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The Measurement of Gas Trapped in the Lungs at Functional Residual Capacity and the Effects of Posture

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Gas trapped in the lungs of normal subjects breathing at functional residual capacity (FRC) was measured by a modification of the closed-circuit helium technique. "Closing volume" (CV) was also measured, by the single-breath nitrogen method. Volumes of as much as 193 ml, representing 10 per cent FRC, were found trapped, and the amount trapped could be correlated with the relationship between "closing volume" and FRC. Significant volumes were trapped only when CV equalled or exceeded FRC. Compared with the sitting position, the supine position was associated with less FRC and a greater VTG when CV was greater than FRC. It is concluded that the results are evidence of the reality of airway closure and the detrimental effect on gas exchange of the supine position. Altered relationships between FRC and CV may cause the hypoxemia associated with anesthesia and that which follows abdominal surgery. (Key words: Trapped gas; Airway closure; Functional residual capacity; Posture; Age.)

THE SMALL AIRWAYS in the lung diminish in size as lung volume decreases from total lung capacity. This phenomenon is most conspicuous in the dependent region of the lung, because of the effect of the weight of the lung itself. A volume of the lung at which these airways start to close has been demonstrated by many authors.[1-6] When a lung is at or below its "closing volume" (CV), it can be predicted that gas will be trapped behind these closed airways.

Burger and Macklem[4] measured the volume of trapped gas (VTG) in normal subjects breathing at residual volume (RV), and Hughes and Rosenzweig measured VTG in the excised lung of the dog.[5] No measurements of VTG in the lungs of human subjects during normal breathing at functional residual capacity (FRC) have been reported. The change from the sitting to the supine position is associated with a decrease in FRC.[6] In those subjects in whom this decrease places FRC below CV, VTG should increase. We thought it of interest, therefore, to measure VTG in the sitting and supine positions to learn whether the volumes were in accord with the predicted relationship between FRC and CV.

The relationship of FRC to CV is an important determinant of whether airway closure, and consequently hypoxemia, occurs. When FRC is above CV, airway closure will be unlikely. If FRC decreases, or CV increases, so that FRC comes to lie below CV, airway closure will occur during tidal breathing, with consequent derangement of gas exchange. This phenomenon is important during surgical operations because both anesthesia[7] and the supine position reduce FRC. In those patients in whom FRC is below CV, hypoxemia will occur.

The purpose of our study was 1) to measure VTG in conscious subjects breathing spontaneously at FRC, and 2) to alter the relationship of FRC to CV by changing the subject from the supine to the sitting position, to determine whether VTG changed accordingly.

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Methods

Measurement of Closing Volume

We used a version of the modified single-breath nitrogen technique described by Anthonisen.[3] The subject breathed air, and exhaled to residual volume (RV), at which point the inspired gas was changed to 100 per cent oxygen. Following an inspiration of oxygen to vital capacity and a 5-second breath-hold, the subject expired slowly into a Wedge spirometer (Med-Science Electronics, St. Louis, Model 170) from total lung capacity (TLC) back to RV. During this expiration, the nitrogen concentration was continuously measured at the mouth by means of a nitrogen analyzer (Vertek VR 3400). The output of the analyzer was fed to the Y axis of an X–Y plotter (Hewlett-Packard 7035 B). The simultaneous volume measurement was recorded on the X axis. The first part of the expirate (fig. 1) represents the deadspace gas, and is free of nitrogen. The concentration of nitrogen then increases to a plateau as alveoli empty. As expiration continues, an increase in the slope of the alveolar plateau occurs. The point of inflection (fig. 1) indicates the lung volume at which airways start to close,[3] and can be presented as a percentage of the total expiration, which is vital capacity (VC). However, we expressed closing volume (CV) as an absolute volume by adding the residual volume.

