best to correct these data for body size.

Methods

The study received approval from the Royal Brompton Hospital ethical committee and informed, written consent was obtained from all parents and children. The study population and exercise protocol have been described previously [7] but are briefly summarized below:

The study population

One-hundred and six healthy children (55 male) were recruited from three local London schools. Two-hundred and thirty-nine out of three-hundred and twelve invited families gave consent and 106/239 were chosen at random to ensure even representation across the age range for each sex; 23 were aged 8–10.5 yrs, 24 were aged 10.5–12.5 yrs, 37 were aged 12.5–14.5 yrs and 22 were aged 14.5–16.9 years. Thirty were pre-pubertal, 36 in early puberty (Tanner stages 2 and 3), 38 in late puberty (Tanner stages 4 and 5) and two males refused to be examined. No attempt was made to subdivide by ethnic group, as 85% were white Caucasians and the rest, a variety of other races.

Entry criteria

All subjects were: >7.5 yrs old, the minimum age which, based on a pilot study, ensured cooperation; >125 cm tall, the minimum height for using the exercise bicycle; without a history of recent (3 weeks) acute or significant chronic respiratory or other conditions; and not receiving medications.

Protocol

Children were studied in pairs and were fasted for at least 1 h prior to study. On arrival, their date of birth, race, height (Harpenden height stadiometer, Holtain Ltd, Crymmych, UK), weight (SECA, Birmingham, UK) and two site skinfold measurements (triceps and subscapular, Holtain, Crymmych, UK) to estimate fat mass [8] were recorded. They then underwent a physical examination to exclude unexpected disease. Spirometry using UK standards [9] (Compact Vitalograph, Lenexa, KS, USA) was carried out to exclude unexpected airways obstruction although no child failed this screening procedure.

Following screening, and a 25-min period spent seated, the child then sat on a calibrated, electromagnetic bicycle (SECA 100, Birmingham, UK) and began mixed expired gas analysis. After a further 3-min rest period, the subject cycled, initially backwards at zero load to loosen up and then forwards at 50–70 revolutions per minute (rpm), initially at 25 $W \cdot m^{-2}$, increasing in 15 $W \cdot m^{-2}$ increments every 3 min until exhaustion. The child then rested whilst seated on the cycle but still underwent mixed expired gas analysis. Gas measurements were made both at the mouth and at the mixing box every 15 s. A typical study lasted 75 min. Both before and during the period of mixed expired gas analysis, the child underwent 12–16 rebreathing manoeuvres, the results of which have been already reported [7].

The mass spectrometer

An Innovision 2000 mass spectrometer (Innovision, Odense, Denmark), separates gases by their mass:charge ratio and their concentration is proportional to their amplified electrical signal. Comparing the signal with a calibration gas allows concentrations to be calculated. Errors due to changes in gas viscosity, the addition of exhaled water vapour or electrical drift were avoided by ensuring that the total electrical signal represented 100% of the gas with the known components correctly apportioned (automatic total pressure correction). The calibration gases (tolerance±2%, BOC, London, UK) had a typical make-up of acetylene 0.3%, argon 1%, helium 1%, sulphur hexaflouride 3%, carbon dioxide 5%, oxygen 25% and balance nitrogen. This tolerance for high concentration gases was further refined by the spectrometer using the known concentration of O_2 in room air, 20.93%.

Ventilatory measurements

Ventilatory measurements were made using helium dilution mixed expired gas analysis [10]. If an inert tracer gas (helium) is injected at a known constant rate into a stream of expired air then the flow of any component in that mixture may be calculated by measuring the concentrations downstream. The greater the flow of expired gas, the greater the dilution of the inert tracer. Assuming no net flux of nitrogen across the alveolar capillary membrane and knowing the composition of the inspiratory gas (air) then total minute ventilation, O_2 consumption and CO_2 production can be calculated without assuming an arbitrary respiratory quotient. The derivations of these equations are given in the appendix. The respiratory quotient (RQ) is calculated from the ratio of CO_2 production to O_2 consumption.

One can calculate further parameters by placing a second sampling probe at the mouth so that mean plateau (alveolar) CO_2 can be measured [11] and compared with the mean concentration in the mixing box to calculate the physiological fractional dead space (defined in appendix).

Calibration

The mass spectrometer was activated at least 12 h prior to any study to ensure maximum stability. A two point calibration (zero and calibration gas) was performed three times for each subject and a one point calibration (calibration gas only) >10 times. The helium gas flow rate was measured 40 times prior to every study for a 3-min period. During the entire study the coefficient of variation was always <2.5%.

Data analysis

Data for each ventilatory variable was recorded after 2.5 min exercise at a particular workload, the last 30 s of the 3 min exercise stage being taken up with performing the rebreathing manoeuvre.

Forward, stepwise, multiple linear regression was used to determine the significant factors in a variable at rest and after the 40 $W \cdot m^{-2}$ exercise stage. The factors used were sex, surface area ((weight.height/3600) 0.5 L), height, weight, age and pubertal stage. Significance was defined as $p<0.05$. Statistics were calculated using Statistical Package for Social Sciences (SPSS) v9 (SPSS, Chicago, USA).

Results

The growth variables for each sex and age group are shown in table 1 together with the number of children completing each stage of exercise. Every child exercised for ≥9 min. One male refused to complete the recovery part of the study.

