Left Lower Lobe Ventilation Is Reduced in Patients with Cardiomegaly in the Supine But Not the Prone Position[1-3]

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SUMMARY To determine the effect of the heart on regional ventilation, Krypton-81m (^{81m}Kr) tomographic (SPECT) ventilation scans were recorded in seven patients with cardiomegaly and four normal subjects in the supine and prone positions. All patients had a cardiothoracic ratio of greater than 0.50 and clear lung fields radiographically. Using standard gamma camera tomographic reconstruction techniques, images of transaxial slices were obtained during a 360 degree rotation around the thorax of the subject breathing the radioactive gas ^{81m}Kr. The transaxial images, acquired over 10 min were aligned in each posture at the level of the cardiac apex, mid-heart, and aortic arch and were matched in relation to a radioactive marker on the chest wall and to anatomic landmarks. A horizontal line (gravity independent and parallel to the couch) was drawn on the transaxial section through the dorsal regions of the right and left lung. Counts per resolution element (12 to 15 mm) were plotted along this line and the ratios of the peak values in right and left lung compared. These ratios represent differences in regional ventilation per unit lung volume. In controls the mean left-to-right (L/R) peak count ratio varied from 0.91 to 1.00 at the three levels (range: 0.76 to 1.04); there were no significant differences between supine and prone. In patients with cardiomegaly the mean (±SEM) L/R peak count ratio at cardiac apex, mid-heart, and aortic arch was 0.46 (± 0.08), 0.55 (± 0.07), and 0.89 (± 0.08) when supine and 1.04 (± 0.07), 1.05 (± 0.05), and 1.08 (± 0.07) when prone, respectively. There was a significant increase in L/R ratio from supine to prone at the cardiac apex and mid-heart levels. These increases were also present when percent total counts for each lung in the whole transaxial slice were compared. In patients with cardiomegaly, there was a reduction in left mid and lower zone ventilation in the supine posture that was probably related to the mass of the heart compressing the lung, leading to airway and/or alveolar closure.
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Introduction

Much is known about how changes in lung volume can cause changes in cardiac function (1). But, in adults, little is known quantitatively regarding the effect of changes in heart volume on ventilation. Qualitatively, an area of dullness with bronchial breath sounds and bronchophony below the angle of the left scapula in patients with large pericardial effusion or massive cardiomegaly (Ewart's sign) was described in the last century (2). Using modern techniques (radioactive gases), regional ventilation has been measured in adult patients with cardiomegaly (mostly studied in *seated erect* position) (3). ^{133}Xe washout was prolonged in the left lower zone in six out of 42 patients (right lower zone cleared more slowly in three) but this was not associated with the degree of cardiomegaly.

In infants with congenital heart disease, compression of the left main or lower lobe bronchus leading to atelectasis is well described. A dilated left main pulmonary artery (4) or left atrium (5) is usually held responsible. Reduction in caliber of the left lower lobe pulmonary arteries has been seen in adults with cardiomegaly undergoing pulmonary angiography (6); the appearances returned to normal when subjects turned from supine to a left anterior oblique position. Compression of the left lower lobe leading to collapse of the lobar bronchus, on the other hand, has not been observed in adults with cardiomegaly. Nevertheless, lower lobe collapse occurs postoperatively three times more frequently on the left than on the right side (7) and the relative frequency increases after cardiac surgery.

The effect of cardiomegaly on regional lung function is likely to be influenced by body position since changes of posture are accompanied by changes in the distribution of blood flow and ventilation. While most of these changes can be related to the influence of gravity acting through the weight of the lung itself, little is known about the effects of the mediastinum and the heart on regional lung function. For example, the ventral-dorsal (or dorsal-ventral) gradient of regional ventilation is considerably smaller in the prone compared to the supine posture (8–10). This may be related to movement of the heart and mediastinum shown on computed tomography (CT) scanning (11).