Measurement of FRC and VTG

These measurements were made by modifying the usual closed-circuit helium FRC technique.[9] The spirometer of the circuit (C. F. Palmer, London) was filled with sufficient gas to allow the subject to inspire to at least 2,000 ml above FRC. The concentration of helium was measured by a catharometer (Cambridge Instrument Co. Ltd.) and the output recorded on a 10-inch-wide Honeywell recorder (Electronik 194). FRC was measured in the usual way, by connecting the subject to the spirometer and asking him to breathe quietly and normally. Oxygen was added to the circuit to maintain a horizontal baseline on the spirometer tracing. When equilibration of the helium between lungs and circuit had occurred, the value for FRC was calculated. While still connected to the spirometer, the subject was instructed to take a large breath to approximately 2,000 ml above FRC, and resume normal breathing. A decrease in helium concentration was taken as evidence that helium-free trapped gas, which had not been in continuity with the spirometer, was mixing with the gas in the circuit. The large breath was repeated until no further decrease in helium concentration occurred. From the total decrease in helium concentration produced by the large breaths, the volume of trapped gas was calculated. This technique was accurate to within approximately 10 per cent. Measuring a volume of 100 ml added by syringe to the circuit, the mean volume calculated was 98 ml, with a standard deviation of 6.7 ml.

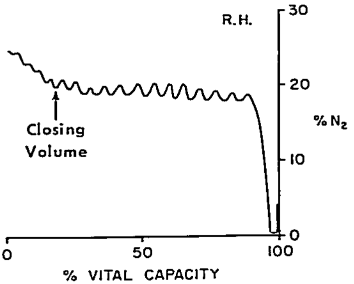

FIG. 1. Vital capacity plotted against percentage nitrogen measured at the mouth. Closing volume represents the lung volume at which airways start to close.

Expiratory reserve volume (ERV) and inspiratory capacity (IC) were then measured.

Procedure

Thirty subjects were studied. They were laboratory personnel, paid volunteers, or patients awaiting surgery. All were free of cardiac and respiratory disease as judged by history and physical examination. Their physical characteristics are shown in table 1.

Each subject was studied in the supine position. A single measurement of FRC and VTG was made. Closing volume was measured in duplicate and repeated if necessary to produce two tracings with similar vital capacities (±10 per cent of mean VC). Seven-

TABLE 1. Physical Characteristics of the Subjects and Results of the Study*

	Sex	Age (Years)	Height (cm)	Weight (kg)	Supine				Sitting			
					FRC (ml)	CV (ml)	FRC-CV (ml)	VTG (ml)	FRC (ml)	CV (ml)	FRC-CV (ml)	VTG (ml)
Subject 1	M	28	185	88	3,110	2,512	598	8	3,960	2,482	1,478	32
Subject 2	M	27	173	73	1,530	1,442	88	−11	1,860	1,248	612	43
Subject 3	M	37	175	75	2,240	2,449	−209	177	3,350	2,523	827	11
Subject 4	F	32	157	68	817	1,023	−206	0	1,220	1,161	59	21
Subject 5	M	35	178	64	3,170	2,940	230	5	4,630	3,120	1,510	−11
Subject 6	F	40	163	104	1,070	1,572	−502	107	1,730	1,744	−14	86
Subject 7	M	32	173	81	1,850	2,173	−323	0	2,380	2,204	176	−1
Subject 8	M	49	178	74	1,900	2,411	−511	70	3,330	2,870	460	25
Subject 9	M	32	176	70	2,660	2,578	82	0	4,070	2,573	1,497	−5
Subject 10	M	78	173	60	3,210	4,035	−825	22	3,910	3,966	−56	54
Subject 11	F	68	160	80	2,100	2,493	−393	75	2,440	2,855	−415	38
Subject 12	F	47	163	57	2,215	2,450	−235	81	3,450	2,912	538	70
Subject 13	F	28	170	60	1,850	1,865	−15	0	2,730	2,380	350	−11
Subject 14	M	24	188	88	2,190	1,989	201	−75	3,820	2,240	1,580	−10
Subject 15	M	56	164	57	3,410	3,770	−360	59	4,460	4,066	394	5
Subject 16	M	48	175	70	2,340	3,024	−684	193	3,280	3,485	−205	21
Subject 17	M	48	170	64	3,330	2,863	467	−64	3,990	3,384	606	−21
Subject 18	M	73	175	95	1,700	2,810	−1,110	81				
Subject 19	M	54	182	88	1,760	2,760	−1,000	64				
Subject 20	M	28	163	61	1,950	1,712	238	−5				
Subject 21	F	48	165	58	1,730	1,890	−160	5				
Subject 22	F	40	152	57	1,610	1,570	40	75				
Subject 23	F	20	165	65	2,280	1,714	566	0				
Subject 24	M	72	167	77	2,270	3,148	−878	124				
Subject 25	F	31	157	50	2,180	1,827	353	0				
Subject 26	F	61	163	66	2,240	2,867	−627	170				
Subject 27	F	26	163	60	1,420	1,330	90	32				
Subject 28	F	18	168	52	2,240	1,050	1,190	0				
Subject 29	F	27	173	57	2,340	2,140	200	0				
Subject 30	M	46	178	77	2,200	2,090	110	0				

* FRC = functional residual capacity. CV = closing volume. VTG = volume of trapped gas. Volumes are in ml, BTPS. In the first 17 subjects, measurements were made in both supine and sitting positions.

