CARDIO-RESPIRATORY RESPONSE TO EXERCISE IN NORMAL CHILDREN

S. GODFREY, C. T. M. DAVIES, E. WOZNIAK AND CAROLYN A. BARNES

Institute of Diseases of the Chest, London, and Medical Research Council Environmental Physiology Unit, London

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SUMMARY

1. The results of studies during simple progressive exercise to exhaustion and steady-state submaximal exercise in 117 boys and girls aged 6–16 years are presented.

2. In the simple progressive exercise test, the highest work load achieved and the submaximal heart rate were related to size and sex. The maximum heart rate and submaximal ventilation were largely independent of size and sex.

3. Steady-state exercise was performed at one-third and two-thirds of the maximum work load achieved in the simple progressive test. The Indirect (CO₂) Fick method was used to measure cardiac output.

4. At any given level of steady-state work, tidal volume, dead space, heart rate and stroke volume were closely related to size, with girls having higher heart rates and smaller stroke volumes than boys. Minute ventilation and cardiac output were virtually independent of size and sex. The cardiac output in children was the same as that in the adult for any given oxygen consumption. Blood lactate was related to size at any given work load, but was independent of size at any given fraction of the maximum working capacity.

The development of the Indirect (CO₂) Fick method for measuring cardiac output during exercise (Higgs, Clode, McHardy, Jones & Campbell, 1967) and of mathematical techniques for analysis of the results (McHardy, Jones & Campbell, 1967; Godfrey, 1970a) have made it possible to study exercise physiology with minimal inconvenience to the patient. Standard techniques for measurement of cardiac response to exercise by either the Direct (O₂) Fick method or the dye-dilution method require cardiac and arterial catheterization and are difficult to justify for the study of normal children. The Indirect (CO₂) Fick method which uses a rebreathing technique for estimating mixed venous Pco₂ (Jones, Campbell, McHardy, Higgs & Clode, 1967) and either end-tidal Pco₂ or ear-lobe blood Pco₂ (Godfrey, Wozniak, Courtenay Evans & Samuels, 1971) is safe, reliable and acceptable to either healthy or sick children (Godfrey, 1970b).

Correspondence: Dr S. Godfrey, Institute of Diseases of the Chest, Fulham Road, London, S.W.3.
Previous information about exercise physiology in children has generally been limited to the measurement of physical working capacity, heart rate and ventilation (Astrand, 1952; Bengtsson, 1956; Adams, Linde & Miyake, 1961). Gadhoke & Jones (1969) succeeded in studying forty normal boys aged 11–14 by using some of the techniques outlined above. To interpret the results of studies in children with heart or lung disease a much wider range of normal values was needed and we therefore decided to study children of both sexes aged from 6 to 16 years.

SUBJECTS AND METHODS

Studies were made on fifty-seven boys and sixty girls evenly distributed in age, height and weight (Table 1). All children were volunteers from local schools and fully informed consent was obtained in writing from their parents. The children were examined clinically on the day of the test and signs of heart, lung or neuromuscular disease were not detected. The studies were performed during the morning and afternoon after light meals and at least 1 h was left between tests in any one subject.

Two types of exercise test were performed by each child on a cycle ergometer (Lode) in the sitting position.
Simple progressive exercise

In this test the work load on the ergometer was increased every minute and the electrocardiograph and inspired ventilation were recorded continuously on a chart recorder (Mingograph 81). Ventilation was measured by using a valve box of low resistance and dead space (53 ml for older children, 30 ml for the younger), with a gas meter (Parkinson–Cowan C.D.4) placed in the inspiratory line. The increments of work depended on the size of the child; 10 W for children less than 120 cm in height, 15 W for children from 120 to 150 cm, and 20 W for children over 150 cm. The child was encouraged to persevere until exhaustion. By using increments of work related to size meant that most children exercised progressively harder for about 6–8 min. The highest work load completed ($W_{\text{max}}$) was noted and the heart rate and ventilation for every load were calculated.