We postulated that if an enlarged heart compressed the left lower lobe in the supine position and compromised local ventilation, relief would be afforded by turning to the prone position because the heart would rest on the ventral chest wall rather than the lung. Therefore, we measured the effect of changing from the supine to prone posture on the relative ventilation to the left and right dorsal lung regions in patients with cardiomegaly compared to control subjects. Because a change of posture itself alters the geometry and tissue attenuation for two-dimensional counting devices, we undertook three-dimensional reconstruction of regional ventilation using single photon emission computed tomography (SPECT) and the steady-state technique of continuous inhalation of ^{81m}Krypton (^{81m}Kr) gas (12).

Methods

Subjects

After giving informed consent, seven patients were chosen on the basis of cardiomegaly as

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measured by a cardiothoracic ratio of greater than 0.50 (table 1). All patients had clear lung fields and no pleural effusion on PA chest X-ray. The mean cardiothoracic ratio for the patients was 0.66 (table 1). Four patients had hypertensive heart disease, two had idiopathic dilated cardiomyopathy, and one had combined aortic and mitral valve disease. Four normal volunteers (three nonsmokers, one smoker) served as controls. The normal subjects did not have chest X-rays.

Tomographic Ventilation Scanning

SPECT ventilation scans were performed as previously described (10) with an IGE 400T gamma camera interfaced with an MDS A2 computer system, taking 64 10-s images during a 360 degree rotation around the subject's thorax. The spatial resolution was 12 to 15 mm. Patients and controls were scanned supine and then prone with abdomen and chest resting on the couch, and with their arms above their head and out of the imaging field, Arterial oxygen saturation was measured with pulse oximetry (Biox II; Ohmeda, Beaverton, OR). The images were filtered and back projected, and tomographic transaxial reconstructions (slices 12-mm thick) were made from the 64 planar images. A radioactive marker was placed laterally over the chest to allow for comparison of prone and supine reconstructions. During the imaging, patients and controls breathed ^{81m}Kr in air through a face mask at a flow of 1.0 L/min. ^{81m}Kr was eluted continuously from a ^{81}Rb source produced by the MRC Cyclotron Unit at Hammersmith Hospital. Subjects were instructed to breathe normally during the study.

Analysis

Tomographic slices (12-mm thick) at the level of the cardiac apex (away from the diaphragm), mid-heart, and aortic arch were chosen for analysis. Volumes of lung below the system resolution (less than 15 × 15 mm) would occur only behind the diaphragm, i.e., more caudal than the images at the cardiac apex. A one-pixel thick (6 mm) horizontal line, parallel to the couch, was drawn through the dorsal lung regions at each anatomic level in the supine and prone scans for comparison of left/right (L/R) ratios of *peak* counts along the line (figure 1), the counts being averaged over the 12 to 15 min duration of the scan. The line was placed to cross through the dorsal region(s) of the left lung with the greatest ventilation in the supine posture, and was kept in the same location for analysis of the prone scans. In addition, the percentage of total ventilation to each lung cross section at the three levels was calculated by outlining the right and left lung section at a threshold level of 10 to 15% of average pixel count and dividing the counts in the slice for each lung by the sum of the counts within the slice for both lungs. We then compared L/R ratios of percent total lung counts in the slice. Comparisons between L/R peak count ratios and total lung count ratios at each anatomic level were made for the prone and supine positions.

TABLE 1

PATIENT CHARACTERISTICS

Patient No.	Age/Sex/Smoking*	Diagnosis	Cardiothoracic Ratio
1	36/M/NS	Dilated Cardiomyopathy	0.65
2	48/M/25	Dilated Cardiomyopathy	0.67
3	69/F/10	Valvular Disease	0.73
4	72/M/NS	Hypertensive	0.71
5	66/M/NS	Hypertensive	0.60
6	76/F/NS	Hypertensive	0.68
7	56/M/NS	Hypertensive	0.55

* Smoking status: NS = non-smoker; number = cigarettes per day.

