CHEST[®]

THE CARDIOPULMONARY
AND CRITICAL CARE JOURNAL

FOR PULMONOLOGISTS, CARDIOLOGISTS, CARDIOTHORACIC SURGEONS,
CRITICAL CARE PHYSICIANS, AND RELATED SPECIALISTS

Estimation of mixed venous PCO₂ for determination of cardiac output in children

SV Jacob, L Hornby and LC Lands
Chest 1997;111;474-480

This information is current as of May 16, 2006

The online version of this article, along with updated information and services, is
located on the World Wide Web at:

<http://www.chestjournal.org>

CHEST is the official journal of the American College of Chest Physicians. It has been published monthly since 1935. Copyright 2005 by the American College of Chest Physicians, 3300 Dundee Road, Northbrook IL 60062. All rights reserved. No part of this article or PDF may be reproduced or distributed without the prior written permission of the copyright holder. ISSN: 0012-3692.

A M E R I C A N C O L L E G E O F
C H E S T
P H Y S I C I A N S

preliminary report

Estimation of Mixed Venous P_{CO_2} for Determination of Cardiac Output in Children*

Sheila V. Jacob, MD;[†] Laura Hornby, MSc; and Larry C. Lands, MD, PhD

Study objectives: Cardiac output ($\dot{Q}$) can be estimated noninvasively during exercise by employing CO_2 -rebreathing techniques (equilibrium and exponential) to estimate the oxygenated mixed venous PCO_2 ($P\bar{V}CO_2$). It has been found in adults and children that the equilibrium method underestimates $\dot{Q}$ as a result of overestimation of $P\bar{V}CO_2$, unless $P\bar{V}CO_2$ is "downstream corrected." In adults, it has been found that the exponential method does not require downstream correction and yields values similar to those obtained by the equilibrium method with downstream correction. The objectives of this study were as follows: to test whether the exponential method gives similar results to the equilibrium method with downstream correction in children; to verify that downstream correction is required in children; and to test whether a single equation could be used in adults and children to predict $\dot{Q}$ from oxygen consumption ($\dot{V}O_2$).

Design: Descriptive.

Setting: Exercise laboratory of a university hospital.

Participants: 23 children (16 boys, 7 girls) with a mean age of 11.0 ± 1.9 years (7.1 to 13.9 years), and 12 adults (7 men, 5 women) with a mean age of 33.6 ± 7.2 years (24 to 48 years).

Interventions: While performing steady-state exercise on an ergometer, $P\bar{V}CO_2$ was determined in 14 children using both the equilibrium and exponential methods, and in all other subjects using the equilibrium method alone.

Measurements and results: For the 14 children who underwent testing by both the equilibrium and exponential methods, the uncorrected equilibrium $P\bar{V}CO_2$ was significantly different from both the corrected $P\bar{V}CO_2$ and the exponential $P\bar{V}CO_2$. We found a strong relationship between $\dot{Q}$ (L/min), calculated using the downstream corrected values of $P\bar{V}CO_2$, and $\dot{V}O_2$ (L/min) ($r^2=0.95$), and this relationship was similar to that obtained by dye dilution in other studies. When weight was included, it was determined that one equation could be used for children and adults: $\dot{Q}$ (L/min) = $1.42 + 5.80 \cdot \dot{V}O_2$ (L/min) + $0.06 \cdot \text{wt}$ (kg), $r^2=0.97$, $SEY=0.67$.

Conclusions: CO_2 -rebreathing techniques can be used to determine $\dot{Q}$ in children; the exponential method gives values that are similar to the equilibrium method with the downstream correction; and one prediction can be used for $\dot{Q}$ in adults and children. (CHEST 1997; 111:474-80)

Key words: equilibrium rebreathing method; exercise; exponential rebreathing method

Abbreviations: $PEQCO_2$ =end-tidal PCO_2 at equilibrium; $PETCO_2$ =end-tidal PCO_2 ; $P\bar{V}CO_2$ =oxygenated mixed venous PCO_2 ; $P\bar{V}CO_2$ eq,corr=corrected equilibrium $P\bar{V}CO_2$; $P\bar{V}CO_2$ exp=exponential $P\bar{V}CO_2$; $\dot{Q}$ =cardiac output; SE=standard error; $\dot{V}CO_2$ =carbon dioxide production; $\dot{V}O_2$ =oxygen consumption

*From the Division of Respiratory Medicine, Montreal Children's Hospital—McGill University, Montreal, Quebec, Canada.

