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Functional Residual Capacity, Thoracoabdominal Dimensions, and Central Blood Volume during General Anesthesia with Muscle Paralysis and Mechanical Ventilation

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Functional residual capacity (FRC), rib cage and abdominal dimensions (rc-ab), central blood volume (CBV), and extra vascular lung water (EVLW) were measured in six lung-healthy subjects awake and during halothane anesthesia, muscle paralysis, and mechanical ventilation. FRC was assessed by multiple breath nitrogen washout, rc-ab dimensions by computerized tomography, and CBV and EVLW by a double-indicator dilution technique (thermo-dye). During anesthesia, FRC decreased by 0.5 l (17%). The cross-sectional chest area was reduced by 12–20 cm^2, causing an approximate reduction in thoracic volume by 0.3 l. Concomitantly, the diaphragm was moved cranially by an average of 1.9 cm, diminishing the thoracic volume a further 0.5 l. The abdominal cross-sectional area did not alter significantly, despite the shift of the diaphragm. CBV decreased by 0.3 l. EVLW did not change significantly. It is concluded that the thoracic volume is reduced during halothane anesthesia, muscle paralysis, and mechanical ventilation as a result of cranial shift of the diaphragm and reduction in transverse area. The decrease in thoracic volume is accompanied by a reduction in FRC and a displacement of blood from the thorax to the abdomen, the transverse area of the latter thus being maintained despite the shift of the diaphragm. (Key words: Anesthetics, volatile: halothane. Lung: FRC; lung water; central blood volume; diaphragm.)

ACCORDING to most reports, the functional residual capacity (FRC) is reduced during general anesthesia. This holds true whether the subject is breathing spontaneously or is paralyzed, and whether the anesthesia is both induced and maintained by intravenous (barbiturate) agents or, after an intravenous induction, it is maintained by an inhalational agent (halothane).[1–6] Although a recurrent finding, the mechanisms underlying the FRC reduction are not understood clearly. Most measurements have been made with gas dilution techniques, which may cause an underestimation of FRC in the presence of closed-off lung regions (gas trapping) and regions with very poor ventilation. However, body plethysmography has been used in two studies, a method that will measure all gas in the lung, whether ventilated or not, and in both studies a reduction of FRC was observed.[5,6] A cranial displacement of the diaphragm has been demonstrated by means of cineradiography during both spontaneous breathing and muscle paralysis,[7] a change that could cause a decrease in FRC. However, measurements of thoracic and abdominal dimensions by means of magnetometry, strain gauge techniques, and inductive plethysmography have shown no alteration of the anteroposterior diameter, circumference, or area at the mamillary and umbilical levels on commencement of anesthesia and after muscle paralysis.[6,8,9] A reduction of FRC caused by a shift in the diaphragmatic level might be expected to cause an equal change in the position of the abdominal wall, but this was not observed.[6,8,9] This may imply that the techniques used to sense a change in the thoracoabdominal dimensions are not sufficiently sensitive or that the recording levels (mamillary and umbilical) do not reflect changes at other levels of the trunk. A third possible reason is that the decrease in FRC is accompanied or caused by pooling of fluid (blood) in the chest or abdomen. Some support for the idea of a redistribution of blood from the periphery (extremities) to the core (chest–abdomen) has been obtained by the observation of a slight reduction in thigh and upper arm volumes during general anesthesia.[10] However, the results of that study indicate no greater blood pooling in the trunk than approximately 0.1 l, which is not enough to explain the 0.4–0.7 l decrease in FRC. The mechanisms underlying the FRC

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reduction during general anesthesia thus are not understood completely.

The present study was undertaken to analyze in further detail the effects of general anesthesia, muscle paralysis, and mechanical ventilation on FRC, as measured by multiple breath nitrogen washout, and to relate any change to thoracoabdominal dimensions, as studied by means of whole body computerized tomography, and to the extravascular lung water and central blood volume, as measured by a double-indicator dilution technique.