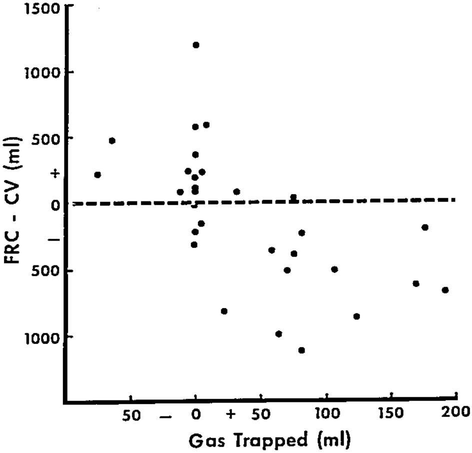

FIG. 2. Functional residual capacity minus closing volume (FRC − CV) plotted against volume of gas trapped, in ml. The dashed line represents the point at which FRC equals CV. Supine position.

teen of the subjects were also studied in the upright position, sitting in a straight-backed chair. At least 10 minutes elapsed following a position change before measurements were made. In no subject was the maximum tidal volume during the period of equilibration with helium more than 500 ml above mean tidal volume.

Results

All volumes are expressed in ml at BTPS. Where a mean value is given, standard deviation (±) is shown. Among the volumes of trapped gas (VTG), there are some negative values (table 1). This indicates that the helium concentrations following the deep breaths were higher than those during prior equilibrium (see Discussion).

SUPINE POSITION

Trapped gas. Mean VTG was 40 ± 65.7 ml. The maximum volume was 193 ml.

Correlation of volume of trapped gas with relationship of FRC to CV. VTG is plotted against (FRC − CV) in figure 2. When CV is less than FRC, no gas should be trapped; when CV exceeds FRC, gas trapping should occur. Figure 2 shows that of the 14 subjects in whom more than 10 ml of gas was trapped, only two had FRC values greater than CV values. Figure 3 shows the same data presented differently. VTG is plotted against CV, both values being expressed as percentages of FRC. Inspection of the results indicates that gas is trapped when CV exceeds FRC.

Effect of tidal volume (V_t) on VTG. VTG is plotted against (FRC + V_t) in figure 4. It is evident that trapped gas is present even when (FRC + V_t) is 500 ml above CV.

SITTING POSITION

Functional residual capacity and closing volume. The change from the supine to the sitting position was invariably associated with an increase in FRC such that, in our subjects, FRC (sitting) = FRC (supine) × 1.19 + 489.38 ($r = 0.92$, $P < 0.001$). Closing volume also increased slightly in the sitting position, as expressed by the equation: CV (sitting) = CV (supine) × 1.03 + 141 ($r = 0.96$, $P < 0.001$). FRC increased disproportionately to CV, so that the ratio decreased as follows: CV/FRC × 100 (sitting) = CV/FRC × 100 (supine) × 0.72 + 5.76 ($r = 0.77$, $P < 0.001$).

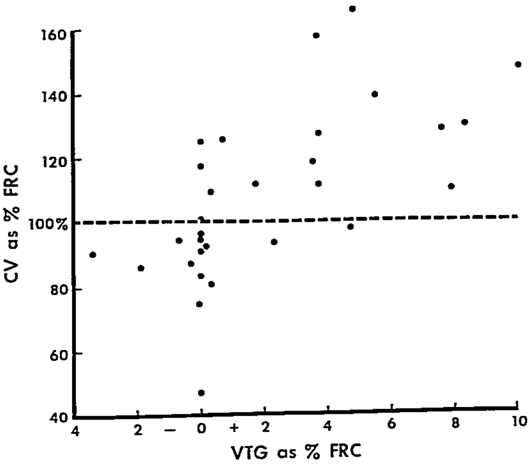

FIG. 3. Closing volume as percentage FRC plotted against volume of trapped gas (VTG), also expressed as percentage FRC. The dashed line represents the point at which CV equals FRC. Supine position.