[†]Currently at UMDNJ/Robert Wood Johnson Medical School, New Brunswick, NJ.

Supported by the MCH-McGill Research Institute (Dr. Jacob) and la Fondation de Recherche en Santé du Québec (Dr. Lands and Ms. Hornby), and la Fondation de Recherche en Santé du Québec (Dr. Lands and Ms. Hornby).

Manuscript received June 18, 1996; revision accepted October 10.

Reprint requests: Dr. Lands, Division of Respiratory Medicine, Room D-380, Montreal Children's Hospital, 2300 Tupper Street, Montreal, Quebec, Canada H3H 1P3.

Cardiac output ($\dot{Q}$) can be determined noninvasively during exercise using the indirect CO_2 -rebreathing method. By this technique, oxygenated mixed venous PCO_2 ($P\bar{V}CO_2$) is estimated using one of two methods: the equilibrium method of Collier¹ or the exponential method of Defares.² In the equilibrium method, a relatively high concentration of CO_2 is rebreathed, which leads to an equilibration of CO_2 in the lungs and blood and a plateau in the

end-tidal PCO_2 (PETCO_2 , at equilibrium known as $\text{P}\bar{\text{E}}\text{QCO}_2$). In the exponential method, a low concentration of CO_2 is rebreathed, which results in an exponential rise in the PETCO_2 .

In exercising adults, it has been found that the equilibrium method overestimates $\text{P}\bar{\text{V}}\text{CO}_2$, as determined by $\text{P}\bar{\text{E}}\text{QCO}_2$, resulting in an underestimation of the $\dot{Q}$ in comparison to dye-dilution measures.^{3,4} This led to the development of a correction factor for $\text{P}\bar{\text{V}}\text{CO}_2$ that is known as the “downstream correction factor” ($\text{P}\bar{\text{V}}\text{CO}_2 = \text{P}\bar{\text{E}}\text{QCO}_2 - [0.24 \cdot \text{P}\bar{\text{E}}\text{QCO}_2 - 11]$).⁵ However, this correction does not appear to be necessary using the exponential method.⁶ The reason for this downstream correction with the equilibrium method remains unclear, but it is likely related to the absence of outward movement of CO_2 from the blood to the rebreathing bag during this method.⁶

In children, there has been some controversy over whether downstream correction is necessary when using the equilibrium method to determine $\dot{Q}$. Godfrey and coworkers⁷ found that the overestimation of $\text{P}\bar{\text{V}}\text{CO}_2$ that had been seen in adults^{4,8,9} was also present in children,⁷ but Godfrey¹⁰ suggests that the use of the downstream correction in children gives an overly high estimate of $\dot{Q}$, so that the uncorrected plateau value for $\text{P}\bar{\text{V}}\text{CO}_2$ should be used.¹⁰ Paterson and coworkers,^{11,12} however, found that the use of the downstream correction in children gave values that were close to those obtained by dye dilution on similar populations,¹¹ and that the equilibrium method with downstream correction allowed reliable and consistent measurement of $\dot{Q}$.¹²

It has been demonstrated recently that the exponential method gives $\dot{Q}$ estimates similar to those of the equilibrium method, after the downstream correction, during steady-state exercise in cystic fibrosis patients and healthy control subjects over the age of 14 years.^{13,14} The exponential method is well tolerated, as it requires the use of a lower concentration of CO_2 than does the equilibrium method, and it can be used during progressive exercise testing.¹⁴ The aims of the present study were as follows: (1) to compare the exponential method for determination of $\text{P}\bar{\text{V}}\text{CO}_2$ using new computer analysis techniques with the equilibrium method in children; (2) to confirm that downstream correction of $\text{P}\bar{\text{V}}\text{CO}_2$ was required in healthy children from 7 to 13 years of age when the equilibrium method was used; and (3) to test whether a single equation could be used in children and adults for prediction of $\dot{Q}$ from oxygen consumption ($\dot{V}\text{O}_2$).

We hypothesized the following in exercising children: (1) $\text{P}\bar{\text{V}}\text{CO}_2$ obtained by the exponential method would be similar to that obtained by the equilibrium method using the downstream correction; (2) when plotted against $\dot{V}\text{O}_2$, corrected values for $\dot{Q}$ would be

similar to those obtained by others using dye dilution; and (3) when plotted against $\dot{V}\text{O}_2$, the values for $\dot{Q}$ in children and adults would not differ when downstream correction was employed.

