

Lung Collapse and Gas Exchange during General Anesthesia: Effects of Spontaneous Breathing, Muscle Paralysis, and Positive End-expiratory Pressure

Leif Tokics, M.D.,* Göran Hedenstierna, M.D.,† Åke Strandberg, M.D.,‡ Bo Brismar, M.D.,§ Hans Lundquist, M.D.¶

Lung densities (atelectasis) and pulmonary gas exchange were studied in 13 supine patients with no apparent lung disease, the former by transverse computerized tomography (CT) and the latter by a multiple inert gas elimination technique for assessment of the distribution of ventilation/perfusion ratios. In the awake state no patient had clear signs of atelectasis on the CT scan. Lung ventilation and perfusion were well matched in most of the patients. Three patients had shunts corresponding to 2-5% of cardiac output, and in one patient there was low perfusion of poorly ventilated regions. CT scans after 15 min of halothane anesthesia and mechanical ventilation showed densities in dependent lung regions in 11 patients. A shunt was present in all patients, ranging from 1% in two patients (unchanged from the awake state) to 17%. Ventilation of poorly perfused regions was noted in nine patients, ranging from 1-19% of total ventilation. The magnitude of the shunt significantly correlated to the size of dependent densities ($r = 0.84$, $P < 0.001$). Five patients studied during spontaneous breathing under anesthesia displayed both densities in dependent regions and a shunt, although of fairly small magnitude (1.8% and 3.7%, respectively). Both the density area and the shunt increased after muscle paralysis. PEEP reduced the density area in all patients but did not consistently alter the shunt. It is concluded that the development of atelectasis in dependent lung regions is a major cause of gas exchange impairment during halothane anesthesia, during both spontaneous breathing and mechanical ventilation, and that PEEP diminishes the atelectasis, but not necessarily the shunt. (Key words: Computed tomography. Lung: atelectasis; ventilation-perfusion. Ventilation: distribution; positive end-expiratory pressure; ventilation-perfusion; zero end-expiratory pressure.)

GENERAL ANESTHESIA is accompanied by impairment of pulmonary gas exchange and oxygenation of the arterial blood.¹⁻³ In recent studies, using computerized tomography (CT), we have demonstrated prompt development of densities in dependent lung regions following induction of anesthesia.^{4,5} These have been interpreted as atelectatic areas created by loss of supporting forces.^{4,6} The density areas have been shown to be perfused⁴ and the degree of right-to-left shunt, assessed by multiple inert

gas elimination, was correlated with the size of the atelectasis in the anesthetized, paralyzed subject.⁷ In the present study we explored in further detail the effects of such atelectatic areas on pulmonary gas exchange both during spontaneous breathing and during mechanical ventilation. We attempted to reduce the atelectasis by applying positive end-expiratory pressure (PEEP) and investigated the consequent effect on the gas exchange. Gas exchange was evaluated by a multiple inert gas elimination technique for the assessment of the distribution of ventilation-perfusion ratios (VA/Q),⁸ and CT scanning was performed for the detection and quantification of atelectasis.

Materials and Methods

MATERIAL

Thirteen patients scheduled for elective abdominal surgery were studied awake immediately before induction of and during general anesthesia. Certain data from eight of the patients have been reported earlier.⁷ There were nine men and four women, ranging in age from 23 to 62 yr (mean 42 yr). They all had a normal body configuration, with a mean height of 174 cm and a mean weight of 71 kg. Seven patients were smokers and one was an ex-smoker. None of the patients exhibited clinical signs of chronic bronchitis, but with spirometry on the day before the study two patients were found to have a forced expired volume in one s (FEV_1) and a forced flow at 75% of expired vital capacity (FEF_{75}) that were reduced by more than two standard deviations below the reference value (patients 5 and 8). Another three patients (7, 11, and 12) showed similar reductions in FEF_{75} . Individual data are given in table 1. Informed consent to the study was obtained from each patient and the study was approved by the Ethics Committee of Huddinge Hospital.

ANESTHESIA

All patients received atropine prior to anesthesia, either 0.25 mg intravenously (iv) 10 min before the awake measurements or 0.5 mg subcutaneously approximately 2 h earlier. No other premedication was given. In five patients anesthesia was induced with thiopental, 250-500 mg, and diazepam 5-7.5 mg iv and was maintained by spontaneous ventilation with halothane (0.5-2%) in oxygen/nitrogen administered through a face mask. After 25-30 min of

* Resident in Anesthesiology.

† Associate Professor in Clinical Physiology.

‡ Resident in Surgery.

§ Associate Professor in Surgery.

¶ Resident in Roentgenology.

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Address reprint requests to Dr. Hedenstierna: Department of Clinical Physiology, Huddinge University Hospital, S-141 86 Huddinge, Sweden.

TABLE 1. Subject Data

Patient No.	Sex	Age (yr)	Height (m)	Weight (kg)	Smoking (cigarette/day)	FVC (% predicted)	FEV ₁ (% predicted)	FEF ₇₅ (% predicted)
1	F	26	1.73	54	0	95	96	104
2	M	37	1.76	76	10	129	124	150
3	M	25	1.85	76	0	108	104	104
4	M	39	1.82	84	0	93	96	81
5	M	62	1.70	61	20	74	71	61
6	M	41	1.75	77	0	102	100	74
7	F	52	1.68	58	10	118	96	30
8	M	49	1.72	79	0*	83	79	63
9	M	44	1.81	74	0	104	107	110
10	F	23	1.66	65	10	108	94	72
11	M	54	1.70	75	20	113	103	60
12	F	46	1.71	62	15	103	84	32
13	M	54	1.74	81	25	96	95	87
Mean \pm SE		42.3 \pm 3.4	1.74 \pm 1.6	70.9 \pm 2.7				

FVC: forced expired vital capacity; FEV₁ = forced expired volumein 1 s, FEF₇₅ = forced expiratory flow at 75% expired vital capacity.

