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Effects of Halothane Anesthesia on Functional Residual Capacity and Alveolar–Arterial Oxygen Tension Difference

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Functional residual capacity (FRC) and alveolar-to-arterial oxygen tension difference ($A\text{-}aD_{O_2}$) were measured and compared in 16 patients prior to and during halothane:oxygen anesthesia with spontaneous respiration. After an hour of anesthesia (end-tidal halothane 1.0 per cent), FRC had decreased to 81 per cent of awake control values (range 50–104 per cent) and $A\text{-}aD_{O_2}$ had increased from a preoperative value of 145 to 232 torr. The decrease in FRC correlated inversely with the changes in $A\text{-}aD_{O_2}$ ($r = 0.63$, $P < 0.01$). Obese patients and those who had low preoperative values of per cent forced expiratory volume in one second ($FEV_{1.0}/FVC$) had the greatest decreases in FRC. The authors conclude that although FRC and $A\text{-}aD_{O_2}$ show inverse changes neither can be used to predict the absolute changes in the other; decreases in FRC during anesthesia are associated with obesity and reduction in forced air flow. (Key words: Functional residual capacity; Alveolar–arterial oxygen tension difference; Halothane anesthesia; Pulmonary shunting.)

MEASUREMENT of the effects of anesthesia on functional residual capacity (FRC) in man has produced conflicting results. Colgan and Whang [1] found no significant changes in FRC in patients anesthetized with halothane and breathing spontaneously. In contrast, Don and co-workers [2] found significant decreases in FRC in patients similarly anesthetized, and correlated this reduction with body build. Should decreases in FRC occur during anesthesia, the resultant effect may be impairment of pulmonary oxygen exchange.

The purpose of this study was to measure and compare the effects of halothane–oxygen anesthesia on FRC and alveolar-to-arterial oxygen tension differences ($A\text{-}aD_{O_2}$) in man. In addition, we examined the relationship of changes in FRC to forced vital capacity, body build, age, anesthesia-induced changes in ventilation, and finally, the effect of endotracheal intubation.

Method

Sixteen patients without clinical evidence of pulmonary disease undergoing operations outside the thorax or upper abdomen were studied. Signed consent was obtained from the patients, and the protocol of the study was approved by the appropriate committee of the university.

After premedication with pentobarbital (75–125 mg) and atropine (0.4–0.6 mg), measurements of minute ventilation, vital capacity, tidal volume, timed vital capacity, FRC, and arterial P_{O_2}, P_{CO_2}, and *p*H were made. Anesthesia was induced with sodium thiopental, 150 to 300 mg, and maintained with halothane–oxygen using a conventional circle system with CO_2 absorber. End-tidal halothane concentrations were measured and held constant for each patient (range 0.71–1.40 vol per cent).

The tracheas of nine patients were intubated following 60–80 mg succinylcholine; in the remaining seven patients, anesthesia was administered via a face mask. Except for the brief period of neuromuscular paralysis, ventilation was spontaneous throughout the study

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period. Measurements of FRC and arterial P_{O_2}, P_{CO_2} and *p*H were made during operation, 20–40 and 50–70 minutes after induction.

Preoperatively, arterial blood was drawn after the patients had breathed pure oxygen through a mouthpiece connected to a one-way valve for 10 minutes. Samples were drawn in heparinized glass syringes, placed in ice, and analyzed for P_{O_2}, P_{CO_2} and *p*H within two hours of sampling. Samples were corrected for changes produced by time and temperature.[3] A blood–gas factor for the oxygen electrode was obtained daily using a tonometer and a 30 per cent mixture of glycerol in water.[4]

FRC was measured by a closed-system helium-dilution method employing a catharometer and spirometer.[5] Preoperative duplicate measurements were made as the patients breathed room air and the spirometer filled with room air. During measurement, oxygen was added to the system to maintain the volume constant. Intraoperatively, the spirometer was filled with oxygen and connected by means of a three-way valve such that the patient's airway could be connected to either the anesthetic circle system or the spirometer. Corrections were made for errors arising from starting the measurements of lung volume at points other than end-expiration. As described by Colgan *et al.*,[6] halothane decreased the catharometer reading. Halothane concentrations were measured by an infrared analyzer calibrated as previously described[7] and a correction applied for the effects of halothane on the catharometer. Our determination of the correction factor for the effects of halothane on the catharometer agreed exactly with that reported by Colgan and co-workers.[6]

Results

FRC and A-aD_{O_2} 20 to 40 minutes after induction of anesthesia were significantly different from awake control values (table 1). FRC decreased to 87 per cent of the value in awake controls and A-aD_{O_2} increased by 65 torr. A further small but significant decrease in FRC occurred 50 to 70 minutes after induction. Corresponding values of A-aD_{O_2} were not significantly different from those found 20 to 40 minutes after induction. Those patients who had decreases in lung volume also tended to have increases in A-aD_{O_2}; a linear inverse correlation between these variables is shown in figure 1.