MATERIALS AND METHODS

Subjects

Hospital staff and their children were recruited for the study. Data obtained from prematurely born children who were participating in a long-term follow-up study and from children who had undergone exercise testing for growth hormone secretion were also employed. Subjects were excluded if they had an FEV_1 of <80% of their predicted value based on age, race, sex, and height.^{15,16} The study had the approval of the Institutional Review Board of the Montreal Children's Hospital/McGill Research Institute. For children, an informed consent was obtained from one of the parents as well as from the child.

Methods

For each subject, height was measured in stocking feet on a stadiometer and weight was measured using an electronic balance. Expiratory spirometry was performed according to American Thoracic Society criteria.¹⁷

To determine maximal work capacity, all subjects, except the two being evaluated for growth hormone secretion, performed a maximal progressive test using an electronically braked cycle ergometer. The workload was increased in 1-min increments, which were chosen according to the sex and height of the subject so that exhaustion would occur within 5 to 10 min.¹⁰ The maximum workload was the highest workload at which a subject was able to maintain a pedaling speed of 60 rpm. Heart rate was monitored continually and recorded via ECG. Inspired ventilation was measured by a dry gas meter (Parkinson Cowan; Manchester, UK). Exhalation was via a unidirectional valve to a variable-volume mixing chamber adjusted to the subject's vital capacity. Mixed expired gas was analyzed and recorded continuously for fractional concentrations of oxygen and carbon dioxide using a mass spectrometer (Marquette Electronics; Milwaukee). $\dot{V}\text{O}_2$ and carbon dioxide production ($\dot{V}\text{CO}_2$) were calculated using the nitrogen balance technique, based on values for ventilation and mixed expired concentrations of oxygen and carbon dioxide obtained during the last 10 s of each workload. Details of the method have been described previously.^{18,19}

After a rest period of at least 30 min, a steady-state exercise test was performed at approximately half maximal work capacity in adults and children with the exception of two adult men who were evaluated at two-thirds maximal work capacity in order to increase the range of $\dot{V}\text{O}_2$ measured. For the two children being tested for growth hormone levels, the steady-state test was performed at half the predicted maximal work capacity based on sex and height.¹⁰ Exercise at a constant workload was performed until steady-state conditions were reached for $\dot{V}\text{O}_2$, $\dot{V}\text{CO}_2$, and heart rate. This usually occurred within 4 to 5 min.

At steady state, a rebreathing procedure was performed using the equilibrium method in which each subject rebreathed from a bag containing a mixture of a high concentration of CO_2 (11 to 13.5%) and oxygen (76.5 to 79%) at a volume of two-thirds the vital capacity.

In children, after steady state had been reestablished (a

minimum of 60 s), a second rebreathing procedure was performed using the exponential method. For this, the subject rebreathed a mixture of 4% CO₂ and 96% oxygen at a volume of 1.5 to 2 times the tidal volume.

PvCO₂ was calculated for the equilibrium method using the method of Collier¹ in which the plateau value of PETCO₂ between 6 and 10 s (PEQCO₂) was determined; the extrapolation procedure described by Denison et al⁸ was used when an absolute plateau was not obtained. The downstream correction was applied to this value to correct for alveolar-to-blood PCO₂ differences.⁵ For the exponential method, PvCO₂ was calculated using the method of Defares.² PETCO₂ values between 1.5 and 13 s were used for $\dot{V}_{O_2} < \frac{2}{3}$ max and those between 1.5 and 11 s for higher values of $\dot{V}_{O_2}$, to avoid the effects of recirculation. PETCO₂ was linearized to time by log transformation and successive iterations of the asymptote were performed to derive a best fit line using least squares linear regression analysis. Using the fitted line, the projected PETCO₂ value at 20 s of rebreathing was used as the estimate of PvCO₂.²⁰

$\dot{Q}$ was determined by dividing the $\dot{V}_{CO_2}$ by the venous-arterial CO₂ content difference, which was derived from the CO₂ tensions,²¹ assuming a hemoglobin of 150 g/L, a pH of 7.40, and an oxygen saturation of 97% for arterial blood. It was assumed that the oxygen saturation of the mixed venous blood was 100% during the rebreathing procedure, because of the high concentration of oxygen in the rebreathing gas mixture. $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ were calculated for the 15 s prior to each rebreathe. PaCO₂ was estimated from PETCO₂ using a correction factor as described by Jones.⁵

$$PaCO_2 = 5.5 + 0.9 \cdot PETCO_2 - 0.0021 \cdot \text{tidal volume}.$$

PvCO₂ was estimated by the equilibrium method.

