Cardiac output during exercise by the open circuit acetylene washin method: comparison with direct Fick

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METHODS

Subjects. All aspects of the study were approved by the Mayo Clinic Institutional Review Board. Subjects consisted of staff clinicians or residents in the Department of Anesthesiology who reviewed and gave written, informed consent before participation. Usual activity levels varied among the subjects; four subjects were former athletes and maintained a moderate level of training during the time of the study. Before testing, subjects were instructed to fast for at least 2 h. The majority of studies were performed in the early morning, thus resulting in a fasting period 8 h. Subjects were also instructed to avoid exercise the day of testing and to avoid heavy exercise training the day before testing.

Exercise protocol. Subjects reported to the General Clinical Research Center Exercise Core Laboratory on two occasions for exercise studies. During the first session, subjects were familiarized with the testing equipment and performed a maximal cycle ergometry test to volitional exhaustion. Dur-
during the initial test, measurements were made of gas exchange (Medical Graphics CPXD), heart rate (Marquette Electronics), and power (electronically braked cycle ergometer). Power was incremented between 25 and 50 W/min, depending on the subject.

During the second session, catheters were placed in the pulmonary and radial arteries and measurements of QT were assessed using the direct Fick and OpCirc methods. Pulmonary artery catheters (7 Fr, 65 cm, double-lumen pulmonary artery catheter; Arrow International, Reading, PA) were inserted via an 8-Fr introducer catheter (Arrow International) under local anesthesia through an antecubital vein during continuous electrocardiogram and pressure monitoring. The correct position of the pulmonary artery catheter was verified by the wedge position and pressure tracings. Flexible, 20-gauge, PVC radial artery catheters were inserted percutaneously under local anesthesia and taped in place to allow multiple arterial blood-gas samples to be taken. Both catheters were continuously flushed with heparinized saline (3 U/ml heparin; 3 ml/h) to maintain patency. Measurements were obtained at rest and during three submaximal steady-state work intensities (20, 40, and 60% of peak power). Each work intensity lasted 7–9 min, the time required to reach steady state followed by two repeat sets of measurements. After 2–3 min at constant power to allow steady state in oxygen consumption (VO2), arterial and mixed venous blood samples were drawn simultaneously, whereas oxygen consumption was measured over approximately a 30-s period. This was followed by an OpCirc measurement (8–12 breaths of acetylene-helium gas mixture). Allowing 1–2 min at constant power setting of the ergometer to wash out the inert gases from the subject's lung, we repeated the measurements of VO2 and OpCirc. On termination of the second OpCirc data collection, power output of the ergometer was increased to the next level and the procedures were repeated. After completion of the three submaximal work levels, a rest period of 5–10 min was taken, and the three work levels were subsequently repeated. When the second set of samples was completed, most subjects had an additional rest period, followed by a final work bout at ~80–85% of the peak power achieved on their initial exercise test. Measurements of VO2, blood sampling, and OpCirc were taken again, similar to the submaximal work load measurements. One subject was unable to complete these last measurements.