Table 1. – Growth variables for each subgroup of children together with numbers of children completing a particular workload

Growth variables	Age group yr							
	<10.50		10.51–12.50		12.51–14.50		>14.50	
	M	F	M	F	M	F	M	F
Subjects n	11	12	13	11	18	19	13	9
Height cm	137 (129–151)	139 (129–147)	150 (144–164)	152 (142–163)	160 (144–174)	157 (145–170)	173 (167–183)	162 (148–167)
Height z-score	0.23 (-1.0–3.0)	1.22 (-1.2–2.3)	0.79 (-0.4–2.5)	0.53 (-0.2–1.6)	0.07 (-1.7–1.9)	-0.1 (-1.6–1.8)	0.27 (-0.6–1.9)	-0.1 (-2.0–0.9)
Weight kg	36 (23–57)	32 (23–46)	41 (37–68)	44 (33–61)	52 (36–61)	48 (31–65)	62 (51–75)	52 (44–66)
Surface area m^2	1.16 (0.9–1.5)	1.12 (0.9–1.4)	1.33 (1.2–1.8)	1.37 (1.1–1.7)	1.54 (1.2–1.7)	1.49 (1.1–1.7)	1.71 (1.5–1.9)	1.53 (1.4–1.7)
Triceps skinfold z-score	1.16 (0.5–2.8)	1.21 (-0.9–2.8)	1.25 (-0.4–2.3)	1.06 (0.1–2.3)	0.69 (-1.0–2.4)	0.82 (-1.3–2.1)	0.72 (-0.9–1.9)	0.83 (-1.2–2.4)
Subscapular skinfold z-score	0.59 (-0.2–2.7)	0.77 (-0.5–2.4)	0.24 (-0.6–2.0)	0.80 (-0.7–1.7)	0.55 (-0.5–1.8)	0.56 (-1.1–2.0)	0.13 (-0.1–1.3)	0.52 (-0.5–1.8)
Children completing exercise protocol stage n								
Exercise protocol								
REST	11	12	13	11	18	19	13	9
25 $W \cdot m^{-2}$	11	12	13	11	18	19	13	9
40 $W \cdot m^{-2}$	11	12	13	11	18	19	13	9
55 $W \cdot m^{-2}$	11	7	12	10	18	19	13	9
70 $W \cdot m^{-2}$	4	3	9	2	18	15	11	9
85 $W \cdot m^{-2}$	1		4	1	11	2	11	2
100 $W \cdot m^{-2}$					1		7	
115 $W \cdot m^{-2}$							3	

Data presented as n or median (range). Z-score: standard deviation score.

Is surface area a better denominator than weight for "body size"?

Table 2 shows the percentage variance explained by the linear relationship of the ventilatory variables with height or weight or surface area for both sexes after the 40 $W \cdot m^{-2}$ exercise stage. It demonstrates that for males, height was most often the best predictor for all the variables although surface area and weight were nearly as good. In contrast, height was usually the worst predictor in females with weight often being better and with surface area close behind even though work load had already been corrected for surface area. Overall therefore, surface area was the best general predictor of the variable for both sexes.

Ventilation at rest

The values at rest are shown as raw data in table 3 and corrected for surface area where relevant in table 4. There is very little overall difference in resting raw values between the sexes except O_2 consumption and CO_2 production was greater in males (Mann-Whitney, both $p<0.03$). After surface area correction, only O_2 comsumption$\cdot m^{-2}$ remains significantly higher in males ($p<0.03$).

Males. There are no age dependent differences in minute ventilation$\cdot m^{-2}$, alveolar ventilation$\cdot m^{-2}$ or tidal volume$\cdot m^{-2}$. The respiratory rate$\cdot m^{-2}$ was lower in those >12.5 yrs old compared with those <10.5 yrs (SPSS – one way analysis

Table 2. – Percentage variance explained by the relationship of height or weight or surface area with the ventilatory variable cited after 9 minutes total exercise having completed 3 minute at 40 $W \cdot m^{-2}$

	Contribution to variance %			
	Sex	Height	Surface area	Weight
$V'E$	M	9	8	6
	F	3	8	9
$V'O_2$	M	36	35	32
	F	5	16	19
$V'CO_2$	M	33	33	30
	F	24	36	38
AV	M	6	4	3
	F	1.9	1.8	1.4
VT	M	39	36	32
	F	38	33	28
VD/VT	M	-1.8	-1.5	-1.5
	F	27	21	18
RR	M	28	26	14
	F	17	16	2.4
CO_2 conc*	M	13	17	17
	F	22	21	19
O_2 conc*	M	11	14	13
	F	14	16	14
Anaerobic threshold	M	12	17	17
	F	30	45	45

M: male; F: female; $V'E$: minute ventilation; $V'O_2$: oxygen consumption; $V'CO_2$: carbon dioxide production; AV: alveolar ventilation; VT: tidal volume; RR: respiratory rate; *: value is mean plateau alveolar average.

Table 3. – Raw ventilatory variables at rest uncorrected for size, for each sex and age group