* Stopped smoking 4 yr earlier.

anesthesia, during which period measurements of gas exchange and atelectasis were made, tracheal intubation was performed after induction of muscle relaxation with succinylcholine 75–100 mg iv. In the other eight patients anesthesia was induced with diazepam, 2.5–7.5 mg, fentanyl, 0.05–0.2 mg, and thiopental, 200–400 mg iv. Muscle relaxation was then achieved with succinylcholine, 75–100 mg iv and the patient's trachea was intubated. During mechanical ventilation, anesthesia was maintained with 0.5–1.0% inspired halothane in oxygen/nitrogen, and pancuronium bromide, 5–9 mg iv, was given. The patients were ventilated at a rate of 12 breaths/min with a Servo 900C® ventilator equipped with a carbon dioxide analyzer (Siemens Elema, Solna, Sweden). Minute ventilation (V_E), read on a vortex meter (Bourns LS-75®), was adjusted to maintain the end-tidal carbon dioxide concentration at approximately 4%. The inspired oxygen fraction (FI_{O_2}) was kept at 0.43–0.48 during all anesthetic measurements and was checked intermittently by mass spectrometry. Inspiratory airway pressure was read on the manometer of the ventilator.

CATHETERIZATION

A triple-lumen thermistor-tipped catheter, Swan-Ganz® 7 Fr (Edward's Laboratories, Santa Ana, CA), was introduced percutaneously by a sleeve technique into a medial cubital vein. The catheter was advanced to the pulmonary artery under radiographic guidance. Pulmonary vascular pressures relative to atmospheric pressure were recorded, and mixed venous blood was drawn for gas analyses (see following). The brachial artery was cannulated for pressure recordings and blood sampling, and an additional venous catheter was inserted in the opposite arm for infusion of inert gases (see following). Cardiac output was determined by thermodilution. Ten milliliters of ice-cold

5% glucose was injected into the right atrium, and the dilution curve was analyzed by a cardiac output computer (model 9250 A, Edward's Laboratories). Under each investigated condition three to four measurements of cardiac output were made and the mean value was calculated.

VENTILATION-PERFUSION RATIOS

Six gases (sulfurhexafluoride, ethane, cyclopropane, enflurane, diethylether, and acetone) were dissolved in isotonic saline and infused into a vein at a rate of 3 ml/min. After 40 min of infusion, under steady-state conditions, arterial and mixed venous blood samples were taken and mixed expired gas was collected for analysis by gas chromatography (Sigma 3,® Perkin-Elmer). (For technical details, see reference 9.) Blood-gas partition coefficients were determined by a two-step procedure.¹⁰ Arterial-mixed venous and mixed expired-mixed venous gas concentration ratios (retention and excretion, respectively) were plotted against blood-gas partition coefficients. By formal mathematical analysis with enforced smoothing, using a scalar smoothing factor of 40, these relationships were transformed into a multicompartmental plot of blood flow and ventilation against VA/Q .^{8,11} Of the available information related to the VA/Q distribution, we present data on shunt (Q_s ; perfusion of lung regions with $VA/Q < 0.005$), "low VA/Q regions" (Q_{low} ; perfusion of lung regions with $0.005 < VA/Q < 0.1$), "high VA/Q regions" (V_{high} ; ventilation of lung regions with $10 < VA/Q < 100$), and dead space (V_D ; ventilation of lung regions with $VA/Q > 100$).

BLOOD GAS ANALYSIS

Arterial and mixed venous blood were drawn for blood-gas analysis, for which standard techniques were employed (ABL-2®, Radiometer).

CT OF THE CHEST

The transverse lung area and the structure and density of the lungs were studied by CT scanning. The subject lay supine on the tomograph table (Somatom 2®, Siemens). A frontal scoutview covering the chest was initially obtained. Two CT scans in the transverse plane were then performed, the lowermost one at a level just above the top of the diaphragm and the other 5 cm cephalad to the first one. The same scan levels, relative to the spine, and the same window were used during the succeeding measurements during anesthesia. The scan time was 5 s, energy 115 mA, slice thickness 8 mm, and the weighted dose-equivalent less than 0.1 mSv.

The transverse area of the thorax was calculated by planimetric measurements on the images, using a computer connected to the tomograph. The external boundary was drawn along the inside of the ribs at a location corresponding to the pleural space. Thus, the transverse areas of the chest did not include any tissue outside or between the ribs, but they did include the mediastinal organs. Regions of contrasting density were identified, a boundary was drawn around the density, and the area was determined as a fraction of the thoracic area at that level.

PROCEDURE

The catheters were introduced at the catheterization laboratory, and the infusion of inert gases was started. The patient was moved to the X-ray department and after at least 20 min of complete rest (40 min of infusion) recordings of central hemodynamic and gas exchange variables were made while the patient was breathing air. CT scans were then obtained and the patient was anesthetized. After 15 min of stable anesthesia, recognized by a stable heart rate, systemic blood pressure, and end-tidal CO₂ concentration, the hemodynamic and gas exchange variables were again recorded and CT scanning was repeated. In the five patients studied during spontaneous breathing, new recordings were made during mechanical ventilation approximately 30 min after intubation. In the other eight patients who were intubated immediately after induction of anesthesia, recordings were made first during mechanical ventilation (making a total of 13 patients studied under this condition) and then after 15 min of PEEP of 10 cmH₂O. After the study the patient, while anesthetized, was moved to the operating room. All recordings, awake and during anesthesia, were made with the patient in the supine position.