Changes in VTG with position. Trapped gas as a percentage of FRC is plotted against (FRC – CV) in the supine and sitting positions in figure 5. Paired analysis of the differences between VTG's in the two positions did not disclose a difference. However, the mean value for (VTG/FRC × 100) in the seven subjects in whom more than 1 per cent FRC was trapped in the supine position was 5.6 ± 3.1 per cent, and this decreased significantly ($P < 0.01$) in the sitting position (1.5 ± 1.7 per cent).

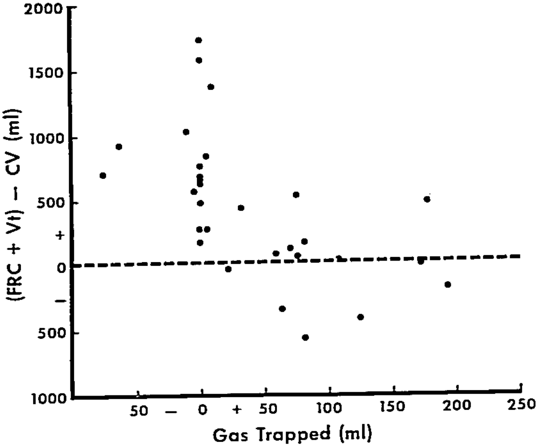

FIG. 4. The volume in the lung at the end of inspiration (FRC + V_t) minus closing volume plotted against gas trapped. The dashed line represents the point at which CV equals (FRC + V_t). Supine position.

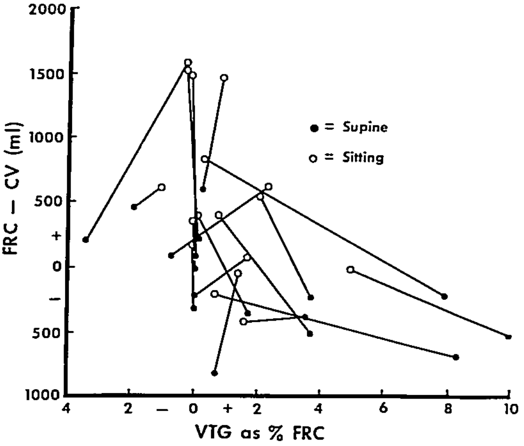

FIG. 5. The effect of a change from the supine to the sitting position on the relationship between volume of trapped gas (VTG) as percentage FRC and (FRC − CV), in ml. Solid circles represent values in the supine position. Continuous lines connect supine values with the values of the same subjects in the sitting position (hollow circles).

FACTORS INFLUENCING THE EFFECT OF POSITION

Age. The correlation between age and CV in the supine position, expressed as a percentage of FRC, is shown in figure 6 (above). The best-fit line has the equation $CV \times 100/FRC = \text{age (years)} \times 1.11 + 61.24$ ($r = 0.72$, $P < 0.001$). Figure 6 (below) shows VTG as a percentage of FRC in the supine position plotted against age. The mean (-0.14 ± 1.2 per cent) for VTG in the 13 subjects less than 35 years old was significantly ($P < 0.01$) lower than that in the 13 subjects more than 45 years old (3.2 ± 2.99 per cent). In the sitting position, CV as a percentage of FRC again increased with age (fig. 7), so that $CV \times 100/FRC = \text{age} \times 0.78 + 52.1$ ($r = 0.7$).

Ratio of weight to height. In the supine position, as the ratio of weight to height increased, CV became a greater proportion of FRC (fig. 8), so that $CV \times 100/FRC = \text{Wt (kg)}/\text{Ht (cm)} \times 215 + 17.76$ ($r = 0.63$, $P < 0.001$). This relationship was not evident in the sitting position.

Height (fig. 9). In the sitting position, as height increased, CV as percentage FRC decreased, so that $CV \times 100/FRC = -\text{Ht} \times 1.39 + 324.2$ ($r = 0.69$, $P < 0.01$). This relationship was not found in the supine position.

Discussion

The method used to detect trapped gas depends on a decrease in helium concentration following one or more deep breaths. This decrease in helium concentration could be caused by air entering the circuit from the atmosphere, in spite of careful instruction of the subjects in the use of the mouthpiece. This is possible, but evidence against it is that, first, a final equilibration with helium was achieved by the subject, with successive deep breaths causing a diminishing effect on helium concentration. If a leak were occurring, the helium concentration would fall in a random manner, and final equilibration would be unlikely. Second, the spirometer tracing did not indicate any added volume in the lung–spirometer system following the deep breaths.

