

Total Oxygen Uptake with Two Maximal Breathing Techniques and the Tidal Volume Breathing Technique

A Physiologic Study of Preoxygenation

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Background: **Three common methods for preoxygenation are 3 min of tidal breathing, four deep breaths taken within 30 s (4DB), and eight deep breaths taken within 60 s (8DB). This report compares these three techniques in healthy volunteers.**

Methods: **Five healthy subjects breathed through a mouthpiece and wore a nose clip; oxygen was delivered at 180 l/min *via* a low-resistance T-piece. Each subject repeated each of the three oxygenation techniques four times. The end-tidal fraction of oxygen was measured, and the oxygen uptake at the mouth was measured breath by breath. The additional difference between oxygen uptake at the mouth during the period of breathing oxygen (as compared with that during air breathing) was taken to represent the total oxygen sequestrated into body stores.**

Results: **The mean ± SD maximum end-tidal fraction of oxygen after the 4DB method was 0.83 ± 0.09, which was significantly less than either after the 3-min method (0.92 ± 0.01; $P < 0.04$) or after the 8DB method (0.91 ± 0.04; $P < 0.03$). The mean additional oxygen taken up during oxygenation with the 4DB method was 1.67 ± 0.45 l, which was significantly lower than with the 3-min method (2.23 ± 0.85 l; $P < 0.04$) or with the 8DB method (2.53 ± 0.74 l; $P < 0.01$). There were no significant differences for these variables between the 3-min and 8DB methods.**

Conclusions: **For the physiologic measurements that were made, both the 3-min and the 8DB method are superior to the 4DB method. The 3-min and 8DB methods seem to be equally effective.**

PREOXYGENATION with 100% oxygen before induction of anesthesia is standard practice and delays the onset of arterial hypoxemia during subsequent apnea. Three methods of preoxygenation are commonly used: 3 min of normal tidal volume breathing 100% oxygen (3-min method),[1] four deep vital capacity breaths of oxygen taken within 30 s (4DB method),[2] and eight deep vital capacity breaths of oxygen taken within 60 s (8DB method).[3] Various endpoints have been used to compare these methods: minimum end-tidal nitrogen fraction,[4–6] maximum arterial oxygen tension (Pa_{O_2}),[2] maximum end-tidal oxygen fraction (FE_{O_2}),[7] and time taken for hemoglobin to desaturate to a certain level after anesthetic-induced apnea.[3,8] The results obtained have often been conflicting.

Three studies using maximum Pa_{O_2} as the endpoint concluded that the 3-min and 4DB methods were equally effective.[1,9,10] In contrast, Russell *et al.*,[11] using FE_{O_2}, concluded that the 4DB method was inferior to the 3-min method.[11] However, Winship and Skinner[7] and McCrory and Matthews[12] reported similar FE_{O_2} values after 3 min of tidal breathing and after four deep breaths. Other studies have used the time for hemoglobin to desaturate to arterial oxygen saturation (Sa_{O_2}) 95% (or 93%) and found 4DB to be inferior to the 3-min method.[3,8,13,14] Furthermore, McCarthy *et al.*[14] observed that although Pa_{O_2} values were similar after 4DB and 3-min protocols, the times to desaturation were significantly longer in the 3-min group. Because theoretically the time to desaturation is more directly related to the available body stores for oxygen than is Pa_{O_2}, this might suggest that it is a more suitable endpoint for preoxygenation studies. Baraka *et al.*[3] confirmed these findings with respect to the superiority of the 3-min *versus* the 4DB method when time to desaturation was used as the endpoint but, in contrast to the result of McCarthy *et al.*,[14] found that Pa_{O_2} was higher after the 3-min method as compared with the 4DB method. Baraka *et al.*[3] emphasized that all of these measures (FE_{O_2}, Pa_{O_2}, and time to desaturation) were "surrogate markers" of oxygen uptake into body stores, although the last of these is probably the most clinically relevant measure.

There are other technical reasons why the results of previous studies might differ. Some studies have used oxygen flow of 5 l/min in a circle system[4]; others have used oxygen flow rates of 20 l/min in Mapleson D circuits[3] or 10 l/min through a Magill (Mapleson A) circuit.[12] In addition, Benumof[15] has suggested that an important reason for failure to achieve maximum oxygenation is the occurrence of leaks around the facemask. The influence of differences between the type of patients studied (*e.g.*, the obese,[10,16] pregnant,[9,11,17] or elderly[13,14]) has also been considered.