Steady-state exercise

After a complete rest of at least 60 min a test was performed in which each child was studied at rest and then at one-third and two-thirds of the previously determined $W_{\text{max}}$, under steady conditions. The work loads were performed without any rest between them. Expired gas was flushed through a large Tissot spirometer and analysed continuously for $O_2$ and $CO_2$. After 2 or 3 min of exercise, when the heart rate, ventilation and expired gas concentrations were seen to be steady from the continuous record (i.e. varying by less than 5%), a collection of expired gas was made over at least 1 min in the spirometer and was immediately analysed. A sample of arterialized ear-lobe blood was obtained by the method of Godfrey et al. (1971) either during the collection or immediately afterwards in the more timid children. This was only used to obtain values for the normal physiological dead space (see below). The oxygenated mixed venous $PCO_2$ ($PvCO_2$) was measured by a rebreathing method (Jones et al., 1967) in which the subject was given an appropriate volume and concentration of $CO_2$ in $O_2$ to rebreathe for 12–15 s. The end-tidal $PCO_2$ was recorded continuously to identify the plateau representing equilibration between mixed venous $PCO_2$, alveolar $PCO_2$ and rebreathing bag $PCO_2$. If a perfect plateau (i.e. one which appeared within 3 or 4 s and broke with recirculation at 10 s) was not obtained, the extrapolation procedure described by Denison, Edwards, Jones & Pope (1969) was used. No correction was applied for the difference between the plateau $PCO_2$ and that in blood arriving at the lungs or leaving them during the equilibrium described by Jones et al. (1967) and Jones, Campbell, Edwards & Wilkoff (1969).

Analyses and calculations

Expired $O_2$ was measured with a paramagnetic analyser (Servomex OA150) modified to give a full-scale deflection on the recorder over an appropriately restricted range. Expired and end-tidal $CO_2$ was measured with an i.r. analyser (URAS-4) which also wrote on the recorder. The analysers were calibrated with four gas mixtures spanning the operative range after every two or three studies. Ear-lobe blood was analysed immediately for blood gases by using Eschweiler microelectrodes calibrated with gases and buffers for every sample. Ear-lobe blood lactate was determined by the method of Gerken (1960). All calibrating gases were analysed chemically with a Lloyd-Haldane apparatus. All ventilations are expressed at B.T.P.S. and all $O_2$ consumptions at S.T.P.D.

The results were calculated with the help of a digital computer program (Godfrey, 1970a). In the present study cardiac output was calculated by using the arterial $PCO_2$ implied by
assuming that the subject had a normal physiological dead space. The values for the dead space in normal children were determined during the study and agreed closely with those based on weight (Radford, 1954). The use of an assumed normal dead space to calculate arterial PCO₂ and subsequently cardiac output has been discussed by Godfrey & Davies (1970).

Preliminary analysis suggested that height was the most useful index of body size for almost all comparisons and the data have therefore been presented in relation to sex and height unless otherwise stated. Since the Indirect (CO₂) Fick method for cardiac output is unreliable at rest (Godfrey & Davies, 1970) regressions were based on work only. Some data on rest are included as stated in the text.

RESULTS

The individual results for body size and the highest work levels completed in the progressive exercise test are presented in Clinical Science Table 40/2, which has been deposited with the Librarian of the Royal Society of Medicine, London, W.1. The individual results for steady-state exercise tests have been deposited as Clinical Science Table 40/3.

Simple progressive exercise

The highest work load completed by the child (Wₘₐₓ) was found to depend significantly on size and sex, boys achieving higher loads than girls of similar height (Fig. 1, Table 2).

![Graph showing maximum work load in relation to height and sex for boys (solid line) and girls (dashed line).](image)

**Fig. 1.** Highest work load completed (Wₘₐₓ) in simple progressive exercise in relation to height and sex. ---, Girls (SE Y = 17); ---, boys (SE Y = 19).

The same applied to the highest ventilation achieved. The highest heart rate achieved was 196±13 (SD) beats/min in girls and 195±13 (SD) beats/min in boys and was independent of height.

At all submaximal work levels the heart rate was significantly related to work load, height and sex, with girls having higher heart rates than boys. Smaller children had higher heart rates.
Exercise performance in children

at any work level than larger children and their increase in heart rate for unit increase in work was also greater. This meant that multiple linear regression could not adequately express the results. Grouping the children by height and performing a simple linear regression for each group improved the analysis, but the height range of the groups had to be large to get a sufficient number of points. A practical compromise was obtained by performing the multiple regression of pulse on logarithm of work and height (Table 2) which adequately expressed the results.