TABLE 1. Effects of Anesthesia on FRC and A-aD_{O_2}, 16 Patients (Mean ± SE; Differences Examined by Analysis of Variance)

	Awake	Anesthesia	
		20–40 min	50–70 min
FRC (l)	2.499 ±0.134	2.184* ±0.207	2.013†‡ 0.172
A-aD_{O_2} (torr)	145 ± 15	205* ± 28	232* ± 35

* Significantly different from control, $P < 0.01$.
† Significantly different from control, $P < 0.001$.
‡ Significantly different from 20–40-min value, $P < 0.05$.

TABLE 2. Effects of Anesthetic Technique on FRC and A-aD_{O_2} 50–70 Minutes after Induction of Anesthesia (Mean ± SE)

	Intubated (n = 9)	Face Mask (n = 7)
FRC (per cent of awake control)	82 ±5.5	79 ±6.8
ΔA-aD_{O_2} (torr) (anesthetized minus control)	78 ±10	105 ±12

There were no differences in FRC or A-aD_{O_2} changes in those patients whose tracheas were intubated compared with those anesthetized using a face mask (table 2). Heavy, short patients and patients with low per cent $FEV_{1.0}$ values had the largest decreases in FRC following induction of anesthesia. Patients studied had $FEV_{1.0}$/FVC ratios that ranged from 57 to 90 per cent, or 85 to 112 per cent of the predicted normal values. Mean of predicted normal was 100.1 ± 9.1 SD per cent of normal. The multiple regression equation for the effect of body build (height (cm)/weight (kg)) and per cent $FEV_{1.0}$ on FRC is: FRC (anesthesia)/FRC (awake) × 100 = 29.8 (ht/wt) ÷ 1.1 (per cent $FEV_{1.0}$) − 78.9. Partial correlation coefficients are height/weight r = 0.75; per cent $FEV_{1.0}$ r = 0.73. The multiple

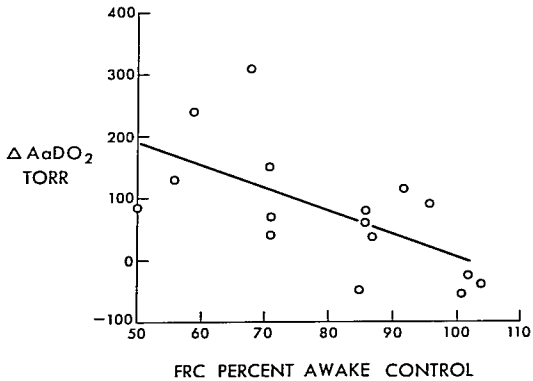

FIG. 1. Relationship between the changes in FRC and $\Delta A\text{-}aD_{O_2}$ 50–70 minutes after induction of anesthesia. $\Delta A\text{-}aD_{O_2}$ equals $A\text{-}aD_{O_2}$ measured during anesthesia minus $A\text{-}aD_{O_2}$ in the awake patient.

correlation coefficient for both variables on FRC is $r = 0.84$ ($P < 0.001$). Figure 2 shows the effect of body build weighted for per cent $FEV_{1.0}$ on reduction in FRC.

The patients ranged in age from 21 to 74 years, with a mean age of 45 (±SD 17) years. No relationship between the age of the patient and the magnitude of the decrease in FRC occurring during anesthesia could be demonstrated by regression analysis. Mean values and ranges of Pa_{CO_2}, minute ventilation ($\dot{V}_E$), and tidal volume (V_T), measured while awake and 50–70 minutes after induction, are shown in table 3. Although large changes in Pa_{CO_2} and V_T occurred during anesthesia, no relationship between changes in these variables and decreases in FRC was found.

Discussion

Our finding that FRC decreases with anesthesia in certain patients agrees with the work reported by Don and co-workers,[2] but appears to conflict with the findings reported by Colgan and Whang.[1] Don *et al.* studied 11 patients and found a mean decrease in FRC to 69 per cent of that measured before induction of anesthesia. Colgan and Whang studied eight patients and found that FRC and $A\text{-}aD_{O_2}$ in the awake patient and an hour after induction of anesthesia were not significantly different. Both Don and Colgan studied patients who were lightly anesthetized with halothane–oxygen and were breathing spontaneously. One possible explanation for the difference in results was the administration of succinylcholine and the presence of an endotracheal tube in Don's patients, whereas Colgan administered anesthesia via face mask. Indeed, Laws [8] found a reduction in FRC following induction of anesthesia and muscle paralysis with succinylcholine. FRC is determined by the balance of chest-wall and lung forces. It is generally agreed that in conscious man in the sitting position at FRC there is neither inspiratory nor expiratory muscle tone in the chest wall or diaphragm. Information concerning muscle tone at FRC in the supine position or in the supine position during anesthesia is not complete. If at end-expiration expiratory muscle tone were increased or inspiratory muscle tone diminished, then FRC would be decreased. An increase in expiratory muscle activity elicited by the presence of an endotracheal tube would contribute to a decrease in FRC. Similarly, if inspiratory muscle tone predominated, its removal by temporary paralysis with succinylcholine would reduce FRC. Findings in the present study indicate that even when succinylcholine and endotracheal intubation are not used, FRC will still decrease (table 2). The patients in this study who had relatively asthenic body builds and high per cent $FEV_{1.0}$ values had neither decreased FRC nor increased $A\text{-}aD_{O_2}$.