Analysis of Data

PvCO₂ as obtained by the equilibrium method, with and without downstream correction, was compared to that obtained by the exponential method using analysis of variance. The relationships between the corrected and uncorrected PvCO₂ values obtained by the equilibrium method and the values obtained by the exponential method were assessed by linear regression analysis.

$\dot{Q}$ obtained by the equilibrium method with and without downstream correction was plotted against $\dot{V}_{O_2}$ and assessed by linear regression analysis. Stepwise linear regression analyses were also performed to look at the effects of weight, sex, and subject category (adults, normal children, prematurely born children, children being evaluated for growth hormone levels).

For regression equations, slopes and intercepts were compared with those in the literature using the unpaired *t* test: because the standard errors (SEs) were not available for the values from the literature, the differences between the values obtained in this study and those in the literature were divided by the standard errors of the values obtained in this study.

RESULTS

A total of 14 children (11 boys and 3 girls), mean age 11.7 ± 1.6 years, range 8.2 to 13.9 years, successfully underwent steady-state exercise tests in which PvCO₂ was measured by both the exponential and

equilibrium methods. Eight were healthy children of hospital staff, four were healthy prematurely born children, and two were otherwise healthy children who had undergone testing for growth hormone secretion due to short stature. Nine other children (five boys and four girls) underwent steady-state exercise tests in which PvCO₂ was obtained by the equilibrium method alone. Five were children of hospital staff and four were prematurely born. The mean age of the 23 children was 11.0 ± 1.9 years, range 7.1 to 13.9 years. Twelve adults (seven men and five women), mean age 33.6 ± 7.2 years, range 24 to 48 years, underwent steady-state exercise tests in which PvCO₂ was measured by the equilibrium method.

PvCO₂

In exercising children, there was a closer agreement between the downstream corrected equilibrium PvCO₂ and exponential values than between the uncorrected equilibrium and exponential measures. As is seen in Figure 1, the equilibrium downstream corrected values of PvCO₂ plotted against the exponential values, fell closer to the line of identity than did the uncorrected equilibrium values of PvCO₂. Mean PvCO₂ by the exponential method was 62.0 ± 5.1 mm Hg. By the equilibrium method, absolute PvCO₂ was 68.4 ± 4.9 mm Hg, and corrected PvCO₂ was 63.0 ± 3.7 mm Hg. By analysis of variance, there was a significant difference between the mean uncorrected equilibrium value and the mean values obtained by the other two methods ($p=0.012$).

When the uncorrected equilibrium PvCO₂ was plotted against exponential PvCO₂ in mm Hg (Fig 1, filled squares), we found a slope of 0.89 (SE, 0.1) and an intercept of 14.1 (SE, 6.8). For corrected equilibrium PvCO₂ (PvCO₂ eq,corr) vs exponential PvCO₂ (PvCO₂ exp) (Fig 1, open squares), we found a slope of 0.67 (SE, 0.08) and an intercept of 21.7 (SE, 5.2). In adults, Heigenhauser and Jones⁶ found the following relationship between the PvCO₂ eq,corr and the PvCO₂ exp:

$$PvCO_2 \text{ eq,corr (kpa)} = 2.38 + 0.7 \cdot PvCO_2 \text{ exp (kpa)} \quad (1)$$

When our regression equation is expressed in kilopascals,

$$\begin{aligned} PvCO_2 \text{ eq,corr (kpa)} \\ = 2.89 \text{ (SE, 0.69)} + 0.67 \text{ (SE, 0.08)} \\ \cdot PvCO_2 \text{ exp (kpa)}, r^2 = 0.83 \end{aligned} \quad (2)$$

the slope and intercept are not significantly different from those obtained by Heigenhauser and Jones.⁶

In a later study from the same group,²⁰ values fell

FIGURE 1. Mixed venous PCO_2 (mm Hg) obtained using the equilibrium method ($\text{P}\ddot{\text{V}}\text{CO}_{2,\text{eq}}$) vs mixed venous PCO_2 obtained using the exponential method ($\text{P}\ddot{\text{V}}\text{CO}_{2,\text{exp}}$). Solid squares represent uncorrected values and open squares represent downstream corrected values for $\text{P}\ddot{\text{V}}\text{CO}_{2,\text{eq}}$. The lines represent the line of identity for $\text{P}\ddot{\text{V}}\text{CO}_{2,\text{exp}}$, and 10% above and below the line of identity. The downstream corrected values of $\text{P}\ddot{\text{V}}\text{CO}_{2,\text{eq}}$ fall closer to the line of identity of than do the absolute values of $\text{P}\ddot{\text{V}}\text{CO}_{2,\text{eq}}$.

closer to the line of identity, with a slope of 0.975 and an intercept of 1.46. Their data encompassed a much broader range than did ours, and our values can be superimposed on their concordance plot.