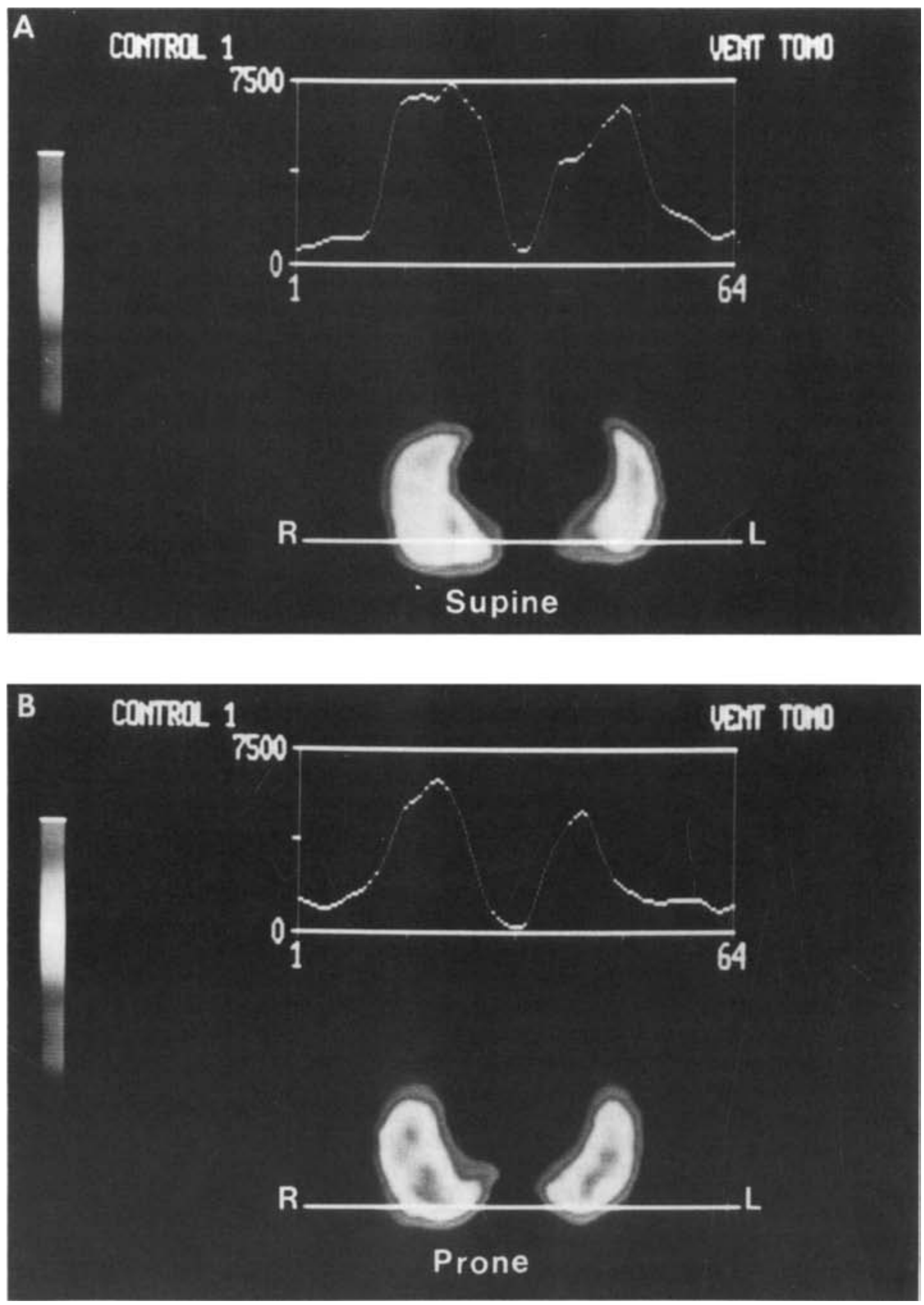

Fig. 1. Transaxial reconstructions of ventilation at mid-heart level in a normal subject with profile of counts per pixel plotted against distance along a horizontal strip from right to left lung near the dorsal border. Note approximately equal peak counts in right and left lung in both supine (A) and prone (B) positions.