We planned to eliminate these technical problems and to use healthy subjects in repeated studies. We wished to estimate the actual amount of oxygen taken up by the body using an analysis of net gas exchange at the mouth. Therefore, this was a physiologic rather than a clinical study, which aimed to assess which of the three methods of oxygenation was best in ideal laboratory circumstances, rather than in the clinical situation.

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Materials and Methods

Subjects

This study had the approval of the Central Oxford Research Ethics Committee (Oxford, United Kingdom). We used five healthy male subjects, and all gave written, informed consent.

Equipment

Subjects were seated in a chair, wore nose clips, and breathed through a mouthpiece that was connected to the gas supply *via* low-resistance tubing (resistance 0.1 mm $H_2O \cdot min \cdot l^{-1}$). The arrangement may be described as a simple T-piece, with the expiratory limb being a large funnel-shaped tube (volume ~3 l) open to the atmosphere. The total gas flow was high to prevent rebreathing (180 l/min). Inspired and expired gas at the mouth were sampled continuously by a mass spectrometer (Airspec 3000; Airspec Ltd., Biggin Hill, Kent, United Kingdom) and analyzed for inspired and end-tidal fractions and partial pressures of oxygen and carbon dioxide (body temperature, ambient pressure, and saturated with water vapor [BTPS]). Respiratory volumes were measured by a turbine volume–measuring device and flows by a pneumotachograph in series with the mouthpiece (dead space 90 ml). Data regarding experimental time, gas flow, and gas composition were stored every 20 ms in a data acquisition computer, which used a program to locate inspiratory and end-expiratory values. For each breath, net oxygen uptake at the mouth was calculated breath by breath (standard temperature and pressure, dry [STPD]) as described previously.[18] Briefly, the records of carbon dioxide and oxygen composition at the mouth were aligned in time with the record of respiratory flow, as measured by the pneumotachograph, using the measured delay of the mass spectrometer. Second, the as yet uncalibrated values of flow from the pneumotachograph were adjusted for changes in gas viscosity due to changes in gas composition. Then, for each half breath, the respiratory flow from the pneumotachograph was calibrated using the volume measurement from the turbine device. Finally, for each gas species, the difference between the amount breathed in and the amount breathed out was calculated.

Protocols

There were three oxygenation protocols. Before each protocol, subjects breathed room air for 3 min, which enabled calculation of their basal (metabolic) oxygen uptake ($Basal_{O2}$). This was taken to be the average value of oxygen uptake at the mouth (in l/min) over this period. Then, the inspired gas was changed surreptitiously to 100% O_2 at end-expiration, and subjects undertook one of the following breathing protocols:

- For the 3-min protocol, subjects continued to breathe normally at tidal volumes for 3 min. The inspired gas was then restored to room air, and the experiment continued until FE_{O_2} had returned to its starting value.
- For the 4DB protocol, on tapping their shoulder, subjects took four deep vital capacity breaths within 30 s. After the end of expiration after the fourth breath, signaled again by a tap on the shoulder, the inspirate was changed back to room air, and the subject returned to normal breathing at tidal volumes until FE_{O_2} had returned to its starting value.
- For the 8DB protocol, on tapping their shoulder, subjects took eight deep vital capacity breaths within 60 s. After the end of expiration after the last breath, signaled again by a tap on the shoulder, the inspirate was changed back to room air, and the subject returned to normal breathing at tidal volumes until FE_{O_2} had returned to its starting value.

Each subject repeated each of the three protocols four times, in random order on separate days, yielding a total of 60 individual experimental periods. If a subject undertook more than one protocol on any given day, the interval between protocols consisted of at least 2 h of air breathing.

Data Analysis

There were two values of interest. First, for each protocol, the maximum FE_{O_2} (BTPS) attained by each subject in each protocol was measured, and these values averaged to give the mean for the group.