	Age yrs							
	<10.5		10.5–12.5		12.5–14.5		>14.5	
	M	F	M	F	M	F	M	F
$V'E$ L·min^{-1}	8.1±2.3	9.8±4.2	12.2±2.8	11.7±3.4	12.4±4.3	11.0±3.0	13.6±2.9	9.9±4.2
AV L·min^{-1}	4.8±1.5	6.5±3.9	7.5±2.2	7.1±2.3	7.4±2.7	6.3±2.4	8.2±2.8	5.4±2.3
$V'CO_2$ production L·min^{-1}	0.18±0.04	0.17±0.06	0.275±0.07	0.27±0.062	0.28±0.07	0.24±0.06	0.30±0.081	0.215±0.069
$V'O_2$ consumption L·min^{-1}	0.20±0.05	0.18±0.08	0.26±0.04	0.25±0.05	0.27±0.06	0.25±0.06	0.33±0.08	0.216±0.066
RR breaths·min^{-1}	22.5±5.8	26.1±8.9	20.2±5.3	21.2±5.8	20.7±6.5	18.0±3.8	21.4±4.1	19.8±6.0
VT L·breath^{-1}	0.38±0.111	0.37±0.08	0.63±0.17	0.56±0.16	0.61±0.14	0.62±0.12	0.65±0.17	0.50±0.14
VD/VT %	0.41±0.091	0.37±0.13	0.39±0.08	0.40±0.05	0.40±0.06	0.44±0.06	0.41±0.11	0.46±0.04
CO_2 conc* %	5.2±0.9	4.2±1.3	5.0±1.0	4.8±0.7	5.0±0.9	5.1±1.0	4.9±0.7	5.4±0.8
O_2 conc* %	15.5±1.2	16.7±1.8	16.2±1.3	16.4±1.1	15.9±1.3	15.6±1.9	15.9±1.1	15.4±1.4

Data presented as mean±SD. M: male; F: female; $V'E$: minute ventilation; AV: alveolar ventilation; $V'CO_2$: carbon dioxide production; $V'O_2$: oxygen consumption; RR: respiratory rate; VT: tidal volume; VD/VT: physiological dead space; *: mean plateau.

of variance (ANOVA), equal variances not assumed and Tamhane's T2 correction for multiple contrasts). Males >14.5 yrs had a lower dead space·m^{-2} than those <10.5 yrs ($p<0.02$).

Females. Again there were no differences in minute ventilation, alveolar ventilation or VT·m^{-2} between age groups at rest. Respiratory rate·m^{-2} was higher ($p<0.05$) in the youngest children compared to older ones but the older three groups were similar. Using nonsurface area corrected data the only difference was a trend for the youngest children to have a lower tidal volume compared to older ones ($p<0.01$).

Ventilatory variables during exercise

After 9 min exercise all children regardless of age had completed the 40 W·m^{-2} stage. The results for all variables for each exercise work load (except the "loosener" first stage) up to 70 W·m^{-2} are shown in table 5 for each age group and sex and are shown as variable per watt (*e.g.* CO_2 production·m^{-2} at 40 W·m^{-2} workload = CO_2 production 40 m^{-2}). Results after 70 W·m^{-2} were hampered by small numbers. At 40 W·m^{-2} there were no significant sex differences in any of the variables for each age group (Mann-Whitney U-test $p>0.05$).

Males. At 40 W·m^{-2} in males there were very few significant effects of age (one way ANOVA with Tamhane's correction for multiple contrasts, equal variances not assumed). These were a higher minute and alveolar ventilation per watt in those <10.5 yrs compared with those 12.5–14.5 yrs ($p<0.03$); a higher respiratory rate in the youngest age groups compared to those older ($p<0.008$) and also between those 10.5–12.5 *versus* those >14.5 yrs ($p<0.01$).

Females. As with males, there were very few differences between age groups. Those significant differences were, alveolar ventilation being higher in the oldest compared to youngest children ($p<0.05$); respiratory rate was higher in the youngest children compared to all other groups ($p<0.02$) but the three older groups were not different from each other.

Children at the end of exercise

Table 6 shows the results of the ventilatory variables as in table 5 but at the end of each child's exercise, together with the nonparametric correlation of age with this final value. At these final values, 73% had a heart rate >170 beats·min^{-1} and 26% had a rate >190 beats·min^{-1}.

Males. There were markedly significant correlations with age for these final values with the exceptions of tidal volume and CO_2 production. Older males had a lower physiological dead space (48% of variance explained by age), mean plateau (alveolar), O_2 concentration (76% variance explained), and respiratory rate (65% variance

Table 4. – Ventilatory variables at rest corrected for surface area subdivided by sex and age group

	Age yrs							
	<10.5		10.5–12.5		12.5–14.5		>14.5	
	M	F	M	F	M	F	M	F
$V'E$ L·min·m^{-2}	7.03±2.05	8.54±3.15	9.01±2.71	8.75±2.68	8.40±2.64	7.46±2.04	7.93±1.98	6.35±2.61
AV L·min·m^{-2}	4.14±1.257	5.60±2.94	5.559±2.05	5.33±1.74	5.02±1.67	4.26±1.63	4.78±1.84	3.45±1.41
$V'CO_2$ L·min·m^{-2}	0.15±0.03	0.15±0.05	0.20±0.06	0.20±0.04	0.19±0.04	0.16±0.05	0.17±0.05	0.14±0.04
$V'O_2$ L·min·m^{-2}	0.17±0.05	0.16±0.06	0.19±0.03	0.19±0.04	0.18±0.03	0.17±0.04	0.19±0.05	0.14±0.04
RR breaths·m^{-2}	19.48±5.14	23.03±6.89	14.64±3.56	15.91±5.08	14.07±4.17	12.28±2.94	12.33±2.39	12.97±4.15
VT L·breath·m^{-2}	0.33±0.10	0.33±0.08	0.468±0.17	0.43±0.13	0.41±0.09	0.42±0.083	0.38±0.12	0.32±0.08
VD/VT ·m^{-2}	0.36±0.11	0.34±0.14	0.28±0.05	0.30±0.05	0.28±0.06	0.30±0.06	0.24±0.05	0.30±0.04

Data presented as mean±SD. M: male; F: female; $V'E$: minute ventilation; AV: alveolar ventilation; $V'CO_2$: carbon dioxide production; $V'O_2$: oxygen consumption; RR: respiratory rate; VT: tidal volume; VD/VT: physiological dead space.