Comparisons of supine and prone L/R percent total count and peak count ratios were made using the paired *t* test with $p < 0.05$ indicating significant differences between the postures.

Results

The group results for the four control subjects are given in table 2. The L/R ratio of peak counts was close to unity at all three anatomic levels and there was no difference between supine and prone at each level. Figure 1 is an example, in a control subject at the mid-heart level, of the analysis of peak counts per pixel. The maximum value in this instance was slightly greater in the right than in the left lung for both the supine and prone positions. The L/R ratio of percent total counts for each lung varied between 0.77 and 0.97 (the area of the left lung being about 10% less than the right) and again, there were no significant supine-prone differences (table 2).

At the mid-heart level in a patient (Figure 2) there was a substantial reduction in peak counts in the left lung in the supine posture, which was abolished when the subject lay prone. No significant supine-prone differences were evident at a more cephalad level (aortic arch) in the thorax in the same patient (Figure 3).

The data for all the patients are summarized in figures 4 and 5. There were significant increases in L/R percent total count and peak count ratios from supine to prone at the mid-heart and cardiac apex levels. There were no changes in oxygen saturation or pulse rate in the supine (mean Sa_{O_2} 95%, pulse 93 min^{-1}) compared to the prone position (mean Sa_{O_2} 96%, pulse 95 min^{-1}).

TABLE 2

LEFT/RIGHT (L/R) RATIOS OF PEAK AND % TOTAL COUNTS (DURING ^{81m}KR INHALATION) IN DORSAL LUNG REGIONS IN FOUR NORMAL VOLUNTEERS*

	L/R Peak Counts					
	Arch		Mid-heart		Apex	
	S	P	S	P	S	P
1	0.76	0.88	0.78	0.79	0.92	0.95
2	0.88	0.98	0.88	1.04	0.82	1.01
3	0.99	1.04	0.99	0.98	0.93	1.03
4	1.02	1.04	0.98	1.00	1.03	1.03
Mean	0.91	0.99	0.91	0.95	0.93	1.00
SEM	0.06	0.04	0.05	0.06	0.04	0.02
	L/R % Total Counts					
1	0.72	0.69	0.82	0.79	0.76	0.82
2	0.89	1.04	0.89	0.92	0.75	1.08
3	0.89	0.92	0.82	0.82	0.67	1.13
4	0.85	0.85	0.82	0.82	0.89	0.85
Mean	0.84	0.88	0.84	0.84	0.77	0.97
SEM	0.04	0.07	0.02	0.03	0.05	0.08

Definition of abbreviations: S = supine; P = prone.

* For tomographic slices at the level of the aortic arch, mid-heart, and cardiac apex.