Second, the additional oxygen uptake (in excess of $Basal_{O2}$) over the course of each protocol (STPD) was calculated in the following manner. It was assumed that breathing oxygen would not itself influence $Basal_{O2}$. If, for any breath during oxygenation, the measured oxygen uptake at the mouth ($Breath_{O2}$, l/min) exceeded $Basal_{O2}$, it was assumed that this excess oxygen uptake represented sequestration of oxygen into body stores. As body stores for oxygen became saturated, it was expected that $Breath_{O2}$ would approximate $Basal_{O2}$. If, for any breath (*e.g.*, after the period of oxygenation), the measured $Breath_{O2}$ was less than $Basal_{O2}$, it was assumed that this represented loss of oxygen from body stores.

Thus, for each breath during the period of oxygenation, the difference: $Breath_{O2} - Basal_{O2}$ yielded the amount of oxygen taken up by (or lost from) the body for that breath (in l/min). This value multiplied by the duration of the breath yielded the amount of oxygen taken up during that breath (in liters). The sum of these values for all breaths during the period of oxygenation gave the total amount of oxygen taken up ($Total_{O2}$; liters). For each protocol, individual subject values for $Total_{O2}$ were calculated, and these subject values averaged to obtain the mean value for the group.

Statistics

The individual subject values for $Basal_{O2}$, FE_{O_2}, and $Total_{O2}$ were first subjected to ANOVA (Minitab for Win-

Table 1. Basal (Metabolic) Oxygen Uptake Breathing Air for Each of the Three Protocols

	Basal Oxygen Uptake Breathing Air, l/min		
Subject	3 min	4 DB	8 DB
156	0.40 (0.03)	0.34 (0.05)	0.39 (0.07)
205	0.46 (0.10)	0.45 (0.02)	0.40 (0.06)
206	0.43 (0.08)	0.45 (0.02)	0.40 (0.03)
1,222	0.22 (0.05)	0.24 (0.03)	0.22 (0.05)
1,223	0.46 (0.05)	0.38 (0.10)	0.51 (0.06)
Mean	0.39 (0.10)	0.37 (0.09)	0.38 (0.10)

Values are mean (SD) and standard temperature and pressure, dry. There were no significant differences between the protocols (ANOVA, not significant).

DB = deep breath.

dows version 9.2, State College, PA). There were two factors: subject (five levels) and protocol (three levels). The interactive term between subject and protocol indicated whether there were any influences of the protocol within subjects. If ANOVA suggested significant effects, then *post hoc* paired *t* tests were undertaken to assess the statistical significance of the differences between the mean results of each protocol. Statistical significance was taken at $P < 0.05$.

Results

The mean (range) age of the subjects was 20.8 (20–23) years, height was 1.79 (1.69–1.88) m, and weight was 74 (61–92) kg. Table 1 shows the $Basal_{O2}$ values for subjects in the three protocols. ANOVA suggested significant differences between subjects ($P < 0.001$), but not between protocols ($P < 0.21$). One subject (1222) had rather low values, but these were consistent across all three protocols for this subject. The interactive term did not indicate a significant influence of protocol within subjects (ANOVA, $P < 0.28$).

Figure 1 shows the profile of inspired oxygen fraction (F_{IO_2}) and FE_{O_2} for single representative experimental periods for each of the three protocols (BTPS). Although FE_{O_2} seemed to reach a plateau in the 3-min and 8DB protocols, it seemed that it may not have reached its maximum possible value in the 4DB protocol. The difference between F_{IO_2} and FE_{O_2} at the end of the protocol was small in the 3-min and 8DB protocols but larger in the 4DB protocol.

Figure 2 shows the profile of $Breath_{O2}$, breath by breath for single representative experimental periods, for each of the three protocols (STPD). Also shown are the values for $Basal_{O2}$. In the 3-min protocol, $Breath_{O2}$ values increased sharply at the start of oxygenation and then declined during the course of oxygenation to values approximating those for $Basal_{O2}$, indicating an equilibration of body stores. Similarly, for the 8DB protocol, $Breath_{O2}$ values increased sharply at the start of oxygen-