Material and Methods

Six subjects (two men and four women) were studied. All were surgical patients who were judged to be free from cardiopulmonary disease on the basis of clinical examination, chest x-ray, and electrocardiography. Their mean age was 57 yr (range 38–76 yr), and they all had a normal body constitution, with a mean height of 167 cm (range 162–186 cm) and a mean weight of 73 kg (range 54–90 kg). Three patients were light to moderate smokers (10–15 cig/day). For the measurements the patients lay in the supine position prior to and during anesthesia before commencement of surgery. The patients gave their informed consent to participation in the investigation, which was approved by the Ethical and Isotope Committees of Huddinge Hospital.

ANESTHESIA

Premedication was given on request to three patients, prior to the catheterization, about 2 h before the awake measurements. Pethidine, 50 mg im, was used for two patients, and oxycodone, 7.5 mg, and scopolamine, 0.3 mg im, for the third patient.

Anesthesia was induced by thiopentone, 5.3 ± 0.7 mg/kg iv. Tracheal intubation was performed after induction of muscular relaxation by pancuronium bromide, 0.1 mg/kg iv. For maintenance of anesthesia, halothane was used in an inspired concentration of 0.5–1.0% in an oxygen–nitrogen mixture, the oxygen fraction being 0.4. The patients were ventilated mechanically at a rate of 12 breaths/min with a Servo 900 B® ventilator equipped with a heat-moisture exchanger and a carbon dioxide analyzer (Siemens-Elema). Minute ventilation was adjusted to maintain an end-tidal carbon dioxide concentration of 4–4.5%.

FUNCTIONAL RESIDUAL CAPACITY

The resting lung volume was measured by a multiple breath nitrogen washout technique, with collection of the expired gas in a Douglas bag. Oxygen administration was discontinued when the nitrogen concentration was less than 2%. The volume and the nitrogen concentration in the bag were measured, nitrogen being determined by an ionization method (Nitralyzer 505®, Med Science). FRC was calculated by the gas dilution formula of Darling *et al.*[11] The factor 1.09 was used for BTPS correction.

Only single determinations of FRC were performed for reasons of time. In previous studies in our laboratory, the coefficient of variation (standard deviation divided by mean value) for a single determination was 8%.

THORACIC AND ABDOMINAL DIMENSIONS

The shapes of the chest and abdomen were studied by computerized tomography (CT scanning). The subject lay supine on the table of the tomograph (Siemens Somatom 2®). The arms were stretched cranially to allow the subject to be moved into the aperture of the tomograph. A frontal tomogram covering the chest and the abdomen initially was obtained. Six exposures then were made, three over the chest and three over the abdomen. The positions of the exposures were determined by identifying the end-plate of the fourth lumbar vertebra. The lowermost abdominal exposure was obtained at this level, and two additional exposures were made at 7-cm distances in the cranial direction. The lowermost exposure of the thorax was made just above, or through, the cranial part of the diaphragm, and two further exposures were made at 5-cm distances in the cranial direction. The scan was obtained with the subject holding his breath at the FRC level. To ensure a true FRC, the subject, when awake, carefully was instructed to relax and not to tense his intercostal, abdominal, or diaphragm muscles. The exposure time was 5 s, and the exposure was commenced immediately at the onset of breath-holding. The breath-holding was required for obtaining sharp images. The thickness of each slice was 4 mm, and the absorbed skin dose was 7 mGy (700 mrad).

The transverse areas of the thorax and the abdomen obtained by these exposures were determined planimetrically, using the computer connected to the tomograph (fig. 1). The area of each hemithorax was calculated individually by drawing a sagittal line in the middle of the mediastinum. 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 included the mediastinal organs. The height of each hemithorax was obtained from the tomogram by measuring the distance from the top of the diaphragm to the apex of the lung. The volume of each hemithorax then was calculated by multiplying the transverse area by the height of that segment (up to the next projection