Table 2. Regression equations for all results

<table>
<thead>
<tr>
<th>Sex</th>
<th>Y</th>
<th>$B_1$</th>
<th>$X_1$</th>
<th>$B_2$</th>
<th>$X_2$</th>
<th>$M$</th>
<th>SE $Y$</th>
<th>$r$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Simple progressive exercise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boys $W_{k_{\max}}$</td>
<td>2.87</td>
<td>Height</td>
<td>—</td>
<td>—</td>
<td>—291</td>
<td>19</td>
<td>0.94</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Girls $W_{k_{\max}}$</td>
<td>2.38</td>
<td>Height</td>
<td>—</td>
<td>—</td>
<td>—238</td>
<td>17</td>
<td>0.91</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Boys $\dot{V}_E$</td>
<td>0.386</td>
<td>$W$</td>
<td>—0.094</td>
<td>Height</td>
<td>22.9</td>
<td>8.4</td>
<td>0.92</td>
<td>406</td>
<td></td>
</tr>
<tr>
<td>Girls $\dot{V}_E$</td>
<td>0.402</td>
<td>$W$</td>
<td>—0.117</td>
<td>Height</td>
<td>23.8</td>
<td>6.1</td>
<td>0.93</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Boys Pulse</td>
<td>87.6</td>
<td>log $W$</td>
<td>—1.073</td>
<td>Height</td>
<td>162</td>
<td>16</td>
<td>0.85</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>Girls Pulse</td>
<td>84.2</td>
<td>log $W$</td>
<td>—1.171</td>
<td>Height</td>
<td>191</td>
<td>15</td>
<td>0.85</td>
<td>351</td>
<td></td>
</tr>
<tr>
<td>(B) Steady-state exercise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boys $\dot{V}_O_2$</td>
<td>11.89</td>
<td>$W$</td>
<td>—</td>
<td>—</td>
<td>329</td>
<td>127</td>
<td>0.96</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Girls $\dot{V}_O_2$</td>
<td>11.20</td>
<td>$W$</td>
<td>1.701</td>
<td>Height</td>
<td>109</td>
<td>94</td>
<td>0.96</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Boys $\dot{V}_E$</td>
<td>0.0305</td>
<td>$\dot{V}_O_2$</td>
<td>—0.117</td>
<td>Height</td>
<td>17.0</td>
<td>5.0</td>
<td>0.93</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>Girls $\dot{V}_E$</td>
<td>0.0370</td>
<td>$\dot{V}_O_2$</td>
<td>—0.211</td>
<td>Height</td>
<td>25.7</td>
<td>4.5</td>
<td>0.92</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Boys $\dot{V}_T$</td>
<td>0.465</td>
<td>$\dot{V}_O_2$</td>
<td>8.03</td>
<td>Height</td>
<td>—826</td>
<td>159</td>
<td>0.91</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>Girls $\dot{V}_T$</td>
<td>0.490</td>
<td>$\dot{V}_O_2$</td>
<td>6.09</td>
<td>Height</td>
<td>—577</td>
<td>111</td>
<td>0.91</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Both $\dot{V}_D$</td>
<td>1.54</td>
<td>weight</td>
<td>0.049</td>
<td>$\dot{V}_T$</td>
<td>2</td>
<td>22</td>
<td>0.78</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Boys Pulse</td>
<td>0.0057</td>
<td>$\dot{V}_O_2$</td>
<td>0.022</td>
<td>Height</td>
<td>0.71</td>
<td>0.92</td>
<td>0.95</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>Girls Pulse</td>
<td>0.0056</td>
<td>$\dot{V}_O_2$</td>
<td>0.021</td>
<td>Height</td>
<td>1.02</td>
<td>0.74</td>
<td>0.94</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>Boys Pulse</td>
<td>159.1</td>
<td>log $\dot{V}_O_2$</td>
<td>—1.204</td>
<td>Height</td>
<td>—143</td>
<td>18</td>
<td>0.71</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>Girls Pulse</td>
<td>173.0</td>
<td>log $\dot{V}_O_2$</td>
<td>—1.395</td>
<td>Height</td>
<td>—140</td>
<td>14</td>
<td>0.81</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Boys $\dot{Q}$</td>
<td>0.0114</td>
<td>$\dot{V}_O_2$</td>
<td>0.636</td>
<td>Height</td>
<td>41</td>
<td>10</td>
<td>0.85</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>Girls $\dot{Q}$</td>
<td>0.0142</td>
<td>$\dot{V}_O_2$</td>
<td>—</td>
<td>—</td>
<td>52.9</td>
<td>4.2</td>
<td>0.70</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Boys $\dot{P}_{\dot{V}_CO_2}$</td>
<td>0.0098</td>
<td>$\dot{V}_O_2$</td>
<td>—</td>
<td>—</td>
<td>52.9</td>
<td>4.2</td>
<td>0.70</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Girls $\dot{P}_{\dot{V}_CO_2}$</td>
<td>0.0142</td>
<td>$\dot{V}_O_2$</td>
<td>—</td>
<td>—</td>
<td>46.9</td>
<td>5.1</td>
<td>0.64</td>
<td>79</td>
<td></td>
</tr>
</tbody>
</table>