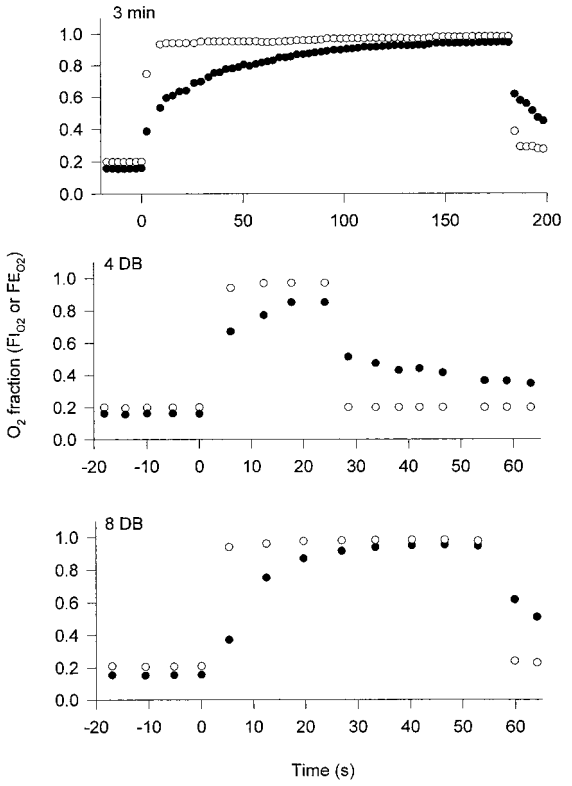

Fig. 1. Graphs of inspired oxygen fraction (F_{IO_2}; *unfilled circles*) and end-tidal oxygen fraction (FE_{O_2}; *filled circles*) for each of the three protocols (BTPS). Each graph is a single representative experimental period from one subject, and each point represents a single breath. The start of oxygenation for each protocol is arbitrarily time = 0. For the 3-min protocol (*3 min*), the period of oxygenation was 180 s. For the 4DB protocol (*4DB*), the four breaths took approximately 20 s in this experimental period. For the 8DB protocol (*8DB*), the eight breaths took approximately 55 s in this experimental period. Note that the time scales for the 4DB and 8DB graphs are the same, but different from the time scale for the 3-min graph. O_2 = oxygen.

ation, and there was a decline in $Breath_{O2}$ values toward the end of the 8DB study. Even for the eighth breath, $Breath_{O2}$ seemed to be slightly larger than $Basal_{O2}$. However, in the 4DB protocol, $Breath_{O2}$ seemed to be higher than $Basal_{O2}$ for each of the four breaths, and there was little, if any, decline in $Breath_{O2}$ value with each breath. After the switch back to room air, $Breath_{O2}$ values were less than $Basal_{O2}$ in all protocols, indicating net loss of oxygen from the body.

The mean (SD) breath volumes for vital capacity breaths achieved were 3.53 (0.53) l for 4DB and 3.57 (1.15) l for 8DB (NS). The mean end-tidal P_{CO_2} during 3 min was 39.9 (2.4) mmHg, and the mean minimum for 4DB was 31.7 (3.2) mmHg ($P < 0.019$ *vs.* 3-min method; Student paired *t* test) and for 8DB was 27.1 (2.1) mmHg ($P < 0.026$ *vs.* 4DB).

Table 2 shows the quantitative values for FE_{O_2} and $Total_{O2}$. For FE_{O_2}, ANOVA indicated that there were significant influences of subject ($P < 0.001$), protocol ($P < 0.001$), and the interactive term ($P < 0.001$), which