OpCirc technique QT was measured noninvasively using the OpCirc inert gas washin method. The technique has been described previously (7, 16, 24). Figure 1 shows the valve set up for the washin of inert gases. A pneumotachograph (Hans Rudolph, Kansas City, MO, 381 series; transducer, Celecso, ±2 cmH2O) was connected to a nonrebreathing Y valve (Hans Rudolph, 273C), whose inspiratory port was connected to a pneumative switching valve with low resistance and low dead space (Hans Rudolph, P0271, controller 4285A), allowing switching between room air and the QT gas mixture (0.7% C2H2, 21% O2, 9% He, balance N2) on the inspired port with minimal dead space (~50 ml). Gases were sampled via a mass spectrometer (Perkin-Elmer, 1100), with a phase delay of 0.27 s. Throughout the resting and exercise breathing, the subjects were encouraged to breathe in a regular rhythm, avoiding coughs, swallows, and partial breaths, if possible. The subjects were allowed to breathe normally from the valve, and the operator switched the pneumatic valve to change the inspiratory air source to the QT mixture. The washin of C2H2 and helium was observed on the computer screen by the operator on a breath-by-breath basis, until eight breaths had been obtained, as shown in Fig. 2. Data analysis was performed immediately after each maneuver using the relatively rapid calculation method (OpCirc1) described by Gan et al. (7) and Stout et al. (24), as outlined in the APPENDIX. In addition, data were analyzed after the exercise session using a finite difference modeling method (OpCirc2), also outlined in the APPENDIX. For both techniques, we used all eight breaths. OpCirc1 calculated the uptake of C2H2, taking breath pairs, with 28 possible pairs. As a part of the data-smoothing process, outlier solutions of the breath pairs (>98th percentile) were removed and the QT was reassessed. OpCirc2 examined all breaths and included a minimization technique to minimize differences between modeled and actual end-tidal gas concentrations (see APPENDIX).
Early in the development of the washin technique, we found it important to minimize valve and breathing apparatus dead space so that full-scale change in inspired acetylene was observed on the first breath of the washin. In addition, it was critical to eliminate small leaks in the tubing, gas reservoir, and nose clip, around the mouthpiece, and in old valves. We redesigned the pneumatic valve to minimize airway resistance during exercise while keeping the valve dead space low. We checked the mass spectrometer response time to ensure that no significant changes occurred over the course of the study and that the response time was adequate to assess acetylene gas concentrations associated with high breathing frequencies.

The acetylene channel of some mass spectrometers may also have faster kinetics when primed with test gas immediately before a measurement is made. We tested this using our system and did not find prior priming of the channel to appreciably alter the acetylene kinetics. Since the technique required accurate assessment of breath-by-breath tidal volumes, we found it critical to develop careful calibration curves for the pneumotachograph and to eliminate or minimize any drift due to temperature, humidity, and electronics. The pneumotachograph was linearized using the technique of Yeh et al. (27) and calibrated using test gas before each study.

Blood gases. Mixed venous blood samples were drawn from the pulmonary artery catheter at the same time that arterial blood was drawn from the radial artery catheter, and measurements of VO₂ were taken. The blood samples were analyzed for oxygen content using an IL 1306 co-oximeter and blood gases (PO₂, pH, and P CO₂) were analyzed by using an IL 482 blood-gas analyzer. Qt was then determined using Fick (VO₂ = Qt × arteriovenous oxygen difference). All blood samples were collected anaerobically, agitated, and immediately chilled in crushed ice before analysis (usually within 5–10 min of collection). The co-oximeter and blood-gas analyzer were calibrated with standards over the broad range of oxygen and carbon dioxide values expected during the studies. An in-dwelling, fast-response thermocouple at the end of the pulmonary artery catheter was used to assess temperature changes during exercise for correcting the blood-gas values before calculation of Qt.

Data analysis. Qt at each work intensity was calculated using OpCirc1 and OpCirc2 methods for each subject. Each subject had four data points per work level, except at the highest work intensities, where only two data points were available. This included repeat measurements of VO₂ and Qt during each of two exercise sessions at the lower work intensities and repeat measurements during one exercise session for the highest work intensity. For each subject, all data points were submitted to least squares regression using the equation Qt = K₀ + VO₂ × K₁ + VO₂² × K₂, where K₀, K₁, and K₂ are the intercept, linear term, and squared term coefficients, respectively. From the regression data on each subject, Qt was estimated at fixed levels of VO₂, and the interpolated data were averaged for all subjects. The fit was very good (R² > 0.97 for OpCirc, R² > 0.93 for Fick). Paired t-tests were applied to the interpolated data to test for differences in techniques (P < 0.05).

RESULTS

Subject characteristics. Five male subjects and one female subject were tested. Four of the subjects were moderately active, typically running or cycling several times per week. The peak VO₂ obtained from the initial cycle ergometry test averaged 120% of age predicted. Peak heart rate averaged 102% of age predicted.