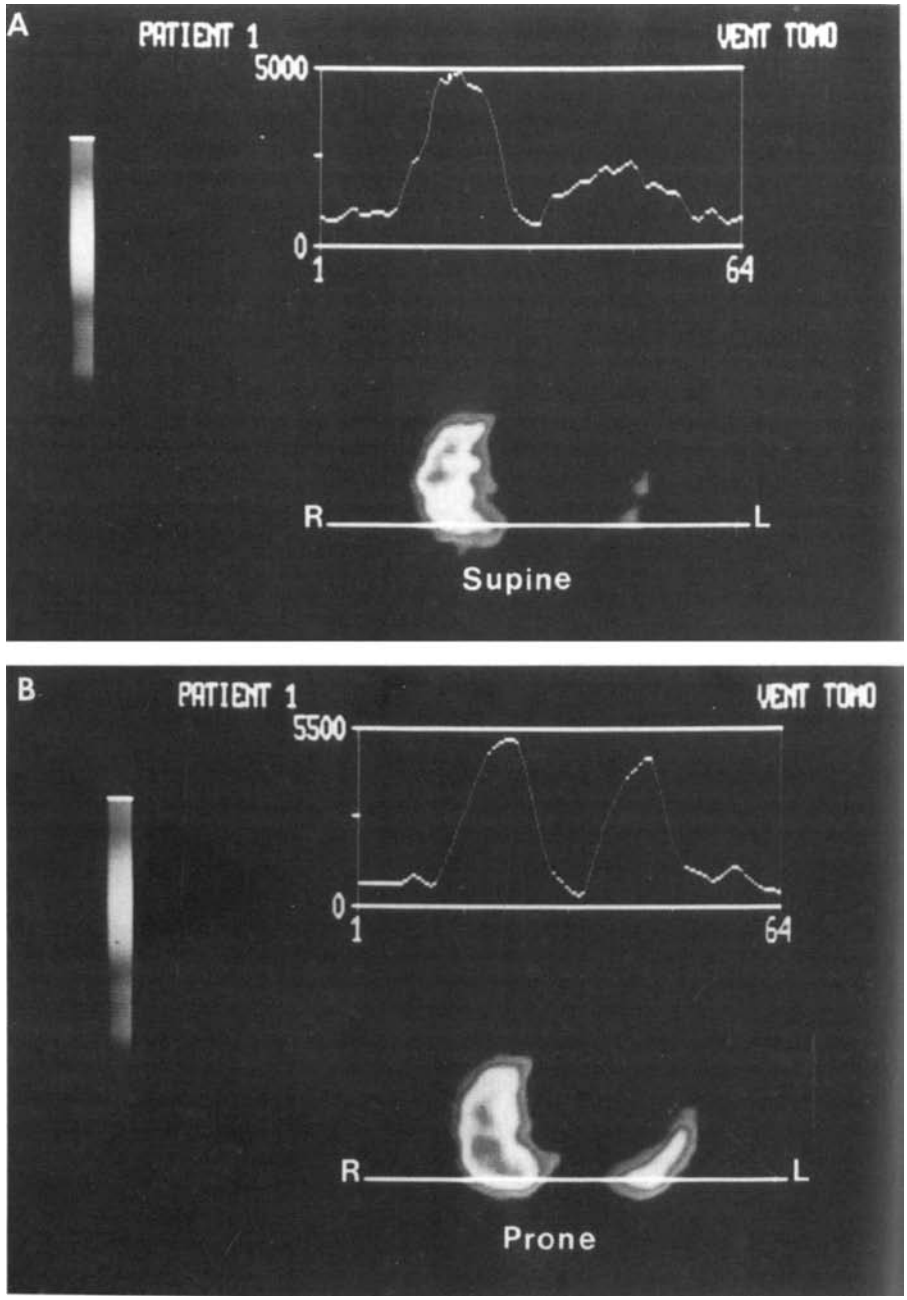

Fig. 2. Similar reconstruction as in figure 1 at same level (mid-heart) in a patient with cardiomegaly. Note depression of peak counts in left lung in the supine (A) but not the prone (B) position.

Discussion

Critique of Methods

The use of ^{81m}Kr to measure regional ventilation has been fully discussed previously (8). In theory, the ^{81m}Kr technique underestimates ventilation in regions with high ventilatory turnover. This could lead to an underestimate of L/R differences of 20 to 30%, but it would not alter the physiological findings of this study.