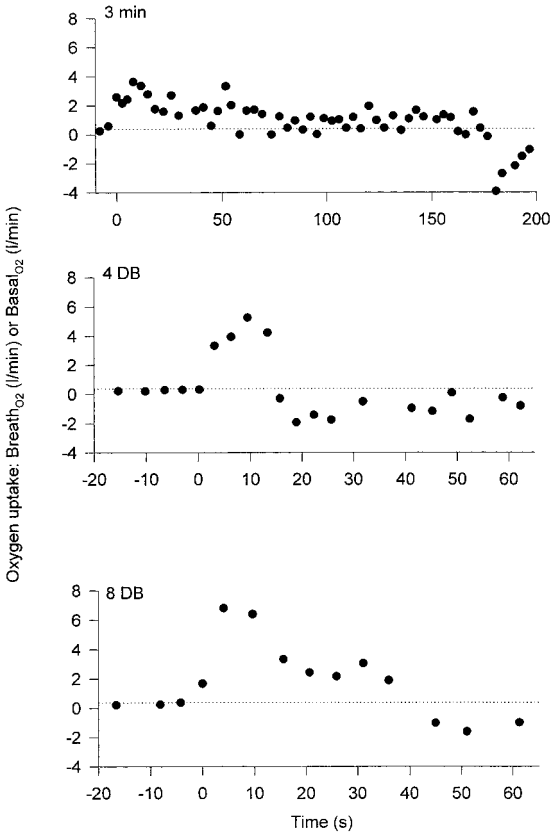

Fig. 2. Graphs of oxygen uptake at the mouth during oxygenation (Breath$_{O2}$; *filled dots*) and basal oxygen uptake breathing air (Basal$_{O2}$; *dotted line*) for each of the three protocols (STPD). For Breath$_{O2}$, each point represents one breath. Each graph is a single representative experimental period from one subject. The start of oxygenation for each protocol is arbitrarily time = 0.

suggested that FE_{O_2} differed between subjects and between protocols and also that FE_{O_2} was influenced by protocol within subjects. *Post hoc t* tests suggested that the mean of the 4DB protocol was different from both the 3-min ($P < 0.04$) and 8DB ($P < 0.03$) protocols. For Total$_{O2}$, ANOVA suggested significant effects of protocol ($P < 0.001$) and subject ($P < 0.001$), which suggested that Total$_{O2}$ differed between protocols and across subjects. The interactive term was also significant ($P < 0.003$), suggesting that Total$_{O2}$ was influenced by the protocol within the subjects. *Post hoc t* tests suggested that the 4DB value was significantly different from both the 3-min ($P < 0.04$) and 8DB ($P < 0.01$) protocols. Differences between the 3-min and 8DB protocols were not significant for either Total$_{O2}$ ($P < 0.20$) or FE_{O_2} ($P < 0.27$).

Finally, we calculated that the mean (SD) total oxygen uptake by the fourth breath of the 8DB technique was 1.67 (0.75) l, which was identical to the Total$_{O2}$ value for the 4DB method (table 2).

Discussion

The main finding of this study is that when technical factors that might limit oxygenation are eliminated and when the additional oxygen uptake at the mouth is used as the endpoint, the 3-min and 8DB methods of preoxygenation are equal in efficacy, and both are superior to the 4DB method.

Critique of Experimental Technique

Our subjects used a mouthpiece and a nose clip, which would not necessarily be applicable to clinical situations. However, it is of interest that some workers have used mouthpieces and nose clips in clinical scenarios with good results.[7,19]

Our method of calculating the additional uptake of oxygen at the mouth is perhaps a novel measure in preoxygenation studies. The method is not influenced by hard exercise,[20] electrically induced exercise,[21,22] or sustained changes in the composition of inspired gases (including breathing hypercapnic[18] and hyperoxic[20] gas mixtures). Taken together, these results confirm agreement of *mean* breath-by-breath calculations with steady state (*i.e.*, Douglas bag) measurements,[23] but an additional issue is that of breath-to-breath *variability*. Various methods have been proposed to estimate breath-by-breath gas transfer.[23–25] Because no direct measurement of gas transfer across the alveolus is possible, these different methods cannot be compared with a standard reference. All of the methods yield estimates of gas exchange with certain differences in breath-to-breath

Table 2. Maximum Oxygen Fraction and Total Oxygen Uptake

	Maximum End-tidal Oxygen Fraction			Total Oxygen Uptake, l		
Subject	3 min	4 DB	8 DB	3 min	4 DB	8 DB
156	0.91 (0.01)	0.67 (0.07)	0.84 (0.05)	3.22 (0.39)	1.32 (0.27)	2.51 (0.48)
205	0.93 (0.01)	0.87 (0.03)	0.94 (0.02)	1.39 (0.47)	2.14 (0.99)	3.33 (0.64)
206	0.93 (0.01)	0.81 (0.08)	0.93 (0.03)	2.94 (0.98)	2.11 (0.61)	3.21 (1.01)
1,222	0.93 (0.01)	0.90 (0.11)	0.91 (0.01)	1.38 (0.09)	1.62 (0.34)	1.67 (0.73)
1,223	0.91 (0.02)	0.90 (0.01)	0.92 (0.02)	2.22 (0.66)	1.15 (0.43)	1.95 (0.81)
Mean	0.92 (0.01)*	0.83 (0.09)	0.91 (0.04)*	2.23 (0.85)*	1.67 (0.45)	2.53 (0.74)*

Values are mean (SD). Maximum oxygen fraction (body temperature, ambient pressure, and saturated with water vapor) and total oxygen uptake (standard temperature and pressure, dry).