<table>
<thead>
<tr>
<th>Table 1. Subject characteristics</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Age, yr</td>
</tr>
<tr>
<td>Height, cm</td>
</tr>
<tr>
<td>Weight, kg</td>
</tr>
<tr>
<td>Peak VO₂, ml·kg⁻¹·min⁻¹</td>
</tr>
<tr>
<td>Peak power, W</td>
</tr>
<tr>
<td>Peak HR, beats/min</td>
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</table>

Subjects included 5 men and 1 woman. VO₂, oxygen consumption; HR, heart rate.

Other characteristics of the group are also shown in Table 1.

OpCirc vs. Fick measurements of Qt. Figure 3 shows identity plots of OpCirc1 (A) and OpCirc2 (B) vs. Fick for all values obtained on all subjects. Each subject typically had four data points per work intensity, except at rest and at the highest work intensity, for which only two data points were obtained per subject. R² values for OpCirc1 and OpCirc2 vs. Fick for the entire data set were 0.90 and 0.89, respectively. The mean differences (±SD) between techniques were −1.5 ± 2.0 and −0.5 ± 1.9 l/min for OpCirc1 vs. Fick and OpCirc2 vs. Fick, respectively.

Table 2 compares mean values for OpCirc1 and OpCirc2 with mean Fick measurements at rest and over the four work levels. Other pertinent exercise and gas exchange data are also shown in Table 2. OpCirc1 and OpCirc2 did not differ from Fick at rest or over the
first two work intensities (37 and 54% of peak $V\dot{O}_2$). However, OpCirc1 (but not OpCirc2) was less than Fick ($P < 0.05$) over the highest two work intensities (71 and 91% of peak $V\dot{O}_2$). Figure 4 shows the OpCirc1 and OpCirc2 data relative to direct Fick measurements of $Q\dot{T}$ at all work intensities. Thus it did not appear that one calculation method was superior in regards to reproducibility.

Among individual subjects, the within-session CV ranged from 1 to 5% for light to moderate exercise and from 1 to 6% for heavy exercise but was generally uniform, with no subjects having uniquely variable data. Between-session CV was ≤1–4% at the lower work intensities and between 1 and 6% with moderate exercise. Repeat measurements with different sessions were not available for the heaviest work intensities.

### DISCUSSION

The focus of the present investigation was to compare the OpCirc washin technique using acetylene to the direct Fick method for determination of $Q\dot{T}$ at rest and during exercise. We used two computational techniques, OpCirc1 and OpCirc2, to quantify the uptake of acetylene and to account for changes in lung volume, dead space ventilation, and breath-by-breath variability. We found that both methods compared favorably with direct Fick measurements of $Q\dot{T}$, particularly at light to moderate exercise intensities. There was a tendency for both OpCirc1 and OpCirc2 to underestimate Fick at the higher work intensities; however, this trend was not significant.

### Table 3. Reproducibility of measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Rest</th>
<th>30–50%</th>
<th>50–70%</th>
<th>70–90%</th>
<th>90–100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V\dot{O}_2$ Within session</td>
<td>8.7</td>
<td>2.5</td>
<td>2.3</td>
<td>3.0</td>
<td>5.5</td>
</tr>
<tr>
<td>$Q\dot{T}$ Between session</td>
<td>6.0</td>
<td>3.1</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fick Within session</td>
<td>10.1</td>
<td>2.9</td>
<td>3.7</td>
<td>4.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Between session</td>
<td>8.1</td>
<td>5.4</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OpCirc1 Within session</td>
<td>7.1</td>
<td>2.6</td>
<td>2.1</td>
<td>2.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Between session</td>
<td>3.8</td>
<td>1.8</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OpCirc2 Within session</td>
<td>12.1</td>
<td>3.8</td>
<td>3.4</td>
<td>1.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Between session</td>
<td>3.2</td>
<td>2.8</td>
<td>1.9</td>
<td></td>
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Numbers represent coefficient of variation (%) of repeat measurements. OpCirc1, calculations using breath-by-breath gas uptake and end-tidal gas values; OpCirc2, calculations using the iterative search technique (see Methods). Within session, measurements obtained within minutes at constant power; between session, measurements obtained at given power, but separate bouts with intervening rest.
only reached significance using the OpCirc1 method. Both OpCirc1 and OpCirc2 were found to be highly reproducible, particularly during exercise.