The use of ^{81m}Kr with SPECT to measure regional ventilation has been described from this laboratory (10). Gravitational gradients of ventilation and blood flow measured with SPECT were not significantly different from conventional two-dimensional studies. Attenuation corrections were not used in this or the previous study (10), since the anatomy of the thorax is complex. The attenuation elements are inhomogeneous (ribs, spine, mediastinum, heart, and large

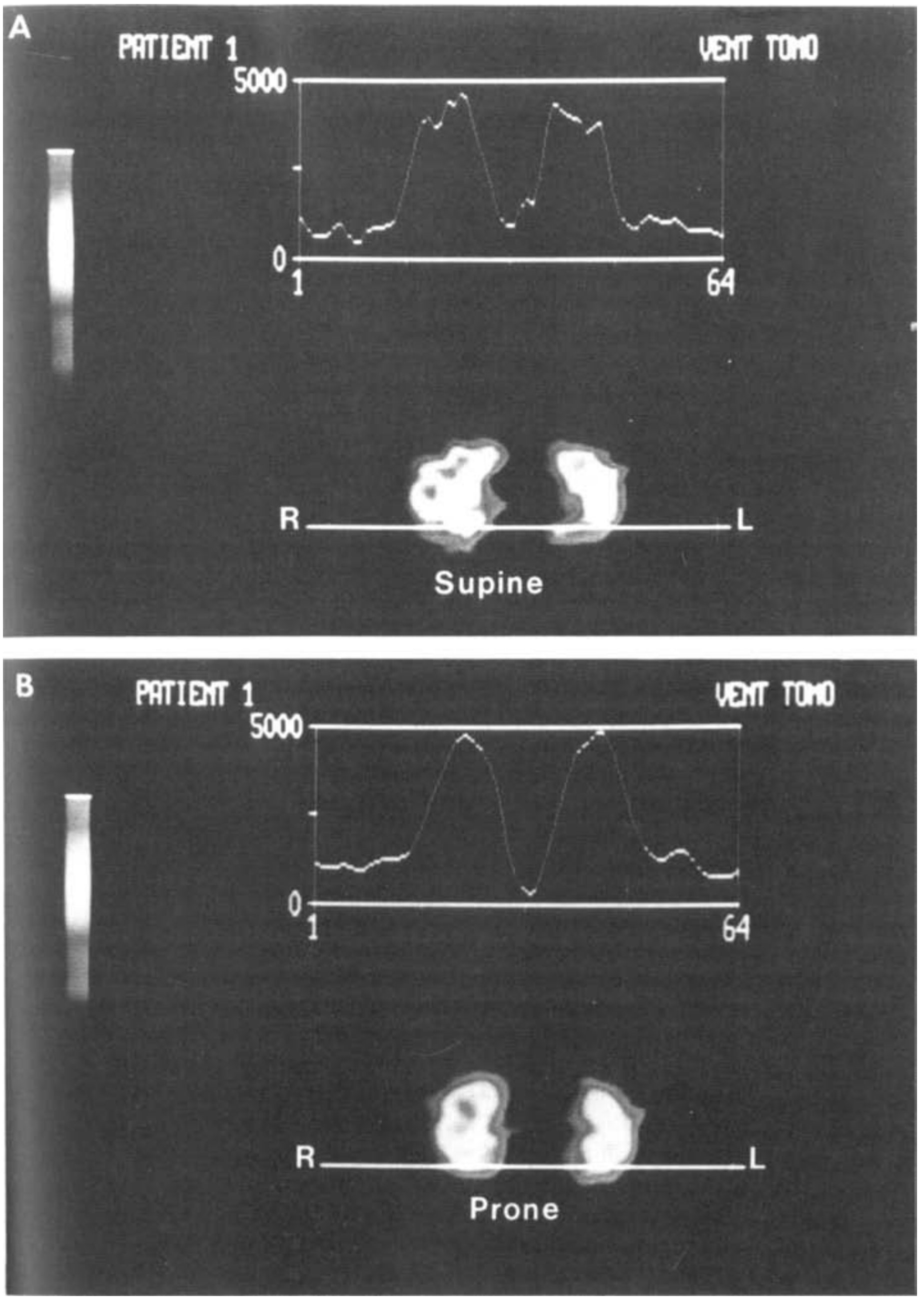

Fig. 3. Similar reconstruction to figure 1, but at the aortic arch level in the same patient as figure 2. Note absence of depression of ventilation in supine (A) posture cranial to the heart.

blood vessels) and, by comparison, there is little attenuation within the lung itself, so the accuracy of present-day algorithms for attenuation corrections is difficult to justify. Postmortem comparisons, using ^{99m}Tc microspheres in dogs, of uncorrected SPECT reconstructions and distributions measured directly on cut sections showed regional differences of less than 10% (13). The use of ratios to express the results further decreases any effect of attenuation. Nevertheless, it is essential to keep interference from the shoulders and arms to a minimum (*see* METHODS).