Another factor which might cause the catharometer to indicate a decrease in helium concentration following the deep breaths is a decrease in the oxygen concentration in the spirometer, due to increased oxygen uptake resulting from the added work of breathing. Again, evidence against this is the fact that

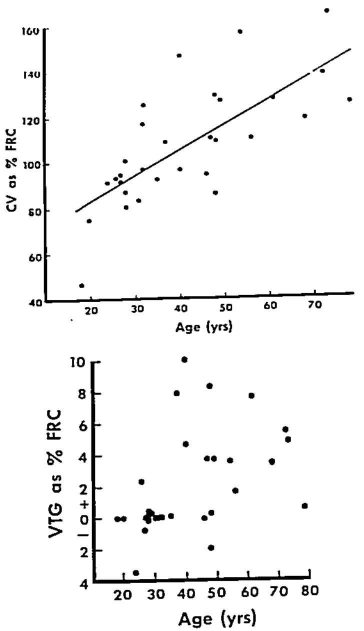

FIG. 6. *Above*, relationship between closing volume, as percentage FRC, and age, in the supine position. The continuous line represents the equation CV/FRC × 100 = age (years) × 1.11 + 61.24. *Below*, relationship between the volume of gas trapped (VTG) as percentage FRC and age in years, in the supine position.

successive deep breaths had diminishing effects on helium concentration, and that there was a final equilibration between lung and spirometer.

In three of the 47 sets of measurements, the deep breaths were followed by increases in the helium concentrations. We could not establish the cause of this, as it could not be reproduced consistently. It may have resulted from an overall increase in oxygen uptake caused by the deep breaths, which resulted in a relative concentrating effect on the helium.

We demonstrated that at functional residual capacity small volumes of gas are trapped in the lungs behind closed airways in some subjects. The presence of this trapped gas in the supine position could be correlated with the relationship of FRC to closing volume (CV). When CV was below FRC, trapped gas was unlikely to be present. As CV increased above FRC, volumes as great as 10 per cent of functional residual capacity were found trapped. This, we interpreted as evidence of the reality of airway closure and the consequent trapping of gas.

The effect of body posture was such that changing from the supine to the sitting position increased closing volume slightly. However, the accompanying increase in FRC was proportionately greater, so that FRC tended to move further above CV. This was reflected in the volume of trapped gas. In the seven subjects in whom more than 1 per cent FRC was trapped when they were in the supine position (fig. 5), there were consistent and significant reductions in the volumes of gas trapped when the measurements were repeated with the subjects sitting.

From the respective regression equations, the ages at which airway closure started to occur at FRC were 35 years in the supine position and 61 years in the seated position. These results are in agreement with those of others,[1, 13] and suggest that maximum benefit to gas exchange from a change in position from supine to sitting would occur in subjects between the ages of 35 and 61 years. Below this age range, CV is below FRC in both positions. Above this age range, CV is above FRC in either position.

An additional factor determining the effect of posture was the body configuration. A tall patient would be likely to benefit from a change to the sitting from the supine position, because increased height tended to place FRC above CV. Equally, a relatively obese subject would be at a particular disadvantage in the supine position, because CV increased in relation to FRC as the ratio of weight to height increased.

It was interesting that the tidal volume did not necessarily prevent the trapping of gas. In our subjects, the end of inspiration could be 500 ml above CV, yet gas would be trapped (fig. 4). The important relationship seemed to be that of FRC to CV. Supporting evidence for this is seen in the results of Burger and Macklem,[4] who found that tidal volumes as great as 1,500 ml did not prevent the increase in elastic recoil in subjects breathing air at residual volume. An alternative explanation might be that airways open and close at diferent lung volumes. Holland *et al.*[14] showed that opening volume exceeded closing volume by approximately 4 per cent TLC, which in our subjects would represent a volume between 150 and 350 ml.