$Y$, dependent variable; $X_1$ and $X_2$, independent variables; $B_1$ and $B_2$, regression coefficients of $X_1$ and $X_2$ respectively; $M$, constant term; SE $Y$, standard error of estimate of $Y$; $r$, (multiple) correlation coefficient; $n$, degrees of freedom. The equations are of the form: $Y = B_1 X_1 + B_2 X_2 + M \pm SE Y$. Where no value is given for $B$ or $X$, the equation was only significant for the remaining parameter shown. Otherwise all equations are significant for both $X_1$ and $X_2$ at least at the 5% level.

The symbols for $Y$ and $X$ are those given in the text. Other abbreviations and units are as follows: height (cm), weight (kg), work ($W$), $\dot{V}_O_2$ (ml/min), $\dot{V}_E$ (l/min), $\dot{V}_T$ (ml), $\dot{V}_D$ (ml), $\dot{Q}$ (l/min), SV (ml), pulse (beats/min), $\dot{P}_{\dot{V}_CO_2}$ (mmHg).

The range of independent variables covered by the regressions were: height 113–182 cm, weight 18–77 kg, work 50–260 W, $\dot{V}_O_2$ 320–2420 ml/min.

Ventilation at submaximal work levels ($\dot{V}_E$) was highly significantly related to work load and independent of sex (Table 2). Although it was also related to height, the variation over the range of normal children studied was less than twice the SE of the estimate.
Steady-state exercise

All steady-state results refer to submaximal work. The most important results are illustrated in the figures and all the regression equations are given in Table 2.

![Figure 2](image1.png)

**Fig. 2.** Ventilation during steady-state exercise in relation to $\dot{V}O_2$ and to height in girls. The lines for theoretical heights of 100 cm and 200 cm are shown. The effect of height was not significant in boys. Boys, SEY = 5.1; girls, SEY = 4.5.

![Figure 3](image2.png)

**Fig. 3.** Tidal volume during steady-state exercise in relation to $\dot{V}O_2$ and height. Small differences due to sex have been omitted. Boys and girls, SE$Y = 135$.

*Oxygen consumption* ($\dot{V}O_2$). This was significantly related to physical work with no significant sex or size difference over the operative range, although it tended to be lower in smaller girls. A regression was calculated for all other measurements on $\dot{V}O_2$ except as described.
Exercise performance in children

**Fig. 4.** Physiological dead-space during steady-state exercise in relation to weight and tidal volume for boys and girls together (see the text). Boys and girls, $SEY = 22$.

**Fig. 5.** Cardiac output during steady-state exercise in relation to $V_{O2}$ for all boys in various height groups. The lines represent $± 1 SEY$ about the regression line. The regression line for girls was not significantly different. The circles represent the results of the study in adult men by Bevegard et al. (1960). Height range (cm): ●, 110–124; ○, 125–139; ■, 140–154; □, 155–169; ▲, 170–185.
Ventilation ($\dot{V}E$). This was significantly related to $\dot{V}O_2$ in all groups with no size difference in boys over the operative range. There was a small but significant size effect in girls (Fig. 2).