The advantage of SPECT lies in the ability to quantify the activity in small regions of the lung that can be located in three dimensions and related to other structures. This is especially valuable in decubitus postures where changes of position are accompanied by rotation and movement of the heart and mediastinal contents. For the supine/prone comparisons in this study, matched areas were chosen with the help of an externally placed radioactive marker. There was possibly some cranial or caudal shift of the lung within the thoracic cavity, but since the postural changes in the L/R ventilation ratio (figures 4 and 5) extended over a distance equivalent to the long axis of the heart, small displacements of the lower lobes were unlikely to have made much difference. The L/R ratio of fractional total counts at each level would be influenced by mediastinal or cardiac displacement of lung tissue on one side more than the other. As such, it reflects total ventilation between right and left lung at a particular thoracic level relative to the heart. The ratio of peak counts, on the other hand, compares ventilation per pixel (or voxel) of lung tissue. This is an indirect reflection of ventilatory turnover (flow per unit gas volume) because the fractional volume of gas in the pixel is not specified. It is possible for a low peak pixel count to be associated with a high ventilation per unit gas volume in pixels with a high density and low gas volume.

Peak counts could be affected by a partial volume effect, that is volumes of lung below the resolution of the detecting system or lung moving in and out of the field of view. To the extent that respiratory excursions on the right and left sides are approximately equal, the L/R ratio would not be affected. The left lung was not displaced out of the counting field, as visualized in figure 2. In three patients (data not shown) CT scans and lung perfusion scans showed that both lungs maintained their position relative to the heart but with some change of shape. Indeed, the count rates for ventilation in the supine posture on the left side at the level of the cardiac apex for peak counts (figure 5) and total section counts (figure 4) still averaged 40 to 50% of those on the right side.

Mechanical Interaction between Heart and Lung

We suppose that the heart is a mobile blood-filled mass capable of compressing the surrounding lung, leading to narrowing or closure of small airways. CT scanning has shown ventral and caudal movement of the heart and great vessels in the prone posture with the heart assuming a more globular shape and increasing substantially its area of contact with the ventral chest wall (11). There was also a 2 to 6 cm ventral shift in the hilar structures. Differences in lung contours (at the same cardiac level) between prone and supine can be seen in figures 1 to 3. Alterations in lung shape going from prone to supine, are quite likely to be associated with changes in the pattern of