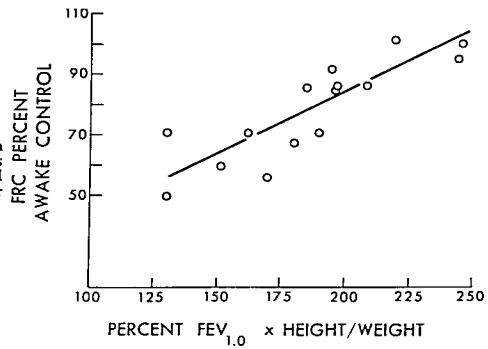

FIG. 2. Relationship between changes in FRC 50–70 minutes after induction of anesthesia and per cent FEV_1 × height/weight ($r = 0.83$, $P < 0.001$).

If Colgan and Whang's patients had similarly favorable characteristics, then the difference in findings can be attributed to selection of patients.

This study confirms the previously reported finding that relative obesity (low height/weight ratio) correlates with the reduction of FRC found during anesthesia.[2] In that study, Don *et al.* postulated that the combination of obesity and anesthesia might accentuate airway closure, thus sequestering a portion of lung volume from measurement by inert gas dilution. In the present study the reduction in FRC also correlated with preoperative reduction in forced air flow. One mechanism for reduction in forced air flow is a loss of elastic recoil of the lung.[9] A loss of elastic recoil of the lung is also found in subjects who have airway closure during normal tidal ventilation.[10] Thus, a common factor, loss of lung elastic recoil, exists in subjects who have low forced air flow and those who have airway closure at lung volumes near FRC. Whether or not airway closure is an important mechanism of the reduction of FRC seen with anesthesia is unknown.

Reductions in V_T and alveolar ventilation (V_A) induced by anesthesia failed to correlate with reduction of FRC. Nevertheless, it should not be assumed that these changes in ventilation would not be causal in reduction of FRC. All patients had reductions in V_T and V_A, but these reductions may have affected FRC only in those patients with specific characteristics such as obesity and reduced elastic recoil of the lung. If so, anesthesia with controlled ventilation and maintenance of V_T and V_A should prevent or minimize reduction in FRC.

An increase in A-aD_{O_2} may be found if venous admixture increases, mixed venous oxygen saturation decreases, or ventilation-to-perfusion abnormalities occur. The high inspired oxygen concentration breathed in this study would prevent any significant increase in A-aD_{O_2} from ventilation-to-perfusion abnormalities.[11] No measurements of mixed venous saturation were made so pulmonary shunt cannot be calculated directly. In other studies where measurements of mixed venous oxygen have been made, the increased A-aD_{O_2} occurring with anesthesia was of similar magnitude to those found in this study, and resulted mainly from increased pulmonary shunt.[12, 13]

Why should a decrease in FRC be associated with an increase in A-aD_{O_2}? Evidence from studies of seated awake man indicates that both ventilation and perfusion decrease in dependent areas of the lung as the subjects voluntarily decrease their lung volumes below FRC. Sutherland and co-workers,[14] in studies with inhaled ^{133}Xe, found areas of zero ventilation in dependent lung at a lung volume below FRC. They related this zero ventilation to airway closure and stated that in their subjects airway closure began at 46 per cent total lung capacity and that at residual volume about half the lung units were closed. Hughes

TABLE 3. The Effects of Anesthesia on Ventilation, 16 Patients (Mean ± SE)

	Awake Control	Anesthetized 50-70 Min
P_{aCO_2} (torr)	39.8 ± 1.1	52.4 ± 2.2
$\dot{V}_E$ (l/min)	8.1 ± 0.4	7.0 ± 0.5
V_T (ml)	580 ± 36	245 ± 18

et al.,[15] using injected ^{133}Xe, demonstrated that at lung volumes below FRC pulmonary perfusion was reduced but maintained to dependent lung. Further evidence of the effect of reduction of FRC on gas exchange is provided by the work of Craig *et al.*[16] These investigators measured FRC, the volume of the lung at which airways close (closing volume), and pulmonary shunt in awake seated man. They then reduced FRC by moving their subjects from the seated to the supine position and repeated the measurements. They found that when FRC was less than closing volume, significant increased pulmonary shunting occurred. Thus, from information obtained in unanesthetized man, an inverse correlation between FRC and $A\text{-}aD_{O_2}$ could be predicted. However, the linear inverse correlation between FRC and $A\text{-}aD_{O_2}$ found in the present study was such that one variable was a poor predictor of the other ($r = 0.63$, fig. 1).

Finally, although changes in FRC and $A\text{-}aD_{O_2}$ have important implications in the conduct of anesthesia, the times of recovery from these changes and their relation to postoperative morbidity are still unknown.

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