STATISTICS

Mean values and SEM were calculated. The significance of a difference between the awake and anesthetized, paralyzed conditions was tested by Student's paired *t* test (*n*

TABLE 2. Gas Exchange, Central Circulation, and Atelectatic Areas in the Awake State and during Anesthesia with Muscle Paralysis and Mechanical Ventilation

	V_E (l/min)	V_D (% V_E)	V_{high} (% V_D)	Q_T (l/min)	Q_a (% Q_T)	Q_{low} (% Q_T)	P_{aO_2} (mmHg)	P_{A-aO_2} (mmHg)	P_{aCO_2} (mmHg)	Vascular Pressures (mmHg)			Density Area (% total area)	
										Pulmonary Arterial		Systemic Arterial	mean	1
										Mean	Wedge	mean		
Awake	6.83 ± 0.41	40.3 ± 4.9	0.5 ± 0.5	5.95 ± 0.33	1.2 ± 0.4	0.5 ± 0.4	91 ± 4.5*	9 ± 3.9*	39.0 ± 1.1	14.2 ± 0.8	8.0 ± 0.6	96 ± 3	0	0
Anesthesia with paralysis, mechanical ventilation	5.33 ± 0.32§	32.1 ± 3.8	6.1 ± 1.9‡	4.99 ± 0.27§	6.5 ± 1.5‡	5.4 ± 2.8‡	169 ± 18*	112 ± 17*	38.3 ± 2.1	12.4 ± 0.6‡	7.7 ± 0.5	63 ± 3§	3.1 ± 0.7§	2.3 ± 0.6§

oxygen tension; P_{A-aO_2} = alveolar-arterial oxygen tension difference; P_{aCO_2} = arterial carbon dioxide tension. *n* = 13; mean ± SE.

* Different $\dot{V}I\dot{O}_2$ awake and during anesthesia.
‡ Significantly different from the awake state: † *P* < 0.05; ‡ *P* < 0.01; § *P* < 0.001.

Area 1: caudal position; area 2: cranial position.
 V_E = minute ventilation; V_D = dead space; V_{high} = ventilation of lung regions with high V_A/Q ratios (10 < V_A/Q < 100); Q_T = cardiac output; Q_a = shunt (V_A/Q < 0.005); Q_{low} = perfusion of lung regions with low V_A/Q ratios (0.005 < V_A/Q < 0.1); P_{aO_2} = arterial

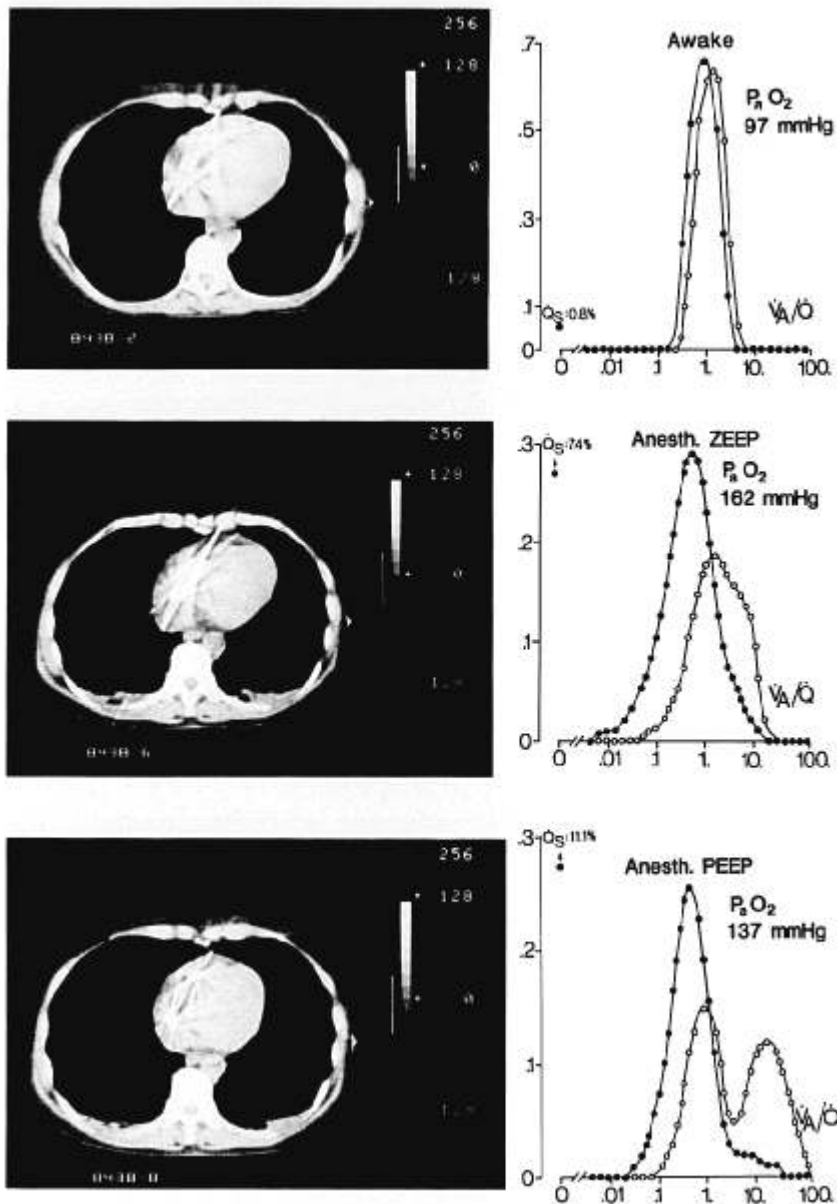


FIG. 1. Transverse CT scans of the chest and VA/Q distributions (O: ventilation; ●: blood flow, l/min) in patient 7 in the awake state (upper panel), during anesthesia with mechanical ventilation (middle panel) with zero end-expiratory pressure (ZEEP); and after the addition of a positive end-expiratory pressure (PEEP) of 10 cmH₂O (lower panel). Note the absence of any lung tissue changes and the unimodal VA/Q distribution, with almost no shunt, in the awake state. Note also the appearance of densities in the dependent lung regions and shunt during anesthesia. PEEP reduced the densities but not the shunt. A distinct "high VA/Q" mode also became evident. PaO₂ is presented in each panel.

= 13), whereas differences between the different ventilatory conditions during anesthesia were tested by the Wilcoxon matched-pairs signed-ranks test ($n = 5$ and 8). Linear regression analyses were performed to study the relationship between the size of regions of contrasting density (atelectatic areas) and the absolute values of various lung function variables.