Computational techniques and assumptions. Both computational methods are based on a simplified conceptual model of the lung that includes a single dead space compartment and a single well-mixed gas-exchanging compartment, the "alveolus." Modeling studies and studies in challenged or diseased lungs of animals and humans have shown that both ventilation inhomogeneity and ventilation-to-perfusion ratio (V˙A/Q˙c) mismatching will cause Qt and lung volumes to be underestimated using rebreathing (4, 14, 19) and OpCirc techniques (16). Acetylene uptake is dependent on lung perfusion, which essentially carries the acetylene away from the lungs; however, acetylene can only be carried away as delivered via ventilation. Thus the technique is clearly dependent on the ventilation-to-capillary perfusion ratio (V˙A/Q˙c). Any gas uptake measure will be affected by V˙A/Q˙c inhomogeneity, leading to underestimation of blood flow. If the test gas is delivered from the ventilation side, the technique will give more information about high V˙A/Q˙c regions and could miss information about low V˙A/Q˙c regions, whereas techniques that deliver the gas by blood (e.g., multiple inert-gas elimination technique) will obtain good information about low V˙A/Q˙c regions. Further study is needed to settle this issue. In other words, the OpCirc technique will, effectively, see low V˙A/Q˙c regions as shunt and may underestimate Qt.

It is known that V˙A/Q˙c inhomogeneity increases with exercise (8), although the cause of this increase is not fully known. In our studies, most subjects showed an increase in alveolar-to-arterial oxygen tension difference (A-aD02), consistent with an increase in V˙A/Q˙c inhomogeneity (Table 2), although diffusion limitation and shunt cannot be ruled out. There was a significant correlation between A-aD02 and the Fick-OpCirc difference for OpCirc1, but not for OpCirc2 as shown in Fig. 5. However, a correlation with OpCirc2 may be evident with more subjects, as there were three outliers that reduced the correlation in the present study. We conclude from these considerations that it is likely that the OpCirc method may underestimate Qt in the presence of V˙A/Q˙c inhomogeneities, possibly reducing its usefulness in presence of pulmonary disease (14). Further work is necessary to explore this in patients with obstructive airway changes and known V˙A/Q˙c abnormalities.

Anatomic shunts (right to left) can also contribute to the differences observed between the OpCirc methods and the Fick technique. Although not fully known, it is estimated that 1–2% of the Qt may be shunted away from the gas exchange units of the lung (through the thebesian and bronchial circulations), and it has been proposed that this may contribute to a substantial portion of the widened A-aD02 during exercise. The influence of the shunt becomes particularly significant at the reduced mixed venous P02 observed during heavy exercise (8). Right-to-left shunts will typically be measured by the Fick method but not by measurements of pulmonary blood flow with gas uptake techniques such as OpCirc with acetylene. Regions of the lung that have perfusion but no or little ventilation (low or zero V˙A/Q˙c), would also give an effective right-to-left shunt. Left-to-right shunts are less common but could occur with a patent foramen ovale depending on the cardiac pressure gradients. However, the left-to-right shunts would be measured by both the Fick and acetylene methods for assessing Qt.