Table 5. – Ventilatory variables for each sex, age group, and work load expressed as per watt of work

Ventilatory variable per watt	Work-load W·m^{-2}	Age group yrs	Male	Female	Ventilatory variable per watt	Work-load W·m^{-2}	Age group yrs	Male	Female	Ventilatory variable per watt	Work-load W·m^{-2}	Age group yrs	Male	Female
V'_E L·min^{-1}·W^{-1}	25	<10.5	0.91±0.39	0.58±0.14	V'_{CO_2} L·min^{-1}·W^{-1}	25	<10.5	0.021±0.005	0.016±0.003	RR breaths ·min^{-1}·W^{-1}	25	<10.5	1.33±0.29	1.12±0.21
		10.5–12.5	0.63±0.17	0.60±0.18			10.5–12.5	0.019±0.006	0.019±0.005			10.5–12.5	0.83±0.25	0.71±0.32
		12.5–14.5	0.66±0.18	0.64±0.13			12.5–14.5	0.020±0.004	0.018±0.004			12.5–14.5	0.83±0.41	0.80±0.23
		>14.5	0.67±0.23	0.57±0.15			>14.5	0.022±0.007	0.018±0.004			>14.5	0.55±0.19	0.70±0.21
	40	<10.5	0.74±0.17	0.60±0.14		40	<10.5	0.017±0.004	0.014±0.003		40	<10.5	0.96±0.24	0.87±0.15
		10.5–12.5	0.58±0.11	0.64±0.29			10.5–12.5	0.018±0.003	0.019±0.005			10.5–12.5	0.61±0.17	0.58±0.22
		12.5–14.5	0.53±0.10	0.53±0.13			12.5–14.5	0.017±0.003	0.016±0.003			12.5–14.5	0.49±0.15	0.54±0.17
		>14.5	0.57±0.25	0.48±0.10			>14.5	0.020±0.009	0.016±0.003			>14.5	0.40±0.13	0.46±0.08
	55	<10.5	0.70±0.13	0.60±0.11		55	<10.5	0.017±0.002	0.013±0.003		55	<10.5	0.76±0.21	0.66±0.08
		10.5–12.5	0.56±0.09	0.58±0.17			10.5–12.5	0.018±0.002	0.017±0.003			10.5–12.5	0.55±0.13	0.49±0.16
		12.5–14.5	0.50±0.12	0.53±0.09			12.5–14.5	0.016±0.002	0.016±0.002			12.5–14.5	0.45±0.14	0.48±0.09
		>14.5	0.50±0.12	0.50±0.11			>14.5	0.017±0.004	0.017±0.002			>14.5	0.33±0.12	0.40±0.10
	70	<10.5	0.72±0.11	0.53±0.10		70	<10.5	0.016±0.003	0.014±0.004		70	<10.5	0.58±0.11	0.58±0.15
		10.5–12.5	0.57±0.10	0.53±0.14			10.5–12.5	0.018±0.003	0.014±0.000			10.5–12.5	0.46±0.08	0.41±0.04
		12.5–14.5	0.53±0.12	0.55±0.10			12.5–14.5	0.017±0.003	0.016±0.002			12.5–14.5	0.43±0.13	0.47±0.11
		>14.5	0.49±0.09	0.52±0.09			>14.5	0.017±0.003	0.017±0.002			>14.5	0.30±0.08	0.36±0.08
AV L·min^{-1}·W^{-1}	25	<10.5	0.69±0.32	0.45±0.16	V_T L·min^{-1}·W^{-1}	25	<10.5	0.023±0.006	0.019±0.004	CO_2 conc* %·W^{-1}	25	<10.5	0.152±0.058	0.174±0.050
		10.5–12.5	0.44±0.13	0.41±0.13			10.5–12.5	0.023±0.004	0.027±0.006			10.5–12.5	0.171±0.031	0.176±0.026
		12.5–14.5	0.44±0.09	0.44±0.10			12.5–14.5	0.024±0.005	0.023±0.006			12.5–14.5	0.156±0.026	0.150±0.033
		>14.5	0.49±0.17	0.39±0.10			>14.5	0.030±0.009	0.022±0.005			>14.5	0.134±0.017	0.149±0.021
	40	<10.5	0.60±0.20	0.53±0.19		40	<10.5	0.017±0.005	0.015±0.003		40	<10.5	0.090±0.030	0.081±0.037
		10.5–12.5	0.43±0.11	0.51±0.32			10.5–12.5	0.018±0.005	0.021±0.005			10.5–12.5	0.098±0.021	0.097±0.026
		12.5–14.5	0.38±0.08	0.38±0.09			12.5–14.5	0.020±0.005	0.018±0.004			12.5–14.5	0.101±0.016	0.095±0.020