Results

AWAKE (TABLE 2)

Ventilation, pulmonary arterial and wedge pressures, and systemic arterial pressures were all within normal

limits in the awake state¹² (table 2). Cardiac output was also normal in all but one patient (13), who had a hypokinetic circulation as reflected by a high arterial-mixed venous oxygen content difference (60 ml/l).

In the awake state the derived retention/solubility and excretion/solubility curves were close to the ideal in eight patients. By ideal we mean retention and excretion in a hypothetically uniformly ventilated and perfused lung with the same dead space as in the subject under consideration. Four patients (4, 6, 11, and 13) showed slightly increased retention of the poorly soluble gases (sulfurhexafluoride and ethane) and another patient (5) showed reduced excretion of the soluble gases (ether and acetone). Conversion of the retention and excretion data to a con-

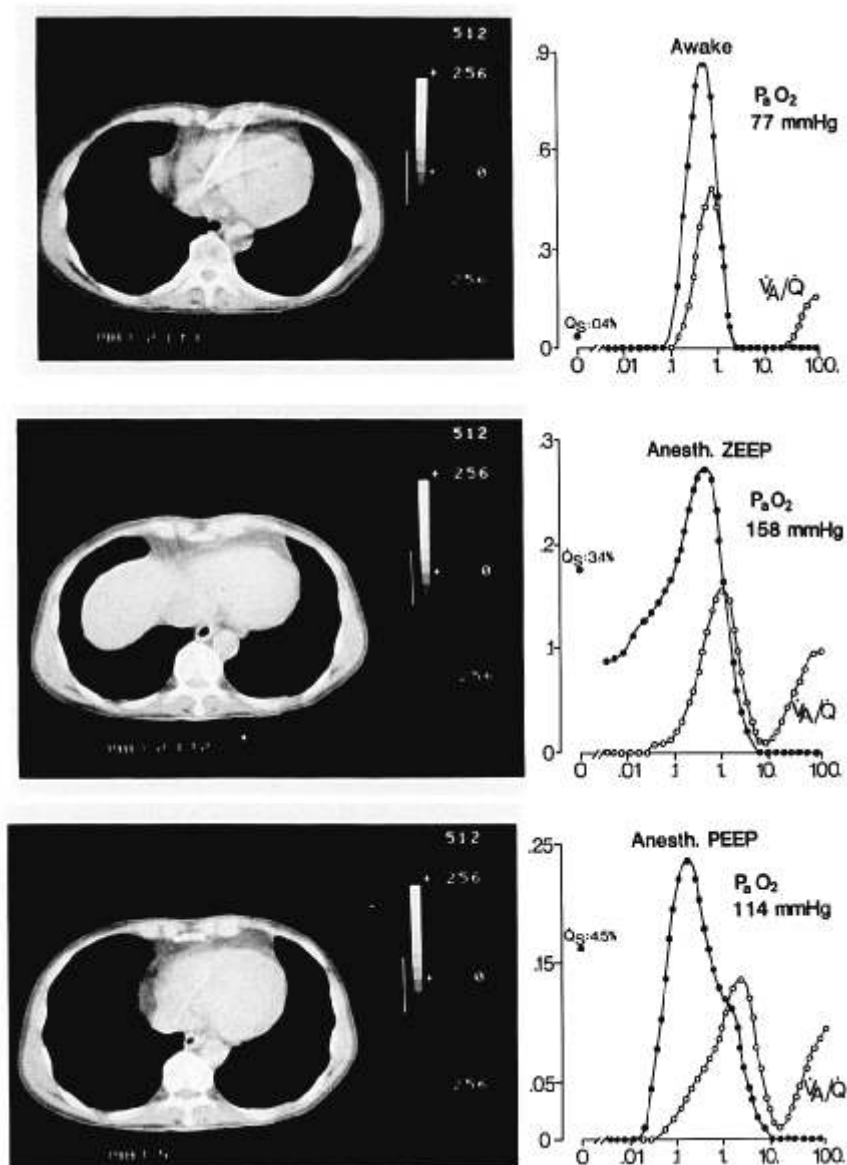


FIG. 2. Transverse CT scans of the chest and VA/Q distributions (O: ventilation, ●: blood flow, l/min) in patient 5, a smoker with spirometric evidence of mild airway obstruction. Recordings during the awake state are shown in the upper panel; during anesthesia without (ZEEP) (middle panel); and with a positive end-expiratory pressure (PEEP) of 10 cmH₂O (lower panel). The white area appearing in the CT scan during anesthesia is the top of the diaphragm, which has moved cranially. Note the small atelectatic area and the moderate shunt during anesthesia. There was considerable perfusion of "low VA/Q" regions, however. PEEP reduced the atelectatic area and had limited effects on VA/Q.

tinuous VA/Q distribution revealed a unimodal distribution of ventilation and perfusion in most of the patients (fig. 1). A small mode within low VA/Q regions (VA/Q < 0.1) was seen in one patient (6), indicating minor perfusion (corresponding to 5% of cardiac output) of poorly ventilated regions. Three patients (4, 11, and 13) had shunts corresponding to 2–5% of cardiac output. All other patients had either no shunt or a shunt of up to 1%. One patient had rather wide modes of ventilation and perfusion, including regions with high VA/Q ratios (VA/Q > 10) (patient 5) (fig. 2). Dead space (VA/Q > 100 and including apparatus dead space) averaged 40%.

The fit of the ventilation and perfusion distributions to the raw retention and excretion data was tested by recalculating the retention and excretion for each gas

from the derived VA/Q distribution. The sum of squared differences between the measured and calculated retention and excretion, the remaining sum of squares (RSS), was 6 or less in eight of 13 tests, indicating a good fit of the data.¹³ (Of all 39 tests in the whole study, RSS was 6 or less in 29.)