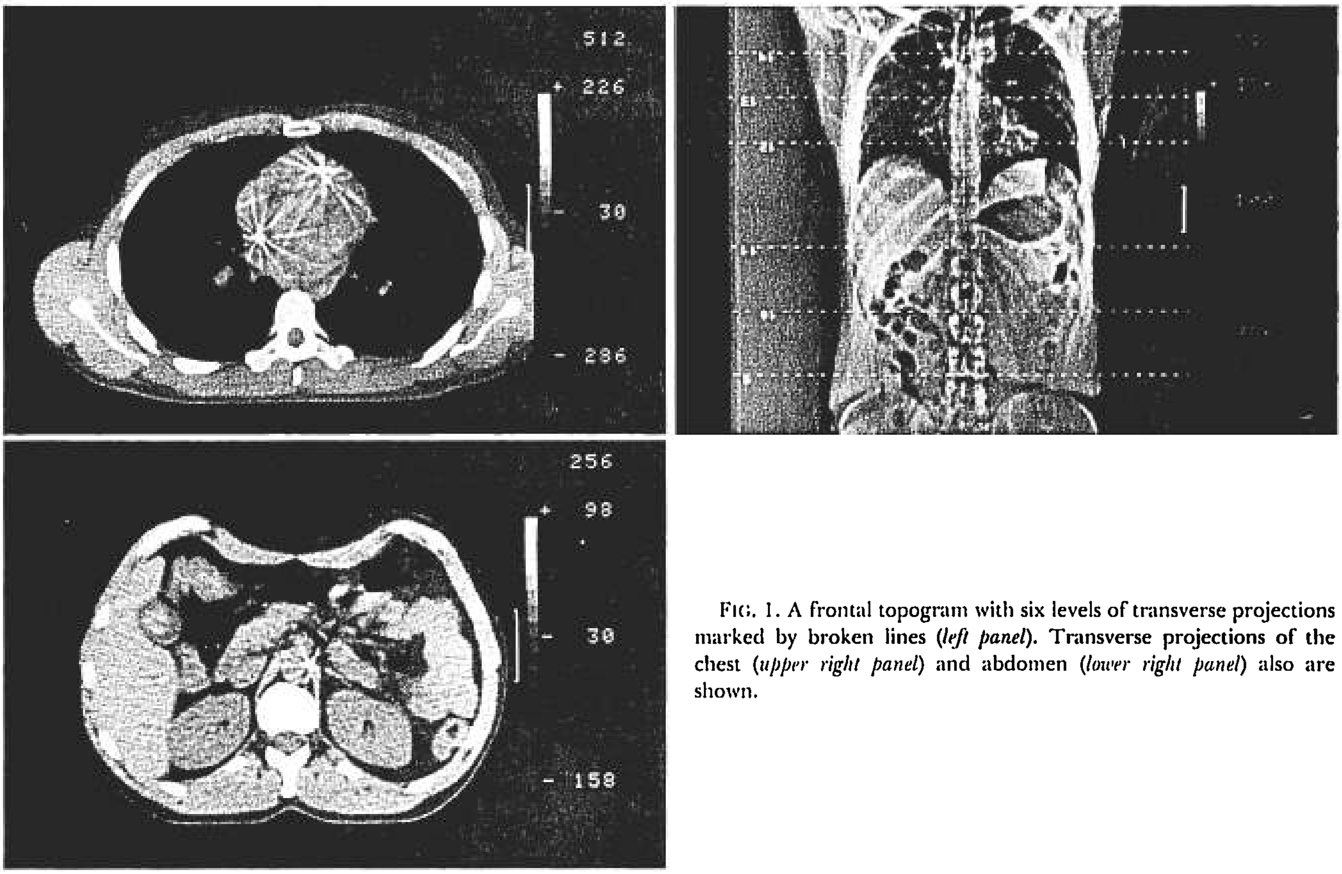


FIG. 1. A frontal topogram with six levels of transverse projections marked by broken lines (*left panel*). Transverse projections of the chest (*upper right panel*) and abdomen (*lower right panel*) also are shown.

or up to the apex). These volumes do not take into account the truncated cone shape of the apex, nor the dome shape of the diaphragm. However, the accuracy of the calculations was tested in a phantom experiment in which each centimeter of the thorax was sectioned tomographically and the volume calculated as described above. A comparison then was made between the thoracic volume calculated in this way and that obtained from three projections positioned as in the human measurements. The thoracic volume calculated on three projections was only 6% larger than that calculated on multiple projections, 1 cm apart. It also may be anticipated that a change in thoracic volume will be measured even more accurately.