Cardiac Output

Downstream corrected equilibrium $\dot{Q}$ in liters per minute plotted against $\dot{V}\text{O}_2$ in liters per minute for all adults and children gave us the following regression equation:

$$\dot{Q} \text{ (L/min)} = 1.79 \text{ (SE, 0.40)} + 7.89 \text{ (SE, 0.31)} \cdot \dot{V}\text{O}_2 \text{ (L/min)}, r^2 = 0.95 \quad (3)$$

for submaximal exercise with a range of $\dot{V}\text{O}_2$ from 0.5 to 2.5 L/min. This equation is very similar to that obtained using the combined values from two previously published dye dilution studies, one involving pubertal boys⁹ and the other involving young men:⁸

$$\dot{Q} \text{ (L/min)} = 1.75 + 7.95 \cdot \dot{V}\text{O}_2 \text{ (L/min)}, r^2 = 0.48 \quad (4)$$

This relationship can be seen in Figure 2.

A small difference in the $\dot{Q}$ - $\dot{V}\text{O}_2$ relationship between children and adults was determined using stepwise linear regression analysis and a grouping factor, gp (0 for children and 1 for adults):

$$\dot{Q} \text{ (L/min)} = 2.40 \text{ (SE, 0.39)} + 7.05 \text{ (SE, 0.36)}$$

$$\cdot \dot{V}\text{O}_2 \text{ (L/min)} + 1.21 \text{ (SE, 0.35)} \cdot \text{gp}, r^2 = 0.96 \quad (5)$$

This difference is eliminated when weight (wt) is factored into the equation

$$\dot{Q} \text{ (L/min)} = 1.42 \text{ (SE, 0.33)} + 5.80 \text{ (SE, 0.53)} \cdot \dot{V}\text{O}_2 \text{ (L/min)} + 0.06 \text{ (SE, 0.01)} \cdot \text{wt (kg)}, r^2 = 0.97 \quad (6)$$

When calculated without an intercept for comparison with the equation suggested by Jones,⁵

$$\dot{Q} \text{ (L/min)} = 5.5 \cdot \dot{V}\text{O}_2 \text{ (L/min)} + 0.06 \cdot \text{wt (kg)} \quad (7)$$

the equation becomes

$$\dot{Q} \text{ (L/min)} = 6.25 \text{ (SE, 0.64)} \cdot \dot{V}\text{O}_2 \text{ (L/min)} + 0.075 \text{ (SE, 0.016)} \cdot \text{wt (kg)} \quad (8)$$

which has coefficients that are not significantly different from those proposed by Jones. Sex was not a contributing factor to the regression equation, nor was subject category (term, prematurely born, or undergoing testing for growth hormone secretion) a contributing factor among children.

When $\dot{Q}$ and $\dot{V}\text{O}_2$ were expressed in mL/min/kg, the following equation was obtained:

$$\begin{aligned} \dot{Q} \text{ (mL/min/kg)} &= 83.5 \text{ (SE, 20.0)} + 6.2 \text{ (SE, 0.8)} \\ &\cdot \dot{V}\text{O}_2 \text{ (mL/min/kg)}, r^2 = 0.66 \quad (9) \end{aligned}$$

FIGURE 2. $\dot{Q}$ (L/min) vs $\dot{V}\text{O}_2$ (L/min). The relationship between $\dot{Q}$, calculated using the downstream corrected values of $\text{P}\ddot{\text{V}}\text{CO}_2$ for children and adults ("X" and asterisks) and $\dot{V}\text{O}_2$ is not significantly different from that of other studies in which $\dot{Q}$ was determined by dye dilution for children and adults (solid squares and open squares) (Adapted from Eriksson et al²⁴ and Ekblom et al²³).