		>14.5	0.43±0.20	0.35±0.06			>14.5	0.021±0.005	0.017±0.001			>14.5	0.083±0.009	0.099±0.013
	55	<10.5	0.57±0.16	0.55±0.16		55	<10.5	0.015±0.004	0.014±0.003		55	<10.5	0.065±0.021	0.052±0.033
		10.5–12.5	0.44±0.11	0.46±0.19			10.5–12.5	0.014±0.003	0.017±0.005			10.5–12.5	0.071±0.013	0.066±0.017
		12.5–14.5	0.37±0.08	0.39±0.07			12.5–14.5	0.014±0.003	0.014±0.003			12.5–14.5	0.072±0.011	0.067±0.012
		>14.5	0.39±0.14	0.37±0.07			>14.5	0.017±0.004	0.015±0.002			>14.5	0.060±0.008	0.069±0.011
	70	<10.5	0.63±0.17	0.43±0.06		70	<10.5	0.017±0.004	0.011±0.001		70	<10.5	0.043±0.021	0.049±0.030
		10.5–12.5	0.43±0.09	0.48±0.21			10.5–12.5	0.013±0.003	0.015±0.003			10.5–12.5	0.056±0.009	0.054±0.005
		12.5–14.5	0.41±0.09	0.40±0.07			12.5–14.5	0.012±0.002	0.012±0.001			12.5–14.5	0.053±0.009	0.051±0.011
		>14.5	0.37±0.07	0.40±0.07			>14.5	0.014±0.002	0.014±0.001			>14.5	0.048±0.005	0.052±0.009
V'_{O_2} L·min^{-1}·W^{-1}	25	<10.5	0.026±0.008	0.019±0.004	V_D/V_T·W^{-1}	25	<10.5	0.0095±0.0038	0.0106±0.0023	O_2 conc* %·W^{-1}	25	<10.5	0.56±0.08	0.56±0.08
		10.5–12.5	0.022±0.005	0.021±0.006			10.5–12.5	0.0095±0.0024	0.0093±0.0024			10.5–12.5	0.43±0.07	0.45±0.09
		12.5–14.5	0.023±0.004	0.021±0.004			12.5–14.5	0.0090±0.0030	0.0088±0.0021			12.5–14.5	0.42±0.07	0.42±0.05
		>14.5	0.024±0.006	0.020±0.003			>14.5	0.0063±0.0011	0.0079±0.0012			>14.5	0.35±0.05	0.39±0.03
	40	<10.5	0.020±0.004	0.017±0.004		40	<10.5	0.0060±0.0026	0.0056±0.0014		40	<10.5	0.38±0.06	0.39±0.06
		10.5–12.5	0.018±0.003	0.019±0.007			10.5–12.5	0.0047±0.0014	0.0048±0.0013			10.5–12.5	0.29±0.03	0.30±0.05
		12.5–14.5	0.018±0.003	0.016±0.003			12.5–14.5	0.0048±0.0012	0.0052±0.0011			12.5–14.5	0.26±0.04	0.27±0.03
		>14.5	0.019±0.006	0.015±0.001			>14.5	0.0036±0.0006	0.0044±0.0009			>14.5	0.22±0.02	0.25±0.01
	55	<10.5	0.019±0.005	0.017±0.003		55	<10.5	0.0046±0.0012	0.0042±0.0013		55	<10.5	0.28±0.06	0.27±0.04
		10.5–12.5	0.017±0.003	0.016±0.005			10.5–12.5	0.0034±0.0007	0.0035±0.0010			10.5–12.5	0.22±0.03	0.23±0.04
		12.5–14.5	0.016±0.002	0.015±0.002			12.5–14.5	0.0032±0.0005	0.0034±0.0005			12.5–14.5	0.19±0.02	0.20±0.02
		>14.5	0.017±0.003	0.015±0.001			>14.5	0.0026±0.0005	0.0031±0.0006			>14.5	0.16±0.01	0.19±0.01
	70	<10.5	0.018±0.005	0.014±0.003		70	<10.5	0.0030±0.0003	0.0032±0.0010		70	<10.5	0.24±0.06	0.21±0.03
		10.5–12.5	0.016±0.003	0.016±0.003			10.5–12.5	0.0025±0.0004	0.0026±0.0004			10.5–12.5	0.17±0.02	0.19±0.01
		12.5–14.5	0.015±0.002	0.014±0.001			12.5–14.5	0.0023±0.0006	0.0027±0.0005			12.5–14.5	0.16±0.02	0.17±0.02
		>14.5	0.015±0.002	0.014±0.002			>14.5	0.0020±0.0002	0.0023±0.0003			>14.5	0.13±0.01	0.16±0.01