The transverse areas of the abdomen were measured by the computer and included all abdominal tissue; thus, the boundary was the air–skin interface. The mean transverse area measured with the three projections was calculated and multiplied by the height from the lowermost abdominal projection to the top of the diaphragm to yield abdominal volume. This calculation did not include any abdominal volume caudal to the lowermost projection, corresponding to that part of the abdomen that is enclosed by the iliac bones and the sacrum.

Any volume change of the thorax and abdomen caused by a shift in the position of the diaphragm during anesthesia was calculated by multiplying the maximum shift of the diaphragm by a factor of 0.75, times the transverse area at the level of the lowermost thoracic projection. The factor was determined in a model analysis, taking into consideration the flattened shape of the diaphragm and the fact that its dorsal portion was attached to the wall more cranially than the frontal portion.

The reproducibility of CT measurements of the cross-sectional area was calculated in five subjects by repeating the lowermost thoracic exposure with a period of tidal breathing in between. The absolute mean difference between the two measurements was less than 2 cm^2, and the coefficient of variation in this limited number of experiments was less than 1%. On the other hand, the area of the diaphragm (the exposure was deliberately made through the top of the dome) varied by a mean of 12%, indicating that the position of diaphragm was subjected to a larger variation than the rib cage. This could be calculated to cause a variation in FRC by an average of 2%.

CATHETERIZATION AND "LUNG WATER" MEASUREMENTS

A Swan-Ganz® 7 F flow-directed thermal dilution catheter (Edwards Laboratories, Santa Ana, California) was introduced into an antecubital or femoral vein under local anesthesia and advanced to the pulmonary artery under fluoroscopic and pressure control. A thermistor-tipped fiberoptic catheter (5 F) was inserted by a sleeve technique into the femoral artery and advanced until its tip lay in the thoracic aorta. Cardiac output (CO) was measured by thermodilution both in the pulmonary artery with the Swan-Ganz® catheter connected to a CO computer (Edwards Laboratory model 5720) and in the aorta (see below) with a "lung water computer" (Partig, System Cold). A 10-ml bolus of 5% glucose containing 4 mg of indocyanine green dye at 0–2°C was used for these measurements.

The total thermal volume (TTV) (distribution volume for temperature between the injection point and sampling point, right atrium—thoracic aorta), central blood volume (CBV) (distribution volume for dye), and "extravascular lung water" (EVLW) (the difference between TTV and CBV) were measured with the lung water computer system. The indicator bolus was injected automatically in 1 s into the right atrium with a temperature-controlled syringe. The dilution curves for dye and temperature were recorded from the aorta with the thermistor-tipped fiberoptic catheter and were recorded as a function of time by the computer, which calculated the mean transit times (MTT) for the indicators. This system offers the advantage of not requiring withdrawal of blood, it rules out the possible distortion of the dye curve in a pump–cuvette system, and it permits simultaneous recording of the two indicators at one and the same point in the vascular tree. This allows calculation of the transit time of each indicator and not only of the difference between the two transit times as in most other systems.[12]

TTV was calculated as follows:

$$\mathrm{TTV} = \mathrm{CO} \cdot \mathrm{MTT\ thermo}$$

CBV was calculated as follows:

$$\mathrm{CBV} = \mathrm{CO} \cdot \mathrm{MTT\ dye}$$

EVLW was calculated as follows:

$$\mathrm{EVLW} = \mathrm{TTV} - \mathrm{CBV}$$

The temperature of the injected solutions that was used in the calculations was corrected for catheter dead space, taking into consideration the different proportions of the catheter that lay intravascularly and in the room air. All measurements were made five times, the injections being distributed randomly over the respiratory cycle. The first measurement was discarded, since the temperature of the injected bolus (cather portion) was different from that in the succeeding injections. The mean value of the four measurements was used for statistical analysis.

The error of the method was calculated on the variance of the four measurements in each subject when awake and in another 13 subjects not recorded in this study, thus in a total of 19 subjects. The standard deviation of the CBV measurement was 226 ml and the coefficient of variation 12%; the corresponding values for the EVLW recording were 1.2 ml/kg and 14%, respectively.

Statistics. Standard statistical methods were employed, with Student's paired t test when applicable. Results are presented as mean ± standard error (SE).