The computational methods of both Stout et al. (24) and Gan et al. (7) make a number of additional simplifying assumptions, most importantly, an estimate of soluble gas uptake at the capillary during the breath cycle that involves two such assumptions. The first is that alveolar gas concentration during the inspiratory phase of the breath cycle is obtained by linear interpolation of end-expiratory points from the previous and current breaths; the second is that driving pressure for diffusion is constant during inspiratory and expiratory phases of the breath. Because of the increasing rate of absorption of soluble gas as V˙O2 and Qt increase, this approximation could lead to errors in Qt estimation at high levels of exercise. Our more complete computational method (OpCirc2) used all data points acquired at 8-ms intervals and thus did not include this approximation. The results from this method were closer to Fick Qt measurements at the high intensities of exercise, and, in fact, the statistics were not significantly different from the Fick method. The disadvantage of this technique is its computational complexity, requiring several minutes of computer time for each analysis. However, it appears to be more accurate at higher intensities of exercise.

The gas solubility used in calculations is a critical assumption. We used the values found by Cander (5) for blood and tissue [0.74 and 0.76 ml C3H8 (STPD)·ml blood⁻¹·atm⁻¹, respectively]. Because solubility is a function of lipid and cell content of the blood, it would ideally be determined at the time of the study on each
subject, potentially improving the accuracy of the method (5, 9).

Because the OpCirc method critically depends on the measurement of gas uptakes per breath, the time delay between gas concentration signals and flow measurements must be accurately determined so that the two signals may be properly aligned in time (21). By adjusting this parameter in the analysis program, we found that $Q_T$ would be underestimated if the time delay were underestimated. The time delay can be obtained in individual subjects by having them perform a rapid inspiratory maneuver after a prolonged expiration. At onset of inspiration, gas concentration should remain at the end-expiratory value until the dead space of the breathing valve has been cleared by the inspired gas, after which gas concentrations should abruptly increase to the inspired value. The time delay we used, 0.27 s, was obtained by averaging time delays from a number of laboratory personnel who performed the rapid inspiratory maneuver during preliminary experiments and was confirmed by spot checking during the course of the study.

Another important determinant of the calculation of $Q_T$ using the OpCirc technique was the time response characteristics of the acetylene channel of the mass spectrometer. Clearly, a slow response time will result in an underestimation of $Q_T$, especially at the higher frequencies of breathing. The 10–90% rise time of our transient was ~0.06 s. We included a correction for the slow rise time of our mass spectrometer that was described by Gan et al. (7). This potential error was tested in preliminary studies by having subjects breathe at two frequencies (30 and 60 breaths/min) at a given work intensity. In a small number of subjects, $Q_T$ did not fall with the higher breathing frequency and was, in fact, slightly augmented, consistent with increased work of breathing (1).

Advantage of the OpCirc technique relative to rebreathe, breath hold, and vital capacity maneuvers. Previous studies have found a good correlation between the rebreathe method for the determination of $Q_T$ relative to invasive measurements in animals and humans at rest and during exercise (11, 15, 17). Similarly, in a limited study performed at rest, $Q_T$ assessed by a single vital capacity breath of acetylene followed by a slow complete exhalation compared favorably to thermodilution measurements (23). However, the washin technique offers several advantages over these methods. Significant problems during rebreathing are the build up of carbon dioxide, especially during heavy exercise, and the difficulty of matching the rebreathe tidal volume to the patient tidal volume without inhibiting breathing. In addition, subjects are often asked to transiently alter breathing patterns during rebreathing (augment breathing, breathe deeper or faster), which likely alters $Q_T$, especially in some patient populations. There are also potential errors during rebreathing because of a change in bag volume over time due to a changing relationship between carbon dioxide production and $V_{O2}$ ($V_{CO2}/V_{O2}$), unless two tracer gases are simultaneously evaluated (12). Similarly, the vital capacity maneuver or a breath hold followed by a slow expiration may introduce errors due to alterations in intrathoracic pressure and is difficult to perform during exercise. In contrast, using the OpCirc method, subjects are switched into a large reservoir containing the gas mixture without altering gas exchange or breathing pattern. In most of our studies, subjects were switched into the $Q_T$ gas mixture with little or no awareness, even near maximal exercise.