Data presented as mean±SD. V'_E: minute ventilation; AV: alveolar ventilation; V'_{O_2}: oxygen consumption; V'_{CO_2}: carbon dioxide production; V_T: tidal volume; V_D/V_T: physiological dead space; RR: respiratory rate; *: mean plateau concentration.

Table 6. – Ventilatory variables at the end of the subjects last exercise stage subdivided by sex and age group

Ventilatory variable	Age group yrs	Male Mean±SD	Male r_s	Male p-value	Female Mean±SD	Female r_s	Female p-value
V'_E L·min^{-1}·W^{-1}	<10.5	0.69±0.10	-0.57	<0.001	0.57±0.10	-0.041	0.778
	10.5–12.5	0.62±0.09			0.58±0.17		
	12.5–14.5	0.54±0.11			0.57±0.11		
	>14.5	0.55±0.10			0.55±0.10		
AV L·min^{-1}·W^{-1}	<10.5	0.58±0.16	-0.507	<0.001	0.51±0.14	-0.213	0.138
	10.5–12.5	0.50±0.13			0.44±0.14		
	12.5–14.5	0.42±0.08			0.42±0.07		
	>14.5	0.43±0.06			0.42±0.07		
$V'O_2$ L·min^{-1}·W^{-1}	<10.5	0.019±0.004	-0.491	<0.001	0.015±0.003	-0.243	0.09
	10.5–12.5	0.017±0.004			0.015±0.003		
	12.5–14.5	0.015±0.002			0.014±0.002		
	>14.5	0.015±0.003			0.014±0.002		
$V'CO_2$ L·min^{-1}·W^{-1}	<10.5	0.016±0.003	-0.033	0.817	0.14±0.003	0.405	<0.005
	10.5–12.5	0.018±0.003			0.018±0.005		
	12.5–14.5	0.017±0.003			0.017±0.002		
	>14.5	0.017±0.002			0.017±0.002		
V_T L·min^{-1}·W^{-1}	<10.5	0.015±0.004	-0.246	<0.08	0.014±0.003	-0.018	<0.901
	10.5–12.5	0.014±0.003			0.016±0.005		
	12.5–14.5	0.012±0.002			0.012±0.002		
	>14.5	0.013±0.003			0.014±0.001		
V_D/V_T %·W^{-1}	<10.5	0.0040±0.0016	-0.691	<0.001	0.0044±0.0014	-0.559	<0.001
	10.5–12.5	0.0024±0.0010			0.0035±0.0009		
	12.5–14.5	0.0020±0.0006			0.0027±0.0005		
	>14.5	0.0014±0.0004			0.0022±0.0003		
RR breaths·min^{-1}·W^{-1}	<10.5	0.70±0.22	-0.814	<0.001	0.76±0.21	-0.615	<0.001
	10.5–12.5	0.51±0.12			0.48±0.14		
	12.5–14.5	0.40±0.13			0.48±0.11		
	>14.5	0.28±0.10			0.36±0.07		
CO_2 conc* %·W^{-1}	<10.5	0.057±0.022	0.649	<0.001	0.061±0.032	-0.25	<0.09
	10.5–12.5	0.053±0.010			0.068±0.015		
	12.5–14.5	0.046±0.009			0.052±0.010		
	>14.5	0.034±0.006			0.049±0.010		
O_2 conc* %·W^{-1}	<10.5	0.25±0.06	-0.876	<0.001	0.32±0.11	-0.769	<0.001
	10.5–12.5	0.19±0.05			0.22±0.04		
	12.5–14.5	0.14±0.02			0.17±0.02		
	>14.5	0.11±0.02			0.15±0.01		

r_s: Spearman's correlation of age against variable; V'_E: minute ventilation; AV: alveolar ventilation; $V'O_2$: oxygen consumption; $V'CO_2$: carbon dioxide production; V_T: tidal volume; V_D/V_T: physiological dead space; RR: respiratory rate; *: mean plateau concentration.

explained) per watt of work than younger ones and a higher minute and alveolar ventilation (25% variance explained) compared to younger children.

Females. Older females did not raise their ventilation but had a lower respiratory rate (37% variance explained), mean plateau (alveolar) O_2 concentrations (54% variance explained) and physiological dead space (27% variance explained) compared with younger females.

Between sexes. Males used more O_2 (Mann-Whitney p<0.02) and reduced their physiological dead space (p<0.001) and mean plateau (alveolar) O_2 concentration (p=0.001) to a greater extent compared with females.

There was, in general, no correlation (Spearman) between the final values and peak heart rate (as a measure of maximum exercise) within each age group. The exceptions were that in the younger females and males (<12.5 yrs) there was a negative correlation with peak heart rate and both physiological dead space (25% variance explained, p<0.05) and mean plateau (alveolar) O_2 concentration (27% variance explained p<0.01).

Respiratory rate and gas concentrations

As respiratory rate and mean plateau (alveolar) gas concentrations are not commonly presented per watt of work, their raw results are given in table 7 at 40 W·m^{-2} work and maximum work. At 40 W·m^{-2} there was a negative relationship especially in males between age and respiratory rate (Spearman's rank correlation: males, 36% variance explained, p<0.001; females, 16% variance explained p<0.003), which disappears completely at maximal exercise in both sexes. For O_2 concentration there is a negative correlation with age in both sexes at 40 W·m^{-2} (males, 24% variance explained, p<0.001, females 15% variance explained, p<0.006) but this correlation becomes much weaker in males (8% variance explained) and disappears in females at maximum exercise. For CO_2 concentrations there is a positive correlation with age at 40 W·m^{-2} for both sexes (males and females 25% variance explained, p<0.001), which weakens but remains significant at maximum exercise (males, 16% variance explained, p<0.003; females 8% explained, p=0.02).

Table 7. – Presentations of certain variables as raw values rather than per watt of work at stages of exercise

	Sex	Exercise stage $W \cdot m^{-2}$	Age group yrs			
			<10.5	10.5–12.5	12.5–14.5	>14.5
RR $breaths \cdot min^{-1}$	M	40	43.4±6.4	33.9±9.4	28.5±7.8	27.6±8.6
		Max	47.6±8.7	44.1±9.9	46.0±11.2	42.2±11.2
	F	40	38.9±4.3	31.0±10.5	31.1±8.9	28.0±5.2
		Max	43.0±8.1	36.7±7.0	47.3±9.0	39.4±8.4
O_2 conc* %	M	40	17.0±1.5	15.9±0.8	15.0±0.2	15.4±0.7
		Max	17.3±1.4	16.8±0.7	16.3±0.7	16.6±0.7
	F	40	17.4±1.9	16.2±1.1	15.7±0.9	15.4±0.7
		Max	17.8±1.5	16.5±0.5	16.7±0.6	16.7±0.7
CO_2 conc* %	M	40	4.1±1.4	5.4±0.9	5.9±0.8	5.8±0.5
		Max	3.9±1.4	5.0±0.9	5.3±0.6	5.2±0.4
	F	40	3.6±1.6	5.3±1.2	5.5±0.7	5.9±0.5
		Max	3.4±1.6	5.2±0.5	5.1±0.6	5.3±0.6
V_D/V_T %	M	40	0.27±0.1	0.26±0.07	0.27±0.04	0.25±0.04
		Max	0.27±0.06	0.23±0.08	0.22±0.05	0.24±0.03
	F	40	0.25±0.05	0.26±0.06	0.30±0.04	0.27±0.05
		Max	0.24±0.04	0.26±0.06	0.27±0.03	0.22±0.04

Data presented as mean±SD. RR: respiratory rate; M: male; F: female; V_D/V_T: physiological dead space; *: mean plateau concentration; Max: maximum exercise.