During the awake state, with air breathing, arterial oxygen tension (P_{aO_2}) exceeded 75 mmHg in 12 patients and was 66 mmHg in one patient (13). Arterial carbon dioxide tension (P_{aCO_2}) ranged from 30 to 43 mmHg. The alveolar–arterial oxygen tension difference (P_{A-aO_2}) varied from 1 to 33 mmHg (alveolar P_{O_2} calculated as inspired oxygen tension – $P_{aCO_2}/0.8$).

The CT scans disclosed no abnormalities of the lung tissue prior to anesthesia in 12 of the 13 patients. How-

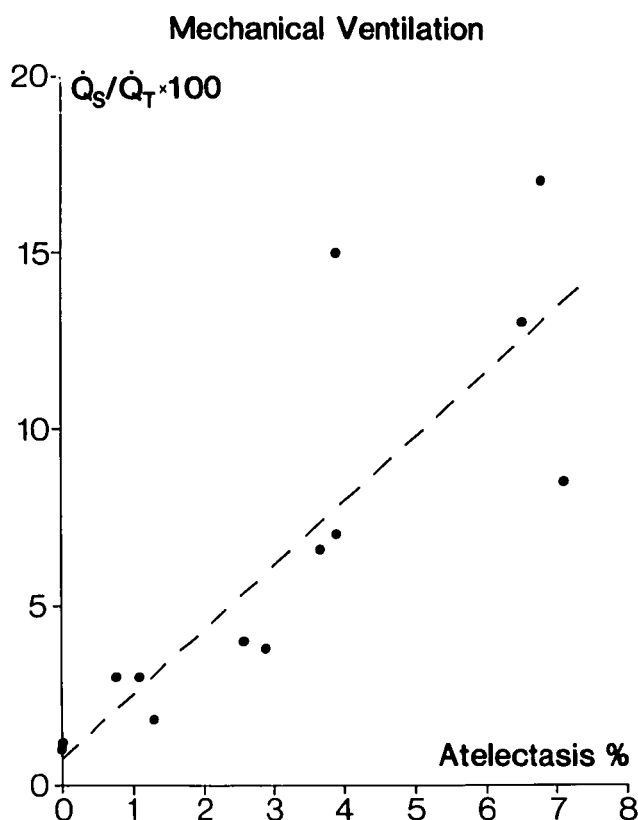


FIG. 3. Plot of shunt in per cent of cardiac output ($Q_s/Q_T \times 100$) (y) against the atelectatic area in the caudal scan, in per cent of the total intrathoracic area (x), during anesthesia with muscle paralysis and mechanical ventilation. There was a strong correlation according to the equation

$$y = 0.88 + 1.81x \quad (r = 0.84; \quad P < 0.001; \quad n = 13)$$

ever, in patient 11 (a smoker) diffuse opacities were observed in dependent regions of both lungs. They comprised 2% of the intrathoracic area in the caudal scan, and the attenuation, or density, increased from the upper to the lower part of the opacity. This patient also had the largest shunt (5%).

ANESTHESIA WITH MUSCLE PARALYSIS (TABLE 2)

Minute ventilation was maintained at approximately 80% of the awake value, the ventilator setting being guided by the recording of the end-tidal CO_2 concentration, which was kept at approximately 4%. Maximum and end-inspiratory airway pressures were 12 ± 1 and 9 ± 1 cmH_2O , respectively. Cardiac output fell by 16% despite an average increase in heart rate from 67 to 82 beats/min. Pulmonary arterial mean pressure, related to atmospheric pressure, fell by 2 mmHg, while the pulmonary wedge pressure remained essentially unaltered. The systemic arterial mean pressure was significantly reduced.

Eleven patients displayed increased retention of the

poorly soluble gases (sulfurhexafluoride, ethane) and in nine patients the excretion of the highly soluble gases (ether, acetone) was reduced. Increased retention of gases of medium solubility (cyclopropane, enflurane) were noted in four patients (5, 7, 8, and 13). Calculation of the VA/Q distribution showed the appearance of a shunt as a major feature in all patients, ranging from 1 to 17% of cardiac output (fig. 1). In two patients (1 and 3) the shunt remained at 1% as under the awake condition. In two heavy smokers (5 and 13) the shunt increased only slightly, to 2–3%, but they were found to have a considerable blood flow, corresponding to 35 and 12% of cardiac output, within regions with low VA/Q ratios (fig. 2). Perfusion of poorly ventilated regions (low VA/Q regions) was also observed in another smoker (7) and an ex-smoker (8) (11 and 7% of cardiac output, respectively). Patient 6, who had low VA/Q regions when awake, displayed no such perfusion during anesthesia, but developed the largest shunt of all patients (17% of cardiac output). In addition, ventilation of high VA/Q regions ranging from 1 to 19% of the total ventilation was noted in nine patients. The dead space ventilation (including apparatus dead space) was slightly reduced to an average of 32%.

With an FI_{O_2} of 0.43–0.48, Pa_{O_2} ranged from 85 to 296 mmHg and Pa_{CO_2} from 26 to 50 mmHg. PA-a_{O_2} varied from 13 to 198 mmHg.

In 11 patients densities developed in dependent lung regions (examples are given in figs. 1 and 2), and they were somewhat larger in the caudal scan than in the scan positioned 5 cm more cranially (table 2). The largest density amounted to 7% of the total intrathoracic area. In two patients (1 and 3) no densities developed at all. In patient 11, who already had opacities in dependent regions when awake, these opacities widened from 2 to 6% and became more dense. Moreover, there was no vertical gradient within the density, contrary to the finding in the awake state. The smokers and the ex-smoker ($n = 8$) had no larger densities than the nonsmokers ($n = 5$) (3.4 and 2.7% in the caudal scan, respectively).

In fig. 3 the shunt has been plotted against the magnitude of the atelectasis in the most caudal exposure. A good correlation was observed, the two patients who did not develop atelectasis having shunts of 1% and the others exhibiting increasing shunt with increasing atelectasis. The regression equation was $y = 0.88 + 1.81x$ ($r = 0.84$, $P < 0.001$; $n = 13$) where y = shunt in per cent of cardiac output and x = atelectatic area in per cent of total intrathoracic area.