Procedure. A half-hour after the catheterization and the transportation of the subject to the x-ray department, recordings were made of central hemodynamics, CBV and EVLW, and FRC, all during resting breathing in the supine position. The CT scans then were obtained during 5-s breath-holds at the FRC level. Since the x-ray study included one frontal topogram and six scans, the subject had to keep his breath at seven occasions with 30 s of resting breathing between each breath-hold. Fifteen minutes after induction of anesthesia, central hemodynamics, CBV, EVLW, and FRC again were measured during mechanical ventilation. The six CT scans then were obtained at the FRC level, during 5-s apnea periods, one for each scan, with 30-s periods of mechanical ventilation in between. After the completion of the study, the subject was moved to the operating theater.

Results

CENTRAL HEMODYNAMICS AND ARTERIAL BLOOD GASES (TABLE 1)

CO measured by thermodilution in the pulmonary artery and the pressures in the right atrium (RA), pulmonary artery (PA), wedge position (PCW), and aorta (AO) were all within normal limits in the awake subject.[13] Arterial blood gases also were within the normal range.[14] After 15 min of anesthesia and mechanical ventilation, CO had decreased by almost 2 l/min, corresponding to a 31% reduction. CO measured by thermodilution in the aorta was, on the average, 15% higher than that measured in the pulmonary artery (awake: 7.25 ± 0.70 l/min; anesthetized: 5.12 ± 0.74 l/min, cf. table 1). The difference was significant ($P < 0.01$) and conforms with previous comparisons of thermodilution recordings in the pulmonary artery and

TABLE 1. Central Hemodynamics and Arterial Blood Gases ($\bar{x}$ ± SE)

	Cardiac Output‡ (l/min)	Heart Rate (beats/min)	$\bar{P}_{RA}$ (mmHg)	$\bar{P}_{PA}$ (mmHg)	$\bar{P}_{PCW}$ (mmHg)	$\bar{P}_{AO}$ (mmHg)	Pa_{O_2} (mmHg)	Pa_{CO_2} (mmHg)
Awake	6.35 ± 0.70	76 ± 3	6.5 ± 1.4	14.0 ± 0.5	7.8 ± 1.2	102 ± 5	80 ± 5	40 ± 1
Anesthetized	4.38* ± 0.47	72 ± 2	5.5 ± 1.1	13.2 ± 0.6	7.4 ± 1.1	80† ± 7	118† ± 19	38 ± 1

$\bar{P}$ = mean pressure.
For other abbreviations, see text.
* Significantly different from the awake value: $P < 0.05$.
† Significantly different from the awake value: $P < 0.01$.
‡ Measured in the pulmonary artery.

aorta.[15] The reduction in CO on commencement of anesthesia was of the same magnitude when CO was determined by thermodilution in the pulmonary artery and in the aorta. The mean RA, PA, and PCW pressures relative to atmospheric pressure were not altered significantly, while the mean AO pressure was reduced significantly by approximately 20 mmHg. Arterial oxygen tension was increased, the inspired oxygen fraction having been increased during anesthesia. Arterial carbon dioxide tension essentially was unchanged.

FRC AND THORACOABDOMINAL DIMENSIONS (TABLE 2)

In the awake state, FRC was, on an average, about 3 l, which corresponds well with the expected reference value[16] (see table 2). Since FRC was determined with the arms down along the chest, whereas the CT scanning was performed with the arms stretched cranially, a comparison of FRC with the arms up and down was made in four healthy, awake volunteers not participating in other parts of the study. No difference was noted, the mean FRC with the arms down being 2.14 l and with the arms up 2.17 l.

The cross-sectional areas obtained by the CT scanning ranged from a mean of approximately 220 cm^2 at the uppermost level of the rib cage to a mean of 470 cm^2 at the upper level of the abdomen, with a small reduction further down at the two lower abdominal levels. The calculated thoracic volume was approximately 5 l, including the lungs and mediastinal organs. The calculated abdominal volume was almost 10 l.