FIGURE 3. $\dot{Q}$ (mL/min/kg) vs $\dot{V}O_2$ (mL/min/kg). Most of the values for adults ("X" = absolute and asterisk = corrected) fall within the 95% confidence interval for values of Faulkner et al²² using the exponential method. The values for children (solid squares = absolute and open squares = corrected) are somewhat higher.

In our study, for men alone, the following equation was obtained:

$$\dot{Q} \text{ (mL/min/kg)} = 80.3 \text{ (SE, 22.8)} + 5.8 \text{ (SE, 0.9)} \cdot \dot{V}O_2 \text{ (mL/min/kg)}, \quad r^2 = 0.88 \quad (10)$$

which has a slope and intercept not significantly different from the equation described by Faulkner and coworkers²² in their study of 50 normal adult male subjects at various steady-state work loads using the exponential method (Fig 3):

$$\dot{Q} \text{ (mL/min/kg)} = 66 + 5.2 \cdot \dot{V}O_2 \text{ (mL/min/kg)} \quad (11)$$

Values in children were slightly higher:

$$\dot{Q} \text{ (mL/min/kg)} = 97.1 \text{ (SE, 27.5)} + 5.9 \text{ (SE, 1.0)} \cdot \dot{V}O_2 \text{ (mL/min/kg)}, \quad r^2 = 0.60 \quad (12)$$

and, when results for adults and children were combined, the grouping factor (adults vs children) contributed significantly to the regression equation (r^2 increased from 0.66 to 0.71).

DISCUSSION

We found in healthy children that $P\bar{V}CO_2$ obtained using the exponential method was similar to the downstream corrected equilibrium value, but significantly different from the uncorrected equilibrium value. This is similar to what has been described in adults.^{6,13,20} This suggests that in children, as in adults, either the equilibrium method with downstream correction or the exponential method can be used when calculating $P\bar{V}CO_2$.

Using the $P\bar{V}CO_2$ obtained by the equilibrium method with the downstream correction, we found a very high correlation, $r^2 = 0.95$, between $\dot{Q}$ and $\dot{V}O_2$ in healthy adults and children of both sexes (equation 3, Fig 2). Our results agree closely with those of dye dilution studies^{23,24} (equation 4, Fig 2). We found that there was a slight additional effect when a grouping factor, indicating whether a subject was a child or an adult, was included, but this effect disappeared when weight was included as one of the independent variables in the stepwise linear regression equation. We therefore suggest, for ease of use and applicability to both children and adults, that the following equation (equation 6) be used in the prediction of $\dot{Q}$: $\dot{Q} \text{ (L/min)} = 1.42 + 5.80 \cdot \dot{V}O_2 \text{ (L/min)} + 0.06 \cdot \text{wt (kg)}$, $r^2 = 0.97$, standard error of the estimate (SEE) = 0.67. Using a forced intercept of zero, our equation (equation 8) was not significantly different from that of Jones (equation 7), which was extrapolated from values in the literature. Since the exponential method is reliable in determination of $\dot{Q}$ in mild to moderate lung disease¹³ as well as in severe lung disease in adults,²⁵ we would suggest that the indirect Fick method may be applicable to a wide patient population, although arterial PCO_2 may need to be measured directly in patients with severe airflow limitation.²⁶ In addition, because the exponential method is well tolerated and can be used during progressive exercise, the indirect Fick method can be used for the determination of $\dot{Q}$ in a wide variety of clinical and research studies.

Our results are in keeping with studies in adults^{3,4,27} and children,¹¹ that found good agreement between $\dot{Q}$ calculated using downstream corrected equilibrium values for $P\bar{V}CO_2$ and that measured by dye dilution techniques. Furthermore, Gadhoke and Jones²⁸ found that the relationship between $\dot{Q}$ and $\dot{V}O_2$ did not differ between boys and men. While Godfrey et al^{7,29} acknowledged the existence of an alveolar to blood gradient in children that was no different from that found in adults, they suggested that the uncorrected value for $P\bar{V}CO_2$ should be used in children to avoid overestimation of cardiac output. It is unclear why our results differ from those of Godfrey et al. While the use of an infrared analyzer to measure PCO_2 can affect CO_2 readings due to collision broadening,³⁰ this would not explain the difference as we used a mass spectrometer, which is not subject to collision broadening, and Godfrey et al controlled for the effects of collision broadening in their study (personal communication). Paterson and Cunningham¹¹ suggested that the CO_2 dissociation derived by Godfrey et al may have raised the values of $\dot{Q}$ in children, as compared to the curve of McHardy, which we used in our study, or that of Comroe. In the present study,

both children and adults were evaluated using the same exercise apparatus and protocol, and both groups had similar values to those obtained by dye dilution.