The functional consequence of airway closure and gas trapping at FRC will be seen as an impairment of gas exchange during normal breathing. The trapped gas presumably will come into equilibrium with pulmonary arterial blood and hence, if perfusion persists, shunting will result. This will contribute to venous admixture and lowering of arterial oxygen tension. Periodically, by means of an inspiration to at least 500 ml above closing volume, the oxygen tension of the trapped gas will be partially restored. The oxygen concentration will then fall, and the cycle will be repeated. The "sigh," or big breath, therefore, would have only a transient effect on gas exchange, but it may help to prevent atelectasis in the parts of the lung where gas trapping occurs.

The degree of impairment of gas exchange will be related to the volume of gas trapped as a proportion of the volume of TLC. It is interesting to speculate on the quantitative relationship between the volume of gas trapped and the shunt.

Sutherland *et al.*[15] have shown that minimal volume (MV) in the lung is approximately 20 per cent of total lung capacity (TLC). At minimal volume, all the airways are closed, and therefore the volume of trapped gas will be 20 per cent of TLC, and perfusion will be to gas which will attain the partial pressures of venous blood. This effectively represents a shunt of 100 per cent of cardiac output. If perfusion were equally distributed to all individual alveoli, a volume of trapped gas equal to 10 per cent of TLC would represent a shunt of 50 per cent. This calculation will probably underestimate the percentage shunt, because the dependent parts of the lung, where airway closure occurs selectively, receive proportionately more perfusion.

Of the subjects we studied in the supine position, no gas trapping, and therefore no contribution to shunt, would be expected in those less than 35 years old. At the age of 50 years, the volume of trapped gas would cause a shunt of approximately 10 per cent, and at the age of 70 years, a shunt of 15 per cent. These results are supported by those of Craig,[16] who found venous admixtures equivalent to shunts of approximately 12 per cent at the age of 50 years and 17 per cent at the age of 70 years.

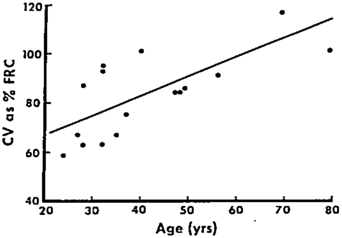

FIG. 7. Relationship between closing volume (CV) as percentage FRC and age in years. Sitting position. The continuous line represents the equation $CV/FRC \times 100 = \text{age (years)} \times 0.78 + 52.1$.

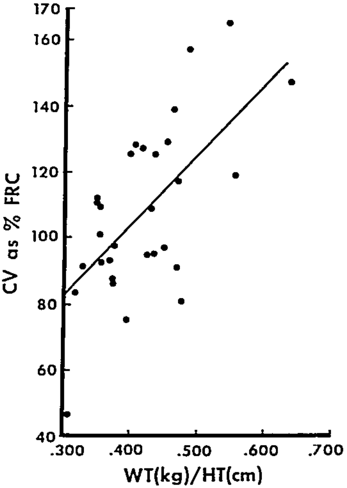

FIG. 8. Relationship between closing volume (CV) as percentage FRC and the ratio of weight (kg) to height (cm) in the supine position. The continuous line represents the equation $CV/FRC \times 100 = Wt\ (kg)/Ht\ (cm) \times 215 + 17.76$.

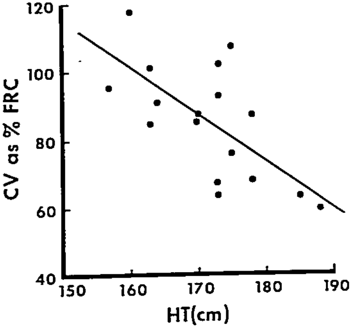

FIG. 9. Plot of closing volume (CV) as percentage FRC against height in cm in the sitting position. The solid line is represented by the equation $CV/FRC \times 100 = -Ht\ (cm) \times 1.39 + 324.2$.

The increases with age of alveolar–arterial oxygen difference[17] can be explained as the basis of airway closure and gas trapping.

Seemingly small volumes of trapped gas, therefore, can be assumed to be associated with considerable impairment of arterial oxygenation. With adoption of the sitting position, because FRC tends to move above CV, improvement in gas exchange can be expected. The predicted shunt in our patients in the sitting position at the age of 50 years is approximately 4 per cent of the cardiac output, and at the age of 70 years, 5 per cent.

We suggest that improved gas exchange might result from placing patients in a sitting or semirecumbent position rather than the supine position. It is also suggested that the reduction in FRC associated with anesthesia[7] and that following upper abdominal surgery[18] may cause the hypoxemia associated with these states, by increasing CV above FRC.

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