Recovery from exercise

Table 8 shows the percentage change from baseline at maximal exercise and after 9 min rest in recovery. Both sexes had slightly raised minute and alveolar ventilation values 9 min into recovery (minute ventilation: males 21.8% (13.2–43.6), females 11.3% (2.1–24.3) difference p<0.08); alveolar ventilation: males 29.4 (13.3–49.9), females 13.7 (7.0–33.3) difference p<0.07). Respiratory rate remained significantly higher in males 9 min post recovery than females (males 19.7% (3.8–52), females 0.66% (-13.8–11), p<0.04). There was no relationship between any of the three variables and the subjects maximum workload relative to their age and sex standardized median, for example males >14.5 yrs who stopped exercising earlier than expected did not have a lower respiratory rate than those who stopped exercising at a workload greater than the predicted age and sex standardized median.

Discussion

Given that there are at least 14 studies in healthy males aged <12 yrs that measured maximum oxygen consumption [3], what does this study provide that others have not? Firstly, it provides data for almost all commonly used variables at rest and every exercise stage allowing direct comparison between this and data collected on disease groups, providing the same protocol is followed. It is not hampered by assumptions of linear regression as elegantly set out by WHIPP *et al.* [11]. Secondly, surface area is the best summary auxological variable correcting for size for both genders. Thirdly, as surface area was the best auxological variable, estimates of adaptability or "efficiency" could be made by studying the result per watt of work (table 4). Fourthly, although providing data at maximum exercise, the study is not reliant on the subject reaching maximum exercise. Fifthly, although mass spectometry is an expensive way of collecting only ventilatory data, it does allow such data to be studied in conjunction with simultaneously collected haemodynamic data [7]. This mass spectrometer does not require high level support and maintenance. Finally, the study defines a rational bicycle exercise protocol on the basis of surface area which is universally applicable to all ages and sexes.

Our results show that although no physical measure (weight, height or surface area) is perfect in "normalizing" for size [12], surface area was the best single measure for each sex and variable. Having tried to correct workload for size, older, larger children still exercised longer and harder than younger children, which on the basis of similar final heart rates did not appear psychological but physiological in origin. At submaximal exercise, older children principally had a lower alveolar ventilation and respiratory rate and similar gas consumption/production. At maximum exercise children had very similar respiratory rates and alveolar gas concentrations. Thus it would appear from a ventilation point of view that the physiological factors associated with cessation of exercise were for example, reaching a certain respiratory rate (about 45 $breaths \cdot min^{-1}$ in males and 40 $breaths \cdot min^{-1}$ in females). This is not necessarily a physiological maximum as maximum voluntary ventilation at rest will exceed this. When one considers that at peak exercise, stroke volume and transfer constant were also falling [7], it is relevant to consider whether exercise termination is principally haemodynamic or ventilatory though both are likely to contribute. Given that maximum exercise is not necessarily maximum ventilation and that "maximum" exercise may be positively dangerous in particular cardiac disease groups, this study exemplifies the value of defining results at submaximal exercise under identical conditions without resort to regression equations.

It has previously been demonstrated that peak O_2 consumption changes with age but no independent effect could be found, as in the study, to relate this to pubertal stage [5]. Changes in muscle mass are thought to be more related to puberty than age. The finding that younger children finish exercise with a lower absolute alveolar

Table 8. – Values for ventilatory variables at maximum exercise and after 9 minutes rest for each sex alone and for each sex and age group

Ventilatory variable	Exercise	Per cent change from initial resting values									
		<10.5 yr		10.5–12.5 yr		12.5–14.5 yr		>14.5 yr		All ages combined mean (95% CI)	
		M	F	M	F	M	F	M	F	M	F
$V'E$	Max	485±130	273±118	343±217	280±124	415±143	398±137	550±178	447±148	465 (408–521)	381 (321–440)
	After 9 min rest	20±43	13±20	25±39	6±37	48±80	19±37	36±37	30±60	38 (22–54)	20 (9–31)
AV	Max	799±309	430±134	506±342	387±199	601±246	577±324	782±283	758±382	663 (576–749)	546 (459–633)
	After 9 min rest	27±54	21±26	33±93	7±45	58±77	25±43	44±46	42±59	48 (28–68)	26 (11–40)
RR	Max	97±53	79±67	116±63	79±68	137±72	147±49	130±97	106±61	120 (101–141)	111 (91–129)
	After 9 min rest	27±74	-4±34	27±44	10±41	27±61	9±35	15±62	13±30	27 (10–43)	9 (-1–19)
VD/VT	Max	-27±21	-40±21	-33±30	-28±27	-44±11	-35±13	-42±19	-48±7	-38 (-32–-44)	-37 (-31–-42)
	After 9 min rest	-1.5±19	5.8±35	2.9±35	4.3±12	6.3±20	2.2±12	-6.4±17	5.9±14	4.5 (-2–11)	4 (-1.5–9.7)
VT	Max	185±78	135±56	94±82	102±52	111±64	115±58	155±70	187±80	135 (112–160)	131 (110–151)
	After 9 min rest	20±60	19±24	-8±32	-8±27	16±41	8±27	25±43	17±44	12 (1–23)	9 (1–18)
$V'CO_2$	Max	575±168	408±165	503±258	401±163	637±190	605±212	808±270	750±279	633 (565–701)	573 (484–662)
	After 9 min rest	20±41	15±28	-5±30	-1±32	35±57	15±30	25±35	17±62	24 (11–37)	14 (4–25)
$V'O_2$	Max	475±245	447±287	457±177	387±182	568±141	480±131	651±241	669±296	541 (484–598)	488 (422–554)
	After 9 min rest	9±35	13±49	-7±40	-4±29	39±38	10±25	27±38	17±48	19 (8–31)	9 (-1–20)

Data presented as mean±SD or mean (95% confidence interval). $V'E$: minute ventilation; AV: alveolar ventilation; RR: respiratory rate; VD/VT: physiological dead space; VT: tidal volume; $V'CO_2$: carbon dioxide production; $V'O_2$: oxygen consumption.