When $\dot{Q}$ in mL/min/kg, calculated using the corrected $\text{P}\bar{\text{V}}\text{CO}_2$, was plotted against $\dot{\text{V}}\text{O}_2$ in mL/min/kg, most of our data points for adults fell within the 95th percentile confidence interval described by Faulkner et al²² in their study of 50 normal adult male subjects at various steady-state work loads using the exponential method (Fig 3), although our values tended to be somewhat higher. Differences between our values and those of Faulkner et al may result from slight differences in the equations used to convert partial pressures to contents as the equations used by Faulkner et al were not specified. Most of our data points for children using the downstream correction were higher than those predicted by the 95th percentile confidence interval of Faulkner et al (Fig 2). In our stepwise regression analysis for prediction of $\dot{Q}$, we found a difference between children and adults. In their study, Faulkner et al found a lower intercept for the normalized relationship in men older than 40 years of age who had a $\dot{\text{V}}\text{O}_2$ of <30 mL/min/kg, and suggested that the difference in intercepts may be due to body fat in excess of 18%. We did not have data on body fat on all the adults and children who we tested, but we speculate that as children tend to have a lower body fat percentage than adults; this is a possible explanation for their relatively higher values for $\dot{Q}$ per kilogram of body weight.

It should be noted that our prediction equations apply to adults and children performing submaximal exercise, with a range of $\dot{\text{V}}\text{O}_2$ from 0.5 to 2.5 L/min. We cannot comment on whether they are applicable to the determination of $\dot{Q}$ at higher levels of $\dot{\text{V}}\text{O}_2$.

We conclude that CO_2 -rebreathing techniques, equilibrium and exponential, may be used in children to estimate $\dot{Q}$ noninvasively. In children, as in adults, the downstream correction factor should be applied to $\text{P}\bar{\text{V}}\text{CO}_2$ obtained by the equilibrium method. With this, a prediction equation for $\dot{Q}$ is obtained, based on $\dot{\text{V}}\text{O}_2$, which is very similar to that obtained from dye dilution studies. When weight is included in the equation, the relationship is further strengthened, and one equation can be used to describe $\dot{Q}$ in children and adults.

ACKNOWLEDGMENTS: We thank Dr. A.L. Coates for his helpful suggestions during the preparation of this manuscript, and C.M. MacNeish, J. Mesiano, and F. Xu for their technical assistance.