During anesthesia, FRC was reduced by 0.51 l, corresponding to a 17% reduction. The cross-sectional areas of the chest were reduced by 13–20 cm^2, and this reduction was statistically significant at the two lower levels (table 2). Small, nonsignificant reductions, 6–8 cm^2, were noted in the abdominal cross-sectional areas. The diaphragm moved cranially, the major part of the dome by an average of 1.9 cm. The net effect of the reduced rib cage dimensions (diminished cross-sectional areas) and the cranial shift of the diaphragm was a reduction in thoracic volume by 0.75 l and thus by 0.24 l more than the reduction in FRC. The abdominal volume increased by an average of 0.34 l as a consequence of the shift in the diaphragmatic level and the minor changes in the cross-sectional areas.

LUNG WATER (TABLE 3)

The total "lung water" was 2.31 l in the awake state. The central blood volume constituted almost 75% of the lung water (1.70 l) and included not only the lung blood volume but also the blood in the heart chambers and part of the systemic arteries. This value is in good accordance with previous results.[17] EVLW was around 0.6 l, corresponding to 8 ml/kg body weight. During anesthesia the total lung water was reduced by an average of 0.34 l, which was almost entirely due to a diminution of CBV (0.29 l). There was a small and nonsignificant decrease in EVLW.

In four other subjects, CBV and EVLW were measured both during mechanical ventilation and after 15–20 s of apnea. During apnea, CBV and EVLW increased by 0.26 ± 0.05 l and 0.08 ± 0.01 l, respectively.

TABLE 2. FRC and Chest and Abdominal Dimensions ($\bar{x}$ ± SE)

	Cross-sectional Areas (cm^2)							Cranial Shift of Diaphragm (cm)	Thorax Volume (l)	Abdomen Volume (l)
	FRC (l)	Lungs (rib cage)			Abdomen					
		Upper	Middle	Lower	Upper	Middle	Lower			
Awake	3.08 ± 0.37	222 ± 18	308 ± 22	348 ± 25	473 ± 37	441 ± 45	443 ± 43	0	4.87 ± 0.39	9.87 ± 0.99
Anesthetized	2.57* ± 0.43	206 ± 19	288* ± 21	335† ± 26	467 ± 40	435 ± 44	435 ± 40	1.9* ± 0.5	4.12* ± 0.41	10.21† ± 1.06

* Significantly different from the awake value: $P < 0.01$.
† Significantly different from the awake value: $P < 0.05$.

TABLE 3. Total Thermal Volume (TTV) and its Subdivisions: Lung (central) Blood Volume (CBV) and Extravascular Lung Water (EVLW) ($\bar{x}$ ± SE)

	TTV l	CBV l	EVLW l
Awake	2.31 ± 0.18	1.70 ± 0.13	0.61 ± 0.09
Anesthetized	1.97* ± 0.17	1.41† ± 0.12	0.57 ± 0.05

* Significantly different from the awake value: $P < 0.01$.
† Significantly different from the awake value: $P < 0.05$.

Discussion

The well-documented decrease in FRC during general anesthesia, muscle paralysis, and mechanical ventilation was verified in the present study using the multiple breath nitrogen washout technique. The reduction amounted to about 0.5 l, corresponding to a 17% decrease when compared with the awake value. This is in good accordance with previous results.[2,3,5,6] It should be mentioned that all of these studies, including the present one, have in common that barbiturates were used for induction or for the whole anesthesia. There are a few reports of an unchanged FRC during inhalational anesthesia with no use of barbiturates.[18,19] However, an indirect method of measuring FRC was used in one study (fractional analysis of multiple breath nitrogen washout rendering it less accurate—the study was mainly aimed at studying gas distribution.[19] This leaves one study with a conventional technique that still showed an unaltered FRC with inhalation anesthesia. However, in another study, measurements more than 30 min after the barbiturate induction, with maintenance of anesthesia by halothane, *i.e.*, at a time when most of the barbiturate effects had subsided, revealed a stable reduction of FRC.[3] Thus, it seems reasonable to conclude that general anesthesia, whether intravenous (barbiturates) or inhalational (halothane), causes a decrease in FRC.

DIAPHRAGM

The observation of a cranial movement of the diaphragm during anesthesia is in agreement with the finding by Froese and Bryan with use of cineradiography.[7] No detailed analysis of the configuration of the diaphragm was undertaken in the present study; this would have required additional transverse projections through the dome, which was not possible for radiation dose reasons.