Tidal volume ($VT$). This was significantly related to $\dot{V}O_2$ and to size, being larger at any given

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**Fig. 6.** Heart rate during steady-state exercise in relation to $\dot{V}O_2$, height and sex. ———, Girls (SEY = 14); ———, boys (SEY = 18).

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**Fig. 7.** Steady-state respiratory exchange ratio ($R$), arterialized ear-lobe blood lactate concentration and arterial $PCO_2$ at rest, one-third and two-thirds of maximum working capacity. ●, Boys; ○, girls. The bar includes ±SEM about the mean value shown by the symbol.

$\dot{V}O_2$ value in taller children. There was no significant sex difference. It was found in this instance that multiple linear regression expressed the results best. The results are illustrated in Fig. 3. There was no consistent relationship between $VT$ and $\dot{V}E$. 
Physiological dead space (\(V_D\)). This was calculated from the Bohr equation by using both arterialized ear-lobe \(PCO_2\) and end-tidal \(PCO_2\) as alternative estimates of arterial \(PCO_2\). In forty-one technically satisfactory studies, each member of the pair of results for dead space lay within ±10% of their mean value. A multiple-regression analysis of these results showed that \(V_D\) was significantly related to weight (more than to height) and to tidal volume (more than to work level). There were not enough studies to enable any conclusions to be made about sex differences. The results are illustrated in Fig. 4.

Table 3. Comparison of parameters at rest, one-third and two-thirds of maximum working capacity; for explanation of calculated rise in blood lactate concentration see the text

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
<th>First work load</th>
<th>Second work load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boys</td>
<td>Girls</td>
<td>Boys</td>
</tr>
<tr>
<td>(R)</td>
<td>Mean 0.97</td>
<td>0.96</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>SEM 0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>(n) 45</td>
<td>45</td>
<td>54</td>
</tr>
<tr>
<td>(Pa,CO_2) (mmHg)</td>
<td>Mean 33.6</td>
<td>32.1</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td>SEM 0.7</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>(n) 36</td>
<td>32</td>
<td>48</td>
</tr>
<tr>
<td>Measured concn. of lactate</td>
<td>Mean 1.2</td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td>(mmol/l)</td>
<td>SEM 0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>(n) 35</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>Calculated rise in lactate concn.</td>
<td>Mean —</td>
<td>—</td>
<td>2.0</td>
</tr>
<tr>
<td>(mmol/l)</td>
<td>SEM —</td>
<td>—</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>(n) —</td>
<td>—</td>
<td>46</td>
</tr>
</tbody>
</table>

Cardiac output (\(Q\)). This was significantly related to \(\dot{V}O_2\) with no sex differences. The influence of height, though significant, was small over the operative range (Fig. 5).

Heart rate (pulse). The heart rate was significantly related to \(\dot{V}O_2\) and was higher for smaller children and girls at any one work level. As in the simple progressive test it was found that the multiple regression of heart rate on the logarithm of \(\dot{V}O_2\) and height fitted the data best (Fig. 6).

Stroke volume (\(SV\)). Stroke volume was not significantly related to \(\dot{V}O_2\) in girls but there was a small, significant increase with \(\dot{V}O_2\) in boys (Table 2). There was a significant increase of SV with height in both sexes but girls had a lower SV value than boys of equivalent height.

Mixed venous \(PCO_2\) (\(PVO_2\)). This was significantly related to \(\dot{V}O_2\). There was no height effect but the regression lines for the sexes were slightly different.

Certain measurements were not significantly correlated with \(\dot{V}O_2\) or height but seemed to be related more to the relative work, i.e. whether it was rest, one-third or two-thirds of \(W_{max}\). (Fig. 7, Table 3).

Respiratory-exchange ratio (\(R\)). This was moderately high at rest and did not change at the first work load. It increased significantly from the first to second work load. There was no sex difference.
Arterial $P_{CO_2}$ ($Pa_{CO_2}$) was calculated from the Bohr equation for all studies in all subjects assuming a normal dead-space and correcting for instrument dead-space. It was rather variable at all levels but rose significantly from rest to the first work level and fell significantly from the first to the second level. The $Pa_{CO_2}$ was higher in boys at every level, but this was only significant at the first work load.