REFERENCES

- 1 Collier CR. Determination of mixed venous CO_2 tensions by rebreathing. *J Appl Physiol* 1956; 9:25-9
- 2 Defares JG. Determination of $\text{P}\bar{\text{V}}\text{CO}_2$ from the exponential CO_2 rise during rebreathing. *J Appl Physiol* 1958; 13:159-64
- 3 Jones NL, Campbell EJM, McHardy GJR, et al. The estimation of carbon dioxide pressure of mixed venous blood during exercise. *Clin Sci* 1967; 32:311-27
- 4 Jones NL, Robertson DG, Kane JW, et al. Effect of PCO_2 level on alveolar-arterial PCO_2 difference during rebreathing. *J Appl Physiol* 1972; 32:782-87
- 5 Jones NL. Clinical exercise testing. Philadelphia: WB Saunders, 1988; 186-207
- 6 Heigenhauser GJF, Jones NL. Comparison of two rebreathing methods for the determination of mixed venous partial pressure of carbon dioxide during exercise. *Clin Sci* 1979; 56:433-37
- 7 Godfrey S, Katzenelson R, Wolf E. Gas to blood PCO_2 differences during rebreathing in children and adults. *Respir Physiol* 1971; 13:274-82
- 8 Denison D, Edwards RHT, Jones G, et al. Direct and rebreathing estimates of the O_2 and CO_2 pressures in mixed venous blood. *Respir Physiol* 1969; 7:326-34
- 9 Denison D, Edwards RHT, Jones G, et al. Estimates of the CO_2 pressures in systemic arterial blood during rebreathing on exercise. *Respir Physiol* 1971; 11:186-96
- 10 Godfrey S. Exercise testing in children. Philadelphia: WB Saunders, 1974; 42-65
- 11 Paterson DH, Cunningham DA. Comparison of methods to calculate cardiac output using the CO_2 rebreathing method. *Eur J Appl Physiol* 1976; 35:223-30
- 12 Paterson DH, Cunningham DA, Plyley MJ, et al. The consistency of cardiac output measurement (CO_2 rebreath) in children during exercise. *Eur J Appl Physiol* 1982; 49:37-44
- 13 Lands LC, Heigenhauser GJF, Jones NL. Cardiac output determination during progressive exercise in cystic fibrosis. *Chest* 1992; 102:1118-23
- 14 McKelvie RS, Heigenhauser GJF, Jones NL. Measurement of cardiac output by CO_2 rebreathing in unsteady state exercise. *Chest* 1987; 92:777-82
- 15 Polgar G, Promodhat V. Pulmonary function testing in children: techniques and standards. Philadelphia: WB Saunders, 1971; 254
- 16 Morris JF. Spirometry in the evaluation of pulmonary function. *West J Med* 1976; 23:110-18
- 17 American Thoracic Society. Standardization of spirometry—1987 update. *Am Rev Respir Dis* 1987; 136:1285-98
- 18 Coates AL, Desmond K, Asher MI, et al. The effect of digoxin on exercise capacity and exercising cardiac function in cystic fibrosis. *Chest* 1982; 82:543-47
- 19 Hortop J, Desmond KJ, Coates AL. The mechanical effects of expiratory airflow limitation on cardiac performance in cystic fibrosis. *Am Rev Respir Dis* 1988; 137:132-37
- 20 Alves Da Silva G, El-Manshaw A, Heigenhauser GJF, et al. Measurement of mixed venous carbon dioxide pressure by rebreathing during exercise. *Respir Physiol* 1985; 59:379-92
- 21 McHardy GJR. Relationship between the difference in pressure and content of carbon dioxide in arterial and venous blood. *Clin Sci* 1967; 32:299-309
- 22 Faulkner JA, Heigenhauser GF, Schork MA. The cardiac output-oxygen uptake relationship of men during graded bicycle ergometry. *Med Sci Sports* 1977; 9:148-54
- 23 Ekblom B, Åstrand P, Saltin B, et al. Effect of training on circulatory response to exercise. *J Appl Physiol* 1968; 24:518-28

- 24 Eriksson BO, Grimby G, Saltin B. Cardiac output and arterial blood gases during exercise in pubertal boys. *J Appl Physiol* 1971; 31:348-52
- 25 Lands LC, Hornby L, Levy RD, et al. Measurement of mixed venous PCO_2 in patients with severe airflow limitation [abstract]. *Am J Respir Crit Care Med* 1994; 149:A783
- 26 Lands LC, Canny G, Xu F, et al. Cardiac output can be determined non-invasively in severe airflow limitation. *Am J Respir Crit Care Med* 1996; 153:981-84
- 27 Higgs BE, Clode M, McHardy GJR, et al. Changes in ventilation, gas exchange and circulation during exercise in normal subjects. *Clin Sci* 1967; 32:329-37
- 28 Gadhoke S, Jones NL. The responses to exercise in boys aged 9-15 years. *Clin Sci* 1969; 37:789-801
- 29 Godfrey S, Davies CTM, Wozniak E, et al. Cardio-respiratory response to exercise in normal children. *Clin Sci* 1971; 40:419-31
- 30 Hornby L, Coates AL, Lands LC. Effect of analyzer on determination of mixed venous PCO_2 and cardiac output during exercise. *J Appl Physiol* 1995; 79:1032-38

Estimation of mixed venous PCO₂ for determination of cardiac output in children

SV Jacob, L Hornby and LC Lands
Chest 1997;111;474-480

This information is current as of May 16, 2006

**Updated Information
& Services**

Updated information and services, including high-resolution figures, can be found at:
<http://www.chestjournal.org>

Citations

This article has been cited by 1 HighWire-hosted articles:
<http://www.chestjournal.org#otherarticles>

Permissions & Licensing

Information about reproducing this article in parts (figures, tables) or in its entirety can be found online at:
<http://www.chestjournal.org/misc/reprints.shtml>

Reprints

Information about ordering reprints can be found online:
<http://www.chestjournal.org/misc/reprints.shtml>

Email alerting service

Receive free email alerts when new articles cite this article sign up in the box at the top right corner of the online article.

Images in PowerPoint format

Figures that appear in CHEST articles can be downloaded for teaching purposes in PowerPoint slide format. See any online article figure for directions.