CO_2 concentration than older ones was not due to a leak, but remains puzzling.

Comparing the present data with other studies is difficult because results are more dependent on the exact nature of the exercise protocol, for example, treadmill *versus* bicycle protocols, continuous or stepwise changes in workload size, together with their rate of change, and less on the equipment collecting the data. In addition, the type of child studied is important, athletes being entirely different from "couch potatoes". When recruiting, the authors concentrated on using "ordinary" children rather than enthusiastic athletes who might be otherwise more prone to volunteer. This may account for our mean "maximum" O_2 consumption·kg^{-1} for males being 38 mL·kg^{-1}·min^{-1}, some 20% less than the study of GODFREY *et al.* [1] despite similar final heart rates although within the wide range (35–61 mL·kg^{-1}·min^{-1}), cited in the literature [3].

All protocols and measurements described in this laboratory study, as in others, are approximations to real life and also assume the lung as a single alveolar model for parameters such as dead space. Nevertheless, adherence to the described protocol allows comparison with disease groups who may have unreliable and indeed undesirable peak exercise responses. Presentation as "per watt of work" allows comparisons of adaptability or efficiency although alternative presentations of the results are available from the authors by e-mail.

Appendix

The calculation of ventilatory parameters using the principle of helium-dilution mixed expired gas analysis.

If a tracer gas (HE) is injected at a known constant rate, M, into a stream of expired air then the flow of any component x in that mixture may be calculated. This is most easily appreciated when one considers a flow, x L·min^{-1} of pure HE, essentially a non-native component of air added to a stream of expired air of flow rate y L·min^{-1}. Measuring the HE concentration, z, downstream after complete mixing allows calculation of y where

$$y + x = \frac{x}{z}$$

Therefore:

$$y = x\left[\frac{1}{z} - 1\right] \quad (1)$$

The total gas flow is y+x as it includes the flow of added tracer gas, x, thus y=0 when z=1. When calculating minute ventilation (V'_E), correction for atmospheric pressure and temperature are necessary. Thus:

$$V'_E = M_{HE}\left[\frac{1}{Fm_{HE}} - 1\right]\frac{310}{273+T} \times \frac{760}{P_B - 47} \quad (2)$$

where Fm_{HE} represents the mean fractional (F) concentration of HE in the mixing box (m), P_B is atmospheric pressure in mmHg and T is ambient temperature in centigrade. As there is effectively zero CO_2 in inspired air, then CO_2 production, V'_{CO_2} is calculated from:

$$V'_{CO_2} = Fm_{CO_2}\left[\frac{V'_E + M_{HE}}{V'_E}\right]V'_E \quad (3)$$

the middle bracketed term correcting the fractional concentration of CO_2 due to the dilution of the stream by the tracer gas. Substituting Equation 2 into Equation 3 produces:

$$V'_{CO_2} = Fm_{CO_2}(V_E + M_{HE})$$

Therefore:

$$V'_{CO_2}(STPD) = Fm_{CO_2}\frac{M_{HE}}{Fm_{HE}} \quad (4)$$

O_2 consumption is more complex as consideration has to be given to the issues of the inspired O_2 concentration (FI_{O_2}) and that the expiratory flow rate does not necessarily equal the inspiratory flow rate (VI). Assuming that there is no flux of nitrogen across the alveolar capillary membrane the following equations can be described. In general terms:

$$V'_{O_2} = (FI_{O_2} \times V_I) - Fm_{O_2}\left[\frac{V_E + M_{HE}}{V_E}\right]V_E \quad (5)$$

and

$$V'_E = V_I + V'_{CO_2} - V'_{O_2} \quad (6)$$

substituting Equations 2, 4 and 6 into 5 and manipulating produces:

$$V'_{O_2} = \frac{\left[M_{HE}\left[\frac{1}{Fm_{HE}} - 1\right]\right] \times [FI_{O_2} - Fm_{O_2}] - M_{HE}\left[\frac{FM_{CO_2}FI_{O_2}}{FM_{HE}} - FM_{O_2}\right]}{1 - FI_{O_2}} \quad (7)$$

If in addition a sample of gas is measured over the last 15% of expiration at the mouth, this will better represent alveolar (A) values than the end tidal value. If this alveolar value is, for example, twice the mean expired concentration in the mixing box then the alveolar gas has been diluted by an equal volume of nonalveolar or dead space gas. Thus:

$$\frac{AV}{V'_E} = \frac{FA_{CO_2}}{Fm_{CO_2}} \quad (8)$$

The physiological fractional dead space V_D/V'_E is given by:

$$\frac{V_D}{V'_E} = \frac{V_E - AV}{V_E} = \frac{V_E - \frac{FA_{CO_2} V_E}{Fm_{CO_2}}}{V_E} = 1 - \frac{FA_{CO_2}}{Fm_{CO_2}} \quad (9)$$

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