Blood lactate. The concentration of lactate in the blood rose very significantly from rest to the first work load and from the first to the second work load. Differences between the sexes were not significant. The increases in blood lactate concentration were calculated theoretically from a CO$_2$ balance equation (Clode & Campbell, 1969) and they are also given in Table 3. The calculated rises were virtually identical with the measured rises at all work levels for girls but were rather higher than the measured rises in boys, especially from the first to the second work load.

DISCUSSION

Details of the simpler measurements contained in this report such as pulse, ventilation and gas exchange are readily available for children (Robinson, 1938; Bengtsson, 1956; Astrand, 1952; Cumming & Friesen, 1967). However, information is not available about cardiac output and stroke volume on exercise, in relation to size over a wide range. This is because the standard techniques of cardiac catheterization are unacceptable for the study of normal children. The object of the present investigation was to provide indices of normal function in children, related to size where relevant, for clinical use. Equations and graphs have purposely been kept as simple as possible for this reason.

The methods used in this study follow the techniques developed by Campbell and his group (Higgs et al., 1967; McHardy et al., 1967; Jones et al., 1967) and they have been fully discussed by those authors. The procedure has been modified slightly for use in children, and in particular we have developed the concept of using an assumed normal dead-space to calculate $Pa_{CO_2}$ (Godfrey & Davies, 1970). The reliability of determining cardiac output by the Indirect (CO$_2$) Fick method, compared with the Direct (O$_2$) Fick or Dye Dilution methods, has been shown in studies in adults (Higgs et al., 1967; Ferguson, Faulkner, Julius & Conway, 1968; Muiesan, Sorbini, Solinas, Grassi, Casucci & Petz, 1968; Denison et al., 1969) but not in children.

Little technical difficulty was encountered in obtaining the heart rate, ventilation and gas exchange on exercise in most of the children, but we failed to obtain reliable results in 7% of work levels in boys and 16% in girls (each child performing two work levels). By using rigid criteria for acceptability of the plateau in measuring mixed venous $P_{CO_2}$ or in extrapolating the value (Jones et al., 1967; Denison et al., 1969) a total of 14% of work loads in boys and 20% in girls could not be used. However, at least one level of exercise was satisfactorily completed (including the measurement of cardiac output) in 91% of boys and 90% of girls.

Simple progressive exercise

By grading the work increments according to size most children, apart from the very smallest and the very largest, completed 6–8 min of progressive exercise. This test was simple to perform and provided information of clinical value on effort tolerance (the maximum load achieved) and on the pulse/work and inspired ventilation/work relationship at submaximal work levels. These values are often abnormal in heart or lung disease (Godfrey, 1970b).

Most of the children exercised up to or close to their limit in this test with a mean maximum
heart rate of 196. Astrand (1952) reported maximum heart rates of 202–211 in Swedish children but this was in steady-state exercise and higher than in most other series. Wilmore & Sigerseth (1967) reported maximum heart rates of 191–197 in girls aged 7–13 by using a similar technique to ours though the work increments used were 150 kpm/min (24.5 W) independent of size. In a clinical context therefore, if a child stops exercising with a heart rate below 190, it is highly suggestive of an abnormality in the cardio-respiratory system unless he is not trying; in that case the pulse/work and ventilation/work relationship at submaximal levels should be normal.

The results obtained in the simple progressive exercise test agree closely with those reported by other workers (Wilmore & Sigerseth, 1967; Gadhoke & Jones, 1969). Thus it was found that the maximum heart rate and the submaximal ventilation/work relationship were largely independent of size, whereas the maximum work (and ventilation) and the submaximal pulse/work relationship was size dependent. Except in the very youngest children, boys could generally achieve more work than girls and had lower pulse-rates for any given work. This conflicts somewhat with the finding of Astrand (1952) that most indices of physical fitness in girls only began to lag behind those of boys after the age of 12–13.

Steady-state exercise

By determining the working capacity in the simple progressive-exercise test it was possible to present each child with two work loads, similar in a relative sense, for steady-state exercise. It was very difficult to obtain reliable gas collections at rest in many of the children but they almost always settled down as soon as exercise began. For this reason we have concentrated on the more reliable exercise studies.