An inverse correlation between Pa_{O_2} in mmHg (y) and atelectatic area (x) in per cent of the intrathoracic area was observed according to:

$$y = 131 + 37.8 \frac{1}{x} \quad (r = 0.79; \quad P < 0.01; \quad n = 13)$$

If two patients were excluded, patient 5 with large perfusion of low VA/Q regions (hardly explained by the atelectasis), and 13 with markedly low cardiac output (causing further lowering of arterial oxygenation) the correlation became even stronger, the equation being:

$$y = 144 + 37.9 \frac{1}{x} \quad (r = 0.90; \quad P < 0.001; \quad n = 11)$$

The area was set at 0.25% in the two patients with no atelectasis (equal to the resolution of the method), so that the y value (Pa_{O_2}) should not become infinite. A smaller area would make the correlation even stronger.

Significant correlations were also observed between the atelectatic area in the cranial scan on one hand, and shunt and Pa_{O_2} on the other, although the correlation coefficients were slightly lower than for the regression on the caudal scan. It should be stressed that the regression equations are only valid within the range studied.

SPONTANEOUS VERSUS MECHANICAL VENTILATION DURING ANESTHESIA (TABLE 3)

Minute ventilation was greater during spontaneous breathing than during mechanical ventilation, and was achieved at an average rate of 20 breaths/min. Cardiac output was also higher, although the significance of this difference was borderline ($P = 0.05$).

One patient had regions of low VA/Q, with perfusion comprising 12% of cardiac output, under both conditions (13). All five patients had moderate shunts of an average 3.7% during spontaneous breathing, with a mean increase to 5% during mechanical ventilation (three patients showing an increase, two patients showing no change or a small decrease; an example is given in fig. 4.) High VA/Q regions were seen during spontaneous breathing, with no significant change on commencement of mechanical ventilation. The mean inert gas dead space, including apparatus dead space, was as high as 72% during spontaneous breathing and was reduced to 44% after intubation and commencement of mechanical ventilation. Pa_{O_2} was higher and $PA-a_{O_2}$ lower during spontaneous than during mechanical ventilation, and Pa_{CO_2} tended to be higher.

All five patients investigated during spontaneous breathing had densities in dependent lung regions under this condition, although no larger than 2%, on an average, in the caudal scan. The density area increased significantly during mechanical ventilation, to a mean of 3.5% in the caudal scan (fig. 4). No clearly significant correlation between atelectatic area and shunt was observed during spontaneous breathing in this small group ($r = 0.63$, $P = 0.10$, $n = 5$).

POSITIVE END-EXPIRATORY PRESSURE (TABLE 4)

The application of PEEP of 10 cm H_2O raised the maximum and end-inspiratory airway pressures from 11

TABLE 3. Gas Exchange, Central Circulation, and Atelectatic Areas in the Anesthetized Subject during Spontaneous Breathing and Mechanical Ventilation (zero end-expiratory pressure)

	V_z (l/min)	V_D (% V_z)	V_{IAP} (% V_z)	Q_{T1} (l/min)	Q_T (% Q_T)	Q_{sh} (% Q_T)	Pa_{O_2} (mmHg)	$PA-a_{O_2}$ (mmHg)	P_{aCO_2} (mmHg)	Vacular Pressures (mmHg)				Density Area (% total area)	
										Pulmonary Arterial		Systemic Arterial		1	2
										Mean	Wedge	Mean	Wedge		
Spontaneous breathing	6.55 ± 0.61	71.6 ± 3.9	4.4 ± 1.2	5.72 ± 0.31	3.7 ± 0.8	3.1 ± 3.1	174 ± 21	67 ± 23	52.4 ± 1.6	13.0 ± 1.8	5.8 ± 0.3	72 ± 4	72 ± 4	1.8 ± 0.8	1.0 ± 0.6*
Mechanical ventilation	4.95 ± 0.16†	42.4 ± 5.4§	1.2 ± 0.9	4.54 ± 0.39	5.0 ± 1.2	3.5 ± 2.4	150 ± 25†	99 ± 24†	45.6 ± 1.7†	12.2 ± 1.6	5.8 ± 0.8	55 ± 3†	55 ± 3†	3.5 ± 1.0†	2.4 ± 1.2*

* $n = 4$.

† Significantly different from spontaneous breathing; † $P < 0.05$; ‡ $P < 0.01$; § $P < 0.001$.

For abbreviations, see table 2.
 $n = 5$. Values are mean ± SE.