* Significantly different from 4 deep breaths (DB) ($P < 0.05$, ANOVA and *post hoc* Student *t* test). Comparisons between 8 DB and 3 min were not statistically significant.

variability. It is currently impossible to assess whether this interbreath variability arises from artifacts in the computation methods or whether it is a true physiologic phenomenon. It is generally assumed that the method of calculation that yields the lowest variability given the same data set (or when compared against a model) is the one that minimizes computational error. We have previously tested our method with three other methods of analysis[26] and found that our method yields the lowest interbreath variation (SD of breath-to-breath oxygen uptake of 20.8 ± 10.4%). Campbell and Beatty,[27] using data from previous studies, have estimated that the maximum total body oxygen uptake is probably approximately 2.7 l after "ideal" preoxygenation. This compares well with our value of 2.5 l after the 8DB method (table 2), which suggests that our method yielded reasonable estimates for total oxygen uptake in this study.

Our measurement method indicates only the total amount of oxygen taken up. Not all of this amount may be available for use by the tissues during any subsequent apnea. Hence, for clinical purposes, the measure of most relevance is probably the time to desaturation.

Our subjects were seated; therefore, our results may not be applicable to situations in which patients lie flat. Baraka[28] has reported that the seated position results in longer times to desaturation during postanesthetic apnea, but other workers have been unable to confirm this result.[29]

There were a number of strengths of our study. The very high oxygen flow rates ensured that there was virtually no rebreathing (or air dilution), a factor that has probably dogged many other studies. Figure 3A shows the effect of oxygen supplied at 40 l/min during one preliminary trial of deep breathing, and the effects of rebreathing (air dilution) are self-evident. Figure 3B shows the dramatic effect of increasing the flow to 180 l/min.

An additional strength of this study was that we were able to perform repeated studies in our subjects to obtain values for both FEo_2 and total oxygen uptake, which minimized the effects of random variability. Also, because this was a physiologic study, all of our subjects were able to undertake each of the three protocols; no matching of subject groups between protocols was necessary, and this further minimized bias.

There are some advantages to performing physiologic studies in cooperative subjects. Salem *et al.*[30] criticized the methodology of some clinical studies. Although eight deep breaths are taken by the patient when awake, oxygenation often needs to be continued by active hand–facemask ventilation of the lungs for a period after induction of anesthesia (which can impart an additional 2–4 breaths). We avoided this problem.

Comparison with Other Studies

Our results are in agreement with those studies that have found the 3-min and 8DB methods to be superior to the 4DB method.[3,8,11,13,14] Our results do not support the notion that the 4DB method is equal to other methods.[2,9,10]

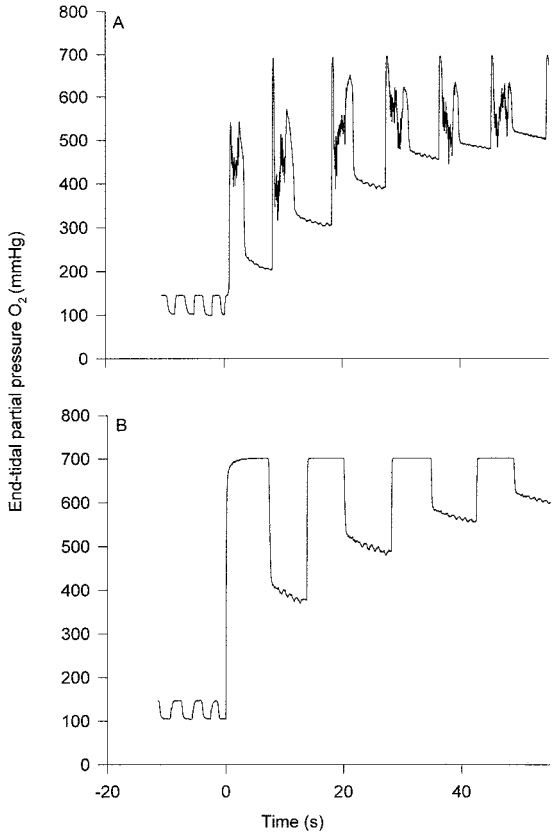

Fig. 3. (*A*) Graph of partial pressure flow profile for oxygen (O_2; 20-ms data points joined by a line; BTPS) against time of one single preliminary trial of deep breathing from one subject with oxygen gas flow at 40 l/min. Note the wide variations in inspired oxygen partial pressures due to rebreathing (air dilution). (*B*) Graph of partial pressure flow profile for oxygen against time (BTPS) of one single preliminary trial of deep breathing from the same subject with oxygen gas flow at 180 l/min. Rebreathing (air dilution) has now been virtually eliminated.