A theoretical advantage to the rebreathe method has been the assumption that rebreathing to equilibration of an insoluble gas, such as helium, helps eliminate potential problems with ventilation distribution. However, both rebreathe and OpCirc should be affected similarly by ventilation and $V_{A}/Q$ inhomogeneity. In both methods, a well-mixed, constantly inspired concentration of gas is inhaled with each breath. Inspired gas is delivered to well-ventilated regions, and the exhaled concentration is a weighted average of concentrations from all lung units contributing to ventilation.

Previous studies using the OpCirc method. Becklake et al. (2) examined the use of steady-state $N_2O$ uptake after washin was complete and compared this to a dye dilution estimate of $Q_T$ during light and moderate steady-state exercise. By using this technique, a repeat value generally ran within 20% of the initial measurement and compared favorably to the dye dilution estimates of $Q_T$ (~20%) difference. The present OpCirc method offers several advantages over the methods described by Becklake et al. (2). It does not require steady-state conditions, no assumptions are made about the magnitude of the lung volumes, and blood flow may be determined in the presence of breath by breath changes in functional residual capacity (FRC). In addition, the method variance is likely reduced using $C_2H_2$ instead of $N_2O$, as the soluble gas, because the smaller solubility coefficient of $N_2O$ decreases the slope of the disappearance curve, making it slightly more susceptible to experimental noise.

A technique similar to that described by Stout et al. (24) and, subsequently, by Gan et al. (7) was used in the present study, with some modifications, for the OpCirc1 method. Stout et al. (24) developed a model that regards the total pulmonary inert gas uptake as the sum of dead space, alveolar, lung tissue, and pulmonary blood flow uptakes. Analysis of any two breaths during breathing of the inert gas mixture yields two simultaneous equations with two unknowns, pulmonary blood flow and tissue volume. Various summing techniques were evaluated for averaging the breaths and reducing the breath by breath variation in measurements. This model was compared with computer simulation of respiratory gas exchange for $N_2O$ and $N_2$ and comparisons were made with direct Fick in five anesthetized dogs. Agreement was observed within ±20%. Limitations to the study, in regards to practical use, were the use of anesthetized, paralyzed, and ventilated animals. Under these controlled, steady-state conditions with low breathing frequencies, reproducible values would be expected.
Gan et al. (7) used computational methods that were similar to those used by Stout et al. (24) for the calculation of OpCirc1 Qₜ but refined them by adding several smoothing techniques. The two smoothing methods described by Gan et al. (7), which we used for OpCirc1, included smoothing the end-tidal gas concentrations during washin by fitting to a polynomial and a method for culling out outliers obtained by solving all pairs of breaths for Qₜ and tissue volume. After the outlier points were excluded, average Qₜ from all possible remaining pairs of solutions were reported. An additional smoothing technique described by Gan et al. (7), but not used in the present study, effectively reduces noise in gas uptake measurements caused by breath-by-breath variations in inspiratory and expiratory volumes. Instead, we included the measured differences between inspiratory and expiratory volumes in our calculations. It is not clear if the differences in calculation methods of Gan et al. (7) and our OpCirc1 technique would have any impact on accuracy or reproducibility of the technique.

Unlike the OpCirc1 method, our OpCirc2 has not been previously described. For the OpCirc2 method, each data point acquired every 8 ms was used to calculate gas uptake at the alveolar level in a homogeneous lung model that included measured dead space (see Appendix). We developed this model to determine if the simplifying assumptions behind the OpCirc1 method had an impact on calculated Qₜ, particularly at high exercise intensities, for which gas uptakes are larger. We found that OpCirc2 was not significantly different from Fick Qₜ, even at high exercise intensities, whereas OpCirc1 results were lower. This suggests that nonlinearities in the OpCirc1 solution become important as gas fluxes increase with exercise. However, further work would be needed to prove this point. It must be stressed that even the OpCirc2 method assumes homogeneous gas distribution; therefore, calculated Qₜ may be affected by Va/Qc mismatch in subjects with lung disease, similar to what has been shown for Qₜ determined by the rebreathe technique (14, 19).