RIB CAGE

The observation at CT scanning of a decrease in the transverse rib cage area is at variance with previous findings at the mamillary level with magnetometry (sagittal diameter), a strain gauge technique (circumference), and inductive plethysmography (area).[6,8,9] The reason for this discrepancy may be that different areas (or distances) were measured, with CT scanning the area enclosed by the inner margin of the ribs, whereas with external sensors the ribs and the tissue outside them also would be included. An area reduction of 12–18 cm^2 will correspond to a change in body surface diameter of about 0.4 cm and in circumference of about 1.3 cm, distances that lay at the limits of detection by magnetometry and the strain gauge technique.[6] It is also worthy of note that in the present study the area reduction at the mamillary level (the same level as tested in earlier studies) did not reach statistical significance, in contrast to the reduction at the other two levels.

ABDOMEN

Interestingly, there was no significant change in the transverse abdominal areas, although a small mean reduction was noted. This is in accordance with previous findings on the abdominal dimensions with use of external sensors[6,8] (here the same area was measured by tomography and external sensors, in contrast to the chest area measurement). Since the diaphragm moved cranially on commencement of anesthesia, corresponding to a volume change of approximately 0.5 l, one would have anticipated a reduction of the transverse abdominal area of about 25 cm^2. This change is greater by far than the sensitivity limits of the method. An increased volume of abdominal gas could cause a cranial shift of the diaphragm with no change, or an outward shift, of the abdominal wall. However, the CT scans showed no increase in abdominal gas, and direct measurements in animals indicate that no such increase occurs during halothane anesthesia, without nitrous oxide.[20]

CENTRAL BLOOD VOLUME

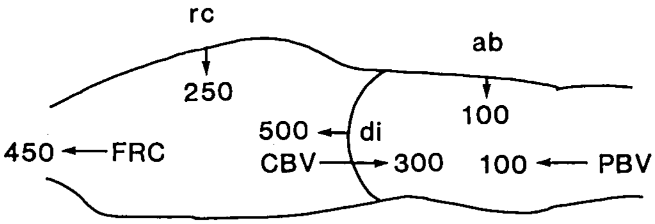
The results described so far, namely a reduced FRC, cranial shift of the diaphragm, and an essentially unaltered position of the abdominal wall, may appear contradictory. However, there was also a shift of blood from the thorax, *i.e.*, of the central blood volume, to extrathoracic locations. In a previous study using segmental thigh and upper arm plethysmography, it was found that there was no blood pooling in the extremities on induction of general anesthesia.[10] On the contrary, a small reduction in segmental volumes was noted, suggestive of an overall displacement of blood from the extremities to the body core of about 0.1 l (assuming that there was no significant pooling in the head). This would indicate that the abdomen receives blood upon induction of general anesthesia, muscle paralysis, and mechanical ventilation both from the thorax and from the extremities, the blood volumes amounting to an average of 0.3 and 0.1 l, respectively. These volume displacements will explain the almost maintained transverse abdominal areas during anesthesia.

It should be stressed that when the mechanical ventilation was discontinued for a period of 15–20 s, the central blood volume returned to the awake value. This indicates that intermittent positive-pressure ventilation has an impact on the distribution of blood volume. Whether any redistribution of blood occurred during the short apnea required for the CT scanning can not be ruled out but every effort was made to shorten the apnoic period as far as possible. Interestingly, there are a few reports from the early 1950s on a reduced central blood volume in anesthetized, spontaneously breathing subjects, using the same principles but more laborious technique than in the present study.[21,22]

On basis of the shifts in CBV, it therefore is concluded that the reduction in FRC cannot be explained by blood pooling within the thorax, neither during anesthesia and muscle paralysis *per se,* nor by the addition of mechanical ventilation. The well-known fall in lung compliance during anesthesia[23,24] also must be attributed to events other than blood pooling in the thorax.