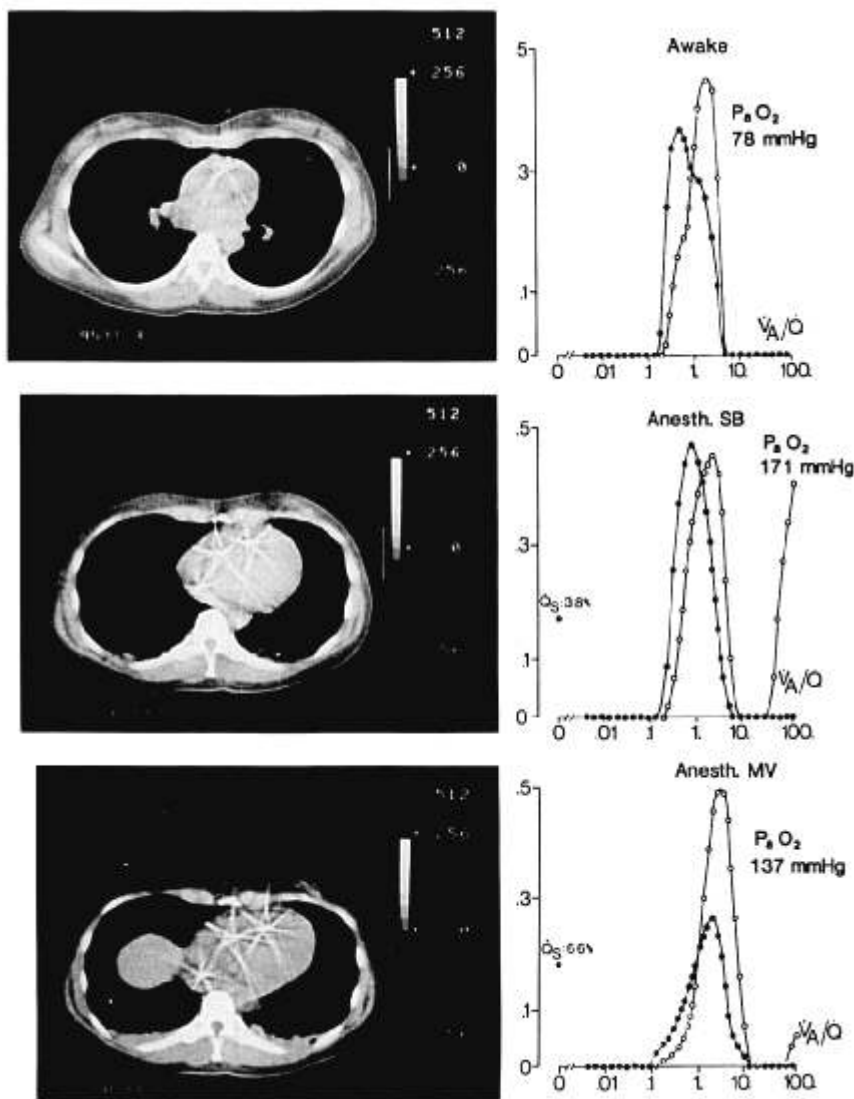


FIG. 4. Transverse CT scans of the chest and VA/Q distributions (O: ventilation, ●: blood flow, l/min) in patient 12 in the awake state (upper panel); during anesthesia, breathing spontaneously (SB, middle panel); and ventilated mechanically after muscle paralysis (MV, lower panel). Note the small atelectasis and the fairly large "high VA/Q" region during SB. During MV, the atelectatic area and the shunt increased.

± 0.5 and 8 ± 0.5 cmH₂O to 18 ± 0.5 and 15 ± 0.7 cmH₂O, respectively. Minute ventilation was slightly reduced during PEEP, and a slight increase in P_aCO_2 from 34 to 37 mmHg was noted. Cardiac output was reduced by 21% compared with that during mechanical ventilation without PEEP, and the pulmonary arterial mean and wedge pressures were increased by 4 mmHg. The systemic arterial mean pressure was not significantly altered.

With application of PEEP the shunt increased in three patients, decreased in one, and remained essentially unaltered in the other four (figs. 1, 2). In one patient the shunt increased to as much as 24% of cardiac output. Ventilation of high VA/Q regions and dead space showed mean increases of borderline significance. PaO_2 was, on an average, unaltered by PEEP, with individual changes in the opposite direction to the changes in shunt. The densities in dependent lung regions observed during mechanical ventilation were reduced by PEEP in all patients

(figs. 1, 2). There was no correlation between change in atelectatic area and change in shunt. However, a new relationship between shunt and atelectasis was noted during PEEP with a slope that was steeper than during mechanical ventilation without PEEP:

$$y = 2.57 + 3.55x \quad (r = 0.81; P < 0.01; n = 8)$$

where y = shunt in per cent of cardiac output and x = atelectatic area in per cent of the total intrathoracic area.

Discussion

The previous observation of a close correlation between the area of the atelectasis in dependent lung regions and the magnitude of shunt in anesthetized, paralyzed patients⁷ was confirmed in the present study on a larger sample. In addition, atelectasis and shunt were also ob-

served in the anesthetized, spontaneously breathing patient. The application of PEEP reduced the size of the atelectasis but had a varying effect on the shunt. These observations will be discussed in further detail below.

ATELECTASIS

The appearance of densities on CT scans of dependent lung regions within 5 min after induction of anesthesia has been interpreted as atelectasis caused by compression of lung tissue.⁴⁻⁶ In a total of 78 patients studied during anesthesia, 73 developed atelectasis (own data). The magnitude of the atelectasis varied from 0 to 11.8% of the total intrathoracic area. One patient in the present study, the first of all patients investigated so far, displayed densities in dependent regions when awake. The opacities were less dense and qualitatively different from those observed during anesthesia, with a vertical gradient in the attenuation that contrasted to the finding of homogenous attenuation all over the density during anesthesia. These differences give reason to consider that the opacities in this awake patient might have been caused by another phenomenon than creating the densities during anesthesia. They may be regions deprived of some gas, as for example after a period of continuous airway closure, or they may reflect congestion of dependent vessels.

GAS EXCHANGE AND ATELECTASIS DURING ANESTHESIA AND MUSCLE PARALYSIS

It has been shown earlier that the atelectatic area in dependent lung regions during anesthesia is perfused, as demonstrated by injections of radioopaque contrast.⁶ Such perfusion should result in a right-to-left shunt. In the present study we observed a correlation between the size of the atelectatic area and the magnitude of the shunt. Moreover, the regression line passed close to the origin, suggesting that the atelectatic area is a major cause of the shunt in the anesthetized subject without apparent lung disease. However, it must be made clear that the methods used do not enable a spatial analysis of the distribution of shunt, and it has therefore not been definitely linked to the atelectasis.

By creating shunt, atelectasis can be expected to impede pulmonary gas exchange. An inverse correlation was also observed, increasing the atelectatic area being accompanied by decreasing Pa_{O_2} . In addition, the two patients who did not develop atelectasis during anesthesia and muscle paralysis also had almost no shunt (1%) and normal arterial oxygenation ($PA-a_{O_2}$: 13–16 mmHg). These observations indicate that in the apparently lung-healthy subject, atelectasis in dependent lung regions is a major cause of impairment of arterial oxygenation during anesthesia and muscle paralysis, and in the absence of atelectasis gas exchange may be normal.