Comparison with the study of Baraka *et al.*[3] is particularly interesting. We found that 8DB results in 860 ml more oxygen taken into body stores than 4DB (table 1). If we assume a mean basal (metabolic) oxygen consumption of 390 ml/min (table 1), this would suggest that the 8DB method might result in approximately 2.2 min longer time to hemoglobin desaturation to a given endpoint than the 4DB method. The results of Baraka *et al.* show that the time to hemoglobin desaturation to 95% is indeed 2.4 min longer with the 8DB than the 4DB method. This similarity might suggest that our novel measure of preoxygenation is also of some clinical relevance.

However, we cannot confirm the finding of Baraka *et al.* that the 8DB method is superior to the 3-min method. Although the total oxygen uptake was greater with 8DB by 300 ml, this did not reach statistical significance in our study (table 2). However, we did observe that in 15

of 20 experimental periods, the net additional oxygen uptake ($Breath_{O2} - Basal_{O2}$) had a small positive value for the last breath of the 8DB protocol (fig. 2). This suggests that in these instances, the body stores for oxygen were not fully saturated at eight breaths. Further oxygen uptake may therefore have continued had more breaths been taken, and it is therefore possible that a 10- or 12-deep-breath technique might produce values for oxygen uptake somewhat greater than those for the 3-min technique.

Conclusion

Results from clinical studies are likely to be influenced greatly by the limitations of the equipment used. Physiologically, in a setting where such technical limitations are minimized, we have shown that the 8DB and 3-min methods are equally effective and that both are superior to the 4DB method. It would be desirable to repeat our methodology in a clinical setting, using time to desaturation as an additional endpoint.

We might speculate on the physiologic basis for our results. Traditionally, the view is held that the largest contribution to the oxygen store is that contained in the functional residual capacity of the lung. Therefore, if methods differ, it is likely that this is because the methods result in different functional residual capacities, and it is plausible that deep breathing might increase functional residual capacity. However, if this is the case, it is does not explain how the 3-min method results in higher oxygen uptake than the 4DB method (table 2). A number of authorities have suggested that differences in oxygen carriage by blood (including venous blood) or tissue stores might be important.[27,31] Benumof[15] has suggested that the presumed respiratory alkalosis induced by the 8DB method might increase oxygen carriage by the blood, and consistent with this, we found lower end-tidal P_{CO_2} values for 8DB as compared with 4DB. Other possibilities include interaction of the preoxygenation method with cardiac output. Our data do not yield any further insight into which of these suggestions is the most important factor in our results. Future studies might measure oxygen carriage by blood or measure functional residual capacity, but it would seem important for any results to be meaningful that technical factors, which might otherwise contribute to apparent differences in oxygenation methods, be minimized.