More recently, Nielsen et al. (16) compared the washin technique with rebreathing in 10 healthy subjects. They found reproducibility of the OpCirc method to be less than the rebreathe method. Although we did not directly compare OpCirc to rebreathe, the CV in OpCirc reported here is less than one-half of that reported by Nielsen et al. (16) and is comparable to or slightly less than what we have reported for rebreathe in other studies (22). We do not have an explanation for the difference in reproducibility between our data and that of Nielsen et al. (16), although with our experiences in both rebreathe and OpCirc, we feel that OpCirc is equivalent to or better than rebreathe for assessment of Qₜ during moderate to heavy exercise.

**APPENDIX**

Definitions of symbols and terms in the appendix are found in the glossary.
The symbol $p^n$ is an approximation of the mean alveolar concentration of acetylene over the inspiratory portion of the breath

$$p^n = F_{\text{A,Acet}}^n \frac{V_{\text{SD}}}{{V}_i^n} + \frac{F_{\text{A,Acet}}^{n-1} + F_{\text{A,Acet}}^n}{2} \left(1 - \frac{V_{\text{SD}}}{{V}_i^n}\right)$$

(6)

$V_{\text{SD}}$ is found from gas dilution of helium

$$V_{\text{SD}} = \frac{F_{E,He} - F_{E,He}}{F_{I,He} - F_{E,He}} \cdot V_E$$

(7)

where $V_E$ is end-expiratory volume.

These $V_{\text{SD}}$ values are only averaged for breaths with an end-expiratory value $<90\%$ of the inspiratory value to avoid an unstable solution due to small numbers in the denominator.

Two data-smoothing techniques outlined by Gan et al. (7) were used in the calculations. First, the end-expiratory gas concentrations for each breath were adjusted slightly by fitting end-expiratory concentrations vs. time to a third- or fourth-order polynomial equation, and then replacing each value with the calculated value from the equation. This process was justified by Gan et al. (7) by pointing out that the end-tidal concentrations vs. time should follow an exponential approach to an equilibrium value. From Taylor's theorem, an exponential curve can be approximated by a polynomial series. Second, in calculating the uptake volumes of each gas by integrating flow and gas concentration over the breath, the response of the gas analyzer (mass spectrometer) was corrected using a first-order differential correction.

With values for $z^n$, $w^n$, and $v^n$ calculated for each breath, pairs of breaths are solved using Eq. 1 to find a solution for $V_{\text{TI}}$ and $Q_{\text{C}}$ for each pair, producing a list of $n \times (n-1)$ solutions, where $n =$ total number of breaths. The mean and standard deviation are then found for the set of solutions, outlying solutions (>98th percentile) are removed, and the average is retaken. This process of culling out outliers is only performed once.

OpCirc2

This technique is more involved computationally, but results in a more precise solution. The lungs are considered to be one well-mixed alveolar compartment separated from the inhaled gas bag by an anatomic dead space. Gas transport in each unit of time, $\Delta t$ (the 8-ms sampling period of the data), is governed by the following mass balance considerations at the alveolar level.

The total acetylene volume in the alveolar compartment is given by $V_{\text{A,Acet}} = F_{\text{A,Acet}} \times V_A + \alpha_{\text{A,Acet}} \times V_{\text{TI}}$. The change in the acetylene volume per unit time is equal to the rate of disappearance into the blood plus the amount entering the alveolar volume by inspired via the anatomic dead space

$$\frac{d[V_A + \alpha_{\text{A,Acet}} \cdot V_{\text{TI}}] \cdot F_{\text{A,Acet}}(t)}{dt} = -\alpha_{\text{A,Acet}} \cdot Q \cdot [F_{\text{A,Acet}}(t) - F_0] + F_{\text{A,Acet}} \cdot \frac{dV}{dt}$$

(8)

where $F_{\text{A,Acet}}$ indicates the fractional concentration of acetylene at the alveolar end of the dead space. This equation can be solved for $\frac{dF_{\text{A,Acet}}}{dt}$

$$\frac{dF_{\text{A,Acet}}}{dt} = -\frac{dt}{V_A + \alpha_{\text{A,Acet}} \cdot V_{\text{TI}} \cdot \alpha_{\text{A,Acet}} \cdot Q \cdot [F_{\text{A,Acet}}(t) - F_0]}$$

where $\alpha_{\text{A,Acet}} \cdot Q \cdot [F_{\text{A,Acet}}(t) - F_0]$ is the amount entering the alveolar space.