TABLE 4. Gas Exchange, Central Circulation, and Atelectatic Areas in the Anesthetized, Paralyzed, and Mechanically Ventilated Subject with Zero End-expiratory Pressure (ZEEP) and a Positive End-expiratory Pressure (PEEP) of 10 cm H_2O

	V_E (l/min)	V_D (% V_E)	$V_{D_{high}}$ (% V_D)	Q_T (l/min)	Q_T (% Q_T)	$Q_{D_{low}}$ (% Q_T)	Pa_{O_2} (mmHg)	$PA-a_{O_2}$ (mmHg)	$P_{a_{O_2}}$ (mmHg)	Vascular Pressures (mmHg)				Density Area (% total area)		
										Pulmonary Arterial			Systemic Arterial			
										Mean mmHg	Wedge mmHg	Mean mmHg				
ZEEP	5.56 ± 0.51	25.6 ± 3.8	9.3 ± 2.6	5.26 ± 0.35	7.5 ± 2.3	6.6 ± 4.3	181 ± 25	119 ± 25	33.8 ± 1.9	12.5 ± 0.3	8.6 ± 0.4	69 ± 3	2.9 ± 1.0	2.2 ± 0.7		
PEEP	5.01 ± 0.46*	30.1 ± 3.9	13.3 ± 3.4	4.15 ± 0.21†	8.3 ± 2.9	3.4 ± 2.9	178 ± 25	118 ± 23	36.5 ± 2.0†	16.4 ± 0.6‡	12.3 ± 0.6‡	67 ± 3	1.6 ± 0.8†	0.9 ± 0.7†		

For abbreviations, see table 2.
n = 8. Values are mean ± SE.

Significantly different from ZEEP: * $P < 0.05$; † $P < 0.01$; ‡ $P < 0.001$.

There were also additional causes of impaired gas exchange in the anesthetized subjects. This is illustrated by patient 5, a smoker with spirometric evidence of airway obstruction. In this patient (and to a lesser extent in three other smokers) a marked perfusion of regions with low VA/Q ratios was observed, and PaO_2 was lower than in patients with a similar shunt, but with no perfusion of low VA/Q regions. Airway closure has been demonstrated during anesthesia and may form the functional basis of lung regions with low VA/Q ratios. However, no firm relationship between gas exchange impairment and airway closure has been established.¹⁴⁻¹⁶

SPONTANEOUS BREATHING VERSUS MECHANICAL VENTILATION AND MUSCLE PARALYSIS

Both atelectasis and shunt were observed in the spontaneously breathing, anesthetized patient. Muscle paralysis was thus not a prerequisite for their development. Previous studies have shown that functional residual capacity (FRC) is reduced during most anesthetic procedures,³ mainly because of a cranial shift of the diaphragm as demonstrated by cineradiography¹⁷ and CT scanning.¹⁸ It is thus likely that anesthesia *per se* reduces or alters the tone of the diaphragm, and it is tempting to attribute the development of atelectasis to such change. Further study is required to resolve the exact mechanism.

Why there was an additional, although small, increase in atelectasis after muscle paralysis (table 2) remains also to be clarified. The diaphragm appears not to be moved further cranially,¹⁷ and FRC is not further reduced by paralysis compared with spontaneous breathing during anesthesia.¹⁹ It is possible that the altered movement of the diaphragm, the dependent part moving more during spontaneous breathing and less during paralysis, explains this difference.

Another observation, not strictly linked to the atelectasis, was the large dead space fraction during spontaneous ventilation, which explains the higher PaCO_2 during this condition than during mechanical ventilation. In addition, a certain fraction of ventilation was distributed to regions with high VA/Q ratios ($\text{VA/Q} > 10$). This ventilation will also act as a functional dead space, leaving no more than one-fourth of the total ventilation for effective alveolar gas exchange. The observations underscore the increased demand on ventilation that is caused by breathing through a face mask, as pointed out earlier by Kain *et al.*²⁰ They found that the functional dead space was 82 ml larger during mask breathing than after intubation (spontaneous breathing under both conditions). The present results show that the dead space, together with regions with high VA/Q, was 64 ml larger during spontaneous breathing through a mask than in the intubated, mechanically ventilated patient.

POSITIVE END-EXPIRATORY PRESSURE

The application of PEEP of 10 cmH₂O reduced the size of the atelectasis in the two CT scans, but it had no significant effect on the shunt. It may be argued that when PEEP was applied, atelectasis developed in more cranial regions not studied by CT scanning. However, an earlier study showed decreasing atelectatic areas with increasing distance from the diaphragm during mechanical ventilation with ZEEP.⁴ It seems unlikely that an increased intrathoracic pressure brought about by PEEP would create atelectasis in regions with minimal or no lung collapse, while reducing or eliminating those that already existed in basal regions. Also, application of PEEP in patients with acute respiratory failure significantly reduced the density regions in hilar and basal lung regions and caused mean reductions in apical areas.²¹

That PEEP may not improve arterial oxygenation in the lung-healthy anesthetized patient has been reported from previous investigations.^{22,23} However, the lack of an effect has been attributed to a reduced cardiac output, offsetting any beneficial effect on shunting. The results of the present study show that shunting may even increase with PEEP. This may indicate that the atelectasis is not the cause of the shunt. However, a more likely explanation is redistribution of blood flow toward dependent, atelectatic lung regions as a consequence of elevated intrathoracic pressure.²⁴ This interpretation gains support by the fact that a new relationship between atelectatic area and shunt during PEEP could be established with a steeper slope than during ZEEP, *i.e.*, fractional shunt blood flow was larger for a given atelectatic area during PEEP than during ZEEP.

It may thus be concluded that the development of atelectasis in dependent lung regions is a major cause of gas exchange impairment during halothane anesthesia, during both spontaneous breathing and mechanical ventilation, and that PEEP diminishes the atelectasis but not necessarily the shunt.

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