Ventilation and heart rate. As in the simple progressive-exercise test our results for expired ventilation, heart rate and also for gas exchange agree with previously published data (Bengtsson, 1956; Gadhoke & Jones, 1969), though direct comparisons of results are somewhat difficult owing to differences in the mode of presentation. Like them we found that tidal volume was related to size at any given value of oxygen consumption, but size had less influence on total ventilation. Compared with the simple progressive-exercise test, heart rate and ventilation were 5–10% higher in the steady-state test. This can be explained by the relative unsteady state existing in the simple progressive test.

Cardiac output and stroke volume. One object of this study was to obtain reliable data on cardiac output over a wide range of size in normal boys and girls. In a previous publication (Godfrey & Davies, 1970) it was shown that the cardiac output in normal subjects was best estimated by using an assumed normal dead-space. This is perhaps more useful in children than adults because the dead-space changes considerably with size and can be predicted with some certainty (Fig. 4). There is very little information about the values for dead space in children other than in the neonatal period, except for that of Robinson (1938), in which he assumed an apparatus dead-space of 100 ml (Radford, 1954). Levinson (personal communication) has provided us with values of dead space at rest in normal children, calculated from directly measured arterial \( PCO_2 \), which closely agree with results given here and with the extrapolations of Radford (1954). Tenney & Bartlett (1967) predicted from comparative studies that dead space should be related to body weight.

The only study known to the authors of cardiac output in normal children during exercise is that of Gadhoke & Jones (1969) which was limited to boys of a narrow size range. There is considerable information about the cardiac output in relation to work in normal adults, that
of Bevegard, Holmgren & Jonsson (1960) being typical of many others. The results of their studies in adults have been included in Fig. 5 which shows that there was no significant difference between the present results and their findings in adults. The values of Gadoke & Jones (1969) were rather higher than ours at lower values of oxygen consumption, presumably because they applied a 'downstream correction' to the mixed venous PCO\(_2\) (Jones et al., 1969), for the observed difference between the alveolar gas PCO\(_2\) and the PCO\(_2\) in the blood leaving the lungs during the rebreathing equilibrium plateau. This results in a smaller veno-arterial PCO\(_2\) difference which is proportionately more significant at lower work levels. We have not applied this correction because its significance is in doubt. Thus Denison et al. (1969) found that cardiac output based on the rebreathing PVCO\(_2\) agreed with that based on rebreathing mixed venous PO\(_2\) (PvO\(_2\)), directly measured PvO\(_2\) and with the predicted cardiac output based on O\(_2\) consumption. The result calculated from directly measured pulmonary arterial PCO\(_2\) ('upstream') gave results that were too high.

Stroke volume was only a little influenced by work in the present study but it was related to size (Table 2). This agrees with previous findings that the stroke volume increases from rest to exercise but not much between exercise loads (Bevegard et al., 1960). Unfortunately the results on cardiac output at rest were not reliable enough to calculate resting stroke volumes for comparison.

**Blood lactate concentration.** The method of grading exercise has allowed a comparison of lactate concentrations to be made; this was relatively unaffected by size. From Table 3 it can be seen that although there were significant rises from rest to work and from the first level to the second, the variation within any one work level was small. This suggests that the level of work at which lactate is produced increases as the child grows, and on a relative scale at submaximal levels of work small children produce no more lactate than larger children.

The increase in lactate was also reflected in the fall of Pa\(_{\text{a}},\text{CO}_2\) which occurred from the first to the second work load, and for the corresponding rise in R (Fig. 7). The rather low resting value for Pa\(_{\text{a}},\text{CO}_2\) reflects the difficulty in obtaining reliable resting studies in children. The relatively good agreement between the observed lactate rises and those predicted from the CO\(_2\) balance equations (Clode & Campbell, 1969) means that this prediction has considerable practical value in reflecting the degree of anaerobic metabolism.

It is concluded that as children grow there is little sex difference in cardiorespiratory performance under the age of 16, apart from the slightly greater maximum work load achieved by boys. Growth has little effect on the relationship between O\(_2\) consumption, total ventilation or cardiac output and the work level. Tidal volume, dead space, pulse rate and stroke volume are closely related to size at any level of work. Moderate alveolar hyperventilation is common in this type of exercise. Anaerobic metabolism, although related to size at any work level, is independent of size at any given fraction of the exercise capacity of the child.

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Exercise performance in children

REFERENCES