This finite difference equation is used at each time-sampling increment to update the fractional concentration of acetylene. The helium concentration is treated similarly, except that $\alpha_{\text{A,He}} = 0$ (negligible tissue solubility for helium).

The process starts with a calculation of $V_{\text{SD}}$, as above, and $V_A$, as follows

$$V_A = \frac{V_I \cdot (F_{\text{I}} - F_{\text{E}}) - \sum_{k=1}^{n} (V_{k}^{\text{i}} - V_{k}^{\text{o}}) \cdot (F_{k}^{\text{f}} - F_{k}^{\text{o}} - 1)}{F_{E}^{n} - F_{E}^{n-1}} + (V_{D_{\text{O2}}} + V_{\text{SD}}) \cdot (F_{E}^{n-1} - F_{E}^{n})$$

(9)

This equation is applied to helium data for all breaths where the ratio of $F_{E}/F_{I}$ is $<95\%$ to avoid unstable solutions.

A computer algorithm then sets up a dead space volume that consists of an ordered list of 1-ml units, the total volume equaling $V_{\text{SD}}$. The $V_A$ and each $V_{\text{SD}}$ element is initially filled with gas concentration equal to expired concentration of the breath immediately before the start of the washin maneuver, simulating end expiration. The computer then samples the first inspiratory data point, obtaining volume change, $\Delta V$, and values for gas concentration at the mouth from the raw data stream. At the mouth end of the dead space, the first $m = \Delta V$ dead space elements are set to the measured gas concentration. At the alveolar end of the dead space, $m$ elements are each added to the alveolar space, using Eq. 9 to update the alveolar concentration and increasing alveolar gas volume by $\Delta V$. As the process continues during inspiration, a front of gas

Fig. 6. Model demonstrating the OpCirc2 method for calculation of $Q_{T}$. Thin line shows raw input data for acetylene concentration at the mouth. Thick black and thick gray lines show model results for mouth and alveolar concentrations, respectively (see APPENDIX for description of the model). In this study, OpCirc2 modeled the entire alveolar gas concentration curves throughout inspiration and expiration. This is in contrast to the work of Stout et al. (24) and Gan et al. (7), who examined end-inspiratory and end-expiratory alveolar gas concentration and estimated the mean alveolar values.
moves through the dead space elements until inspired gas appears at the alveolar end of the dead space. Further inspiration adds inspired gas to the alveolar compartment. During expiration, Eq. 9 is again applied and the dead space elements are filled from the alveolar end with the current value for alveolar gas concentration. This process continues until the entire data stream has been used, and end-tidal values for each of the breaths is obtained from the model. The sum of squared differences between measured and modeled end-tidal concentration is obtained for use in an iterative search procedure that finds the best Q and Vti.

Taylor minimization (20) was used to find the best combination of Vti and Q that minimized the sum of squared errors between modeled and actual end-tidal gas concentrations. I imagine a three-dimensional surface shaped like a large bowl with the value for sum squared errors as the height above a plane defining the ranges of values for Vti and Q. The algorithm finds the low point of this surface (bottom of bowl) by finding its local slope and descending the steepest path down the slope to the minimum. This process generally took 50–100 steps. A typical solution is shown in Fig. 6. The solution for Vti was occasionally unphysiological, and we were unable to find methods resulting in consistently reasonable values for it. The solution for Q usually appeared reasonable despite the occasional unstable values for Vti. Thus Vti values were not reported in this study.

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