THORACOABDOMINAL DIMENSIONS, NET EFFECTS

Summing up the volume shifts during general anesthesia and mechanical ventilation, the following balance is obtained (fig. 2). The reduction in rib cage transverse areas, times the average lung height (15.7 cm), results in an approximate volume reduction of 250 ml. In addition, the diaphragm is moved cranially by a distance corresponding to a volume reduction of about 500 ml. This results in a total loss in thoracic volume of 750 ml. (This is a simplified calculation—the effects on thoracic volume of the simultaneous changes in transverse area and diaphragm position cannot be separated clearly.) Gas is expelled through the mouth and nose, resulting in a reduction of FRC by around 450 ml (to make a *balanced* account), and a blood volume of 300 ml is moved out of the thorax. This results in a total gas-blood volume loss of 750 ml, balancing the reduction in thoracic volume. The cranial shift of the diaphragm adds 500 ml to the abdominal volume, and the small reduction in transverse areas reduces the volume by approximately 100 ml, ending up with a net increase of 400 ml. This increase is made up of 300 ml of blood from the thorax and another 100 ml from the extremities.



Thoracic volume

thoracic area	– 250 ml	FRC	– 450 ml
diaphragm shift	– 500 ml	CBV	– 300 ml
	– 750 ml		– 750 ml

Abdominal volume

abdominal area	– 100 ml	CBV	+ 300 ml
diaphragm shift	+ 500 ml	PBV	+ 100 ml
	+ 400 ml		+ 400 ml

FIG. 2. Mean changes in thoracic and abdominal dimensions and in gas and blood volumes after induction of general anesthesia and mechanical ventilation. Data from the present study and a previous one on peripheral blood volume[11] have been "smoothed" to fit each other. Volumes in milligrams. rc = rib cage; di = diaphragm; ab = abdomen; CBV = central blood volume; PBV = peripheral blood volume.

POSSIBLE CAUSE OF CHEST VOLUME REDUCTION

So far the discussion has dealt with the components involved in the reduction of FRC during general anesthesia, muscle paralysis, and mechanical ventilation. While these appear to be explained clearly by the present findings, the underlying causes remain unresolved. Some points may be mentioned, however. In the awake subject, abdominal pressure is higher than intrathoracic pressure (at FRC) and the vertical abdominal pressure gradient, around 1 cmH_2O/cm distance, is higher than the pleural pressure gradient, which is approximately 0.2–0.4 cmH_2O/cm.[25,26] These differences in pressure and gradient can exist only if the diaphragm is tense. If it is relaxed, and no longer offering resistance to abdominal pressure, the abdominal pressure will be transmitted to the pleural space. An increased vertical pleural pressure gradient has been observed on relaxing the diaphragm from a voluntarily tense state in awake subjects.[27] Moreover, findings on regional lung volume and pressure-volume curves of each lung in the lateral position in anesthetized subjects suggest an increased verticle pleural pressure gradient of about 1 cmH_2O/cm.[28,29] These observations would fit with a relaxation of the diaphragm as the initial change in the chest–abdominal dimensions, the other events possibly being secondary. Thus, there appears to be an interaction between the rib cage and the diaphragm.[30] Tensing the latter will expand the rib cage, the diaphragmatic dome being supported by the abdominal organs. Relaxing the diaphragm will cause a narrowing of the rib cage, as was found here. It is also conceivable that relaxation of the diaphragm causes the minor shift of blood from the extremities to the trunk (abdomen) shown in a previous study.[10] The additional blood shift from the thorax to the abdomen that occurred with mechanical ventilation (intermittent positive-pressure ventilation) is explained reasonably by the increase in intrathoracic pressure, reducing transmural vascular pressure, not only in the lung but also in the heart and the systemic veins in the thorax.

Conclusion

In conclusion, general anesthesia with muscle paralysis and mechanical ventilation causes changes in the volumes of gas and blood, both in the chest and in the abdomen. Thus, the diaphragm is displaced cranially and the rib cage aperture is narrowed to a lesser degree. This is accompanied by a decrease in FRC and a shift of blood from the thorax to the abdomen, which also may receive a minor fraction of the blood from the extremities. By these means the position of the abdominal wall almost is maintained. Relaxation of the diaphragm may be the initial cause of the lowered FRC and increased intrathoracic pressure by mechanical ventilation the reason for a reduced central blood volume.

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