References

1. Gold MI: Preoxygenation. Br J Anaesth 1989; 62:241–2
2. Gold M, Duarte I, Muravchik S: Arterial oxygenation in conscious patients after 5 minutes and after 30 seconds of oxygen breathing. Anesth Analg 1981; 60:313–5
3. Baraka AS, Taha SK, Aouad MT, El-Khatib MF, Kawkabani NI: Preoxygenation: Comparison of maximal breathing and tidal volume breathing techniques. ANESTHESIOLOGY 1999; 91:612–6
4. Hamilton W, Eastwood D: A study of denitrogenation with some inhalation anesthetic systems. ANESTHESIOLOGY 1955; 16:861–7
5. Berthoud M, Read DH, Norman J: Preoxygenation: How long? Anaesthesia 1983; 38:96–102
6. Beatty PCW, Kay B, Healy TEJ: Measurement of the rates of nitrous oxide uptake and nitrogen excretion in man. Br J Anaesth 1984; 56:223–32
7. Winship S, Skinner A: Vital capacity and tidal volume preoxygenation with a mouthpiece. Br J Anaesth 1998; 81:787–9
8. Gambee AM, Hertzka RE, Fisher D: Preoxygenation techniques: Comparison of three minutes and four breaths. Anesth Analg 1987; 66:468–70
9. Norris MC, Dewan DM: Preoxygenation for cesarean section: A comparison of two techniques. ANESTHESIOLOGY 1985; 62:827–9
10. Goldberg ME, Norris MC, Laryani GE, Marr AT, Seltzer JL: Preoxygenation in the morbidly obese: A comparison of two techniques. Anesth Analg 1989; 68:520–2
11. Russell G, Smith C, Snowdon S, Bryson T: Pre-oxygenation and the parturient patient. Anaesthesia 1987; 42:346–51
12. McCrory JW, Matthews JN: Comparison of four methods of preoxygenation. Br J Anaesth 1990; 64:571–6
13. Valentine SJ, Marjot R, Monk CR: Preoxygenation in the elderly: A comparison of the four-maximal-breath and three-minute techniques. Anesth Analg 1990; 71:516–9
14. McCarthy G, Elliott P, Mirakhur RK, McLoughlin C: A comparison of different pre-oxygenation techniques in the elderly. Anaesthesia 1991; 46:824–7
15. Benumof JL: Preoxygenation: Best method for both efficacy and efficiency? ANESTHESIOLOGY 1999; 91:603–5
16. Farmery AD, Roe PG: A model to describe the rate of oxyhaemoglobin desaturation during apnoea. Br J Anaesth 1996; 76:284–91
17. Russell GN, Smith CL, Snowdon SL, Bryson THL: Preoxygenation techniques. Anesth Analg 1987; 66:1341–2
18. Pandit JJ, Robbins PA: Ventilation and gas exchange during sustained exercise at normal and raised CO_2 in man. Respir Physiol 1992; 88:101–12
19. Everatt J, Ng WS: Pre-oxygenation using face mask or mouthpiece with and without nose clip: Patient preferences and efficacy. Anaesthesia 1998; 53:382–403
20. Pandit JJ, Robbins PA: Respiratory effects of breathing high oxygen during incremental exercise in humans. Adv Exp Med Biol 2001; 499:331–6
21. Pandit JJ, Robbins PA: Acute ventilatory responses to hypoxia during voluntary and electrically induced leg exercise in man. J Physiol 1994; 477:161–8
22. Pandit JJ, Bergstrom E, Frankel HL, Robbins PA: Increased hypoxic ventilatory sensitivity during exercise in man: Are neural afferents necessary? J Physiol 1994; 477:169–75
23. Swanson GD: Breath-to-breath consideration for gas exchange kinetics, Exercise, Bioenergetics and Gas Exchange. Edited by Cerretelli P, Whipp BJ. Amsterdam, Elsevier, 1980, pp 211–22
24. Auchincloss JH, Gilbert R, Baule GH: Effect of ventilation on oxygen transfer during early exercise. J Appl Physiol 1966; 21:810–8
25. di Prampero PE, Lafortuna CL: Breath-by-breath estimate of alveolar gas transfer variability in man at rest and during exercise. J Physiol 1989; 415:459–75
26. Busso T, Robbins PA: Evaluation of estimates of alveolar gas exchange by using a tidally ventilated nonhomogenous lung model. J Appl Physiol 1997; 82:1963–71
27. Campbell IT, Beatty PCW: Monitoring preoxygenation. Br J Anaesth 1994; 72:3–4
28. Baraka AS, Hanna MT, Jabbour SI, Nawfal MF, Sibai AAN, Yazbeck VG, Khoury NI, Karam SK: Preoxygenation of pregnant and nonpregnant women in the head-up versus supine position. Anesth Analg 1992; 75:757–9
29. Chiravuri SD, Nimmagadda U, Salem MR, Joseph NJ, Wafai Y: Positioning does not affect preoxygenation using tidal volume breathing. ANESTHESIOLOGY 2001; 92:S95
30. Salem MR, Joseph NJ, Crystal GJ, Nimmagadda U: Preoxygenation: Comparison of maximal breathing and tidal volume techniques (letter). ANESTHESIOLOGY 2000; 92:1845
31. Anonymous: Preoxygenation: Physiology and practice. Lancet 1992; 339: 31–2