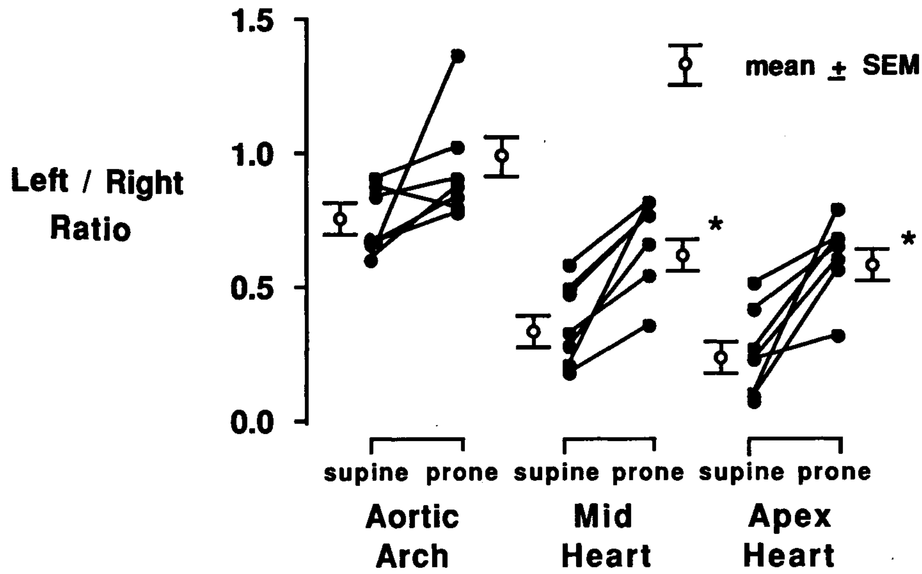

Fig. 4. Ratio of L/R counts (as % total counts in that slice) at different thoracic levels in patients with an enlarged heart. Note supine-prone difference. * = $p < 0.005$.

lung expansion and the related gradients of pleural surface pressure. Increasing the weight of the heart in a dead animal (dog) with mercury doubled the vertical gradient (cm H_2O/cm distance) of pleural pressure in the erect posture and must have changed the distribution of lung expansion (14). Using a sophisticated method of image reconstruction from CT scans, Hoffman (15) found that the vertical gradient of lung expansion (there is decreased expansion in dependent regions) in dogs disappeared when the animals were turned from the supine to the prone position. The dog's natural position is prone, but similar changes were found in the naturally supine two-toed sloth (16). Although there were changes in the shape of the rib cage in the dog (but minimal in the sloth) on changing from supine to prone, the large changes in the position of the mediastinal contents, which were common to both species, were thought to be responsible for the changes in regional lung expansion. Similar changes (supine versus prone) in vertical gradients of lung expansion (8) and in regional ventilation (more uniform when prone) (8, 10) have been found in humans using radioactive gases. Using positron emission tomography, no difference in right to left lung density or lung expansion were seen in supine normal subjects at mid-heart level (17). A reasonable hypothesis would be that the effect of the heart on supine/prone differences in regional lung expansion would be present when the volume and weight of the heart is increased.

Possible Mechanism of Decreased Left Lung Ventilation in Cardiomegaly

Further experiments are underway to investigate possible mechanisms. Obstruction of the left main or lower lobe bronchus, as described for infants (4, 5), seems unlikely in view of the low resting left lung volume seen on CT in patients with cardiomegaly (unpublished observations). Compression of the left lower lobe by an enlarged heart could lead to airway or alveolar closure and diminution of local ventilation. On the other hand, in normal subjects, airway closure (for the whole lung) does not occur at a different lung volume in the supine compared to the prone position (18) although the slope of the alveolar plateau (phase III) is steeper in the supine posture than in the prone posture, indicating greater unevenness of ventilation (19).

Clinical and Physiological Implication

The diminished left lung ventilation in the supine posture, particularly if associated with left lower lobe airway closure and atelectasis (7), might be expected to lead to hypoxemia, though none was seen in this study. In humans with ARDS (20) and in dogs with oleic acid-induced pulmonary edema (21), both on ventilators, a change from the supine to prone position improved arterial oxygenation substantially. In dogs, there was no correlation with changes of lung volume, regional diaphragm motion, cardiac output, or pulmonary hemodynamics (21). Data on L/R blood flow distribution, breathing air and 100% oxygen, would be of great interest from the standpoint of compression of vessels and hypoxic vasoconstriction.

Orthopnea in congestive heart failure is conventionally attributed to pulmonary venous congestion, which is more marked in the supine position (2). However, a local reduction in left lower lobe gas volume due to compression by an enlarged heart, might be the stimulus for an increase in ventilation. In cardiac disease, the severity of breathlessness has been correlated with the ratio of closing volume to vital capacity (22).

Conclusions

Cardiomegaly is associated with a marked reduction in regional ventilation to the left mid and lower zones in the supine but not in the prone posture. Normal subjects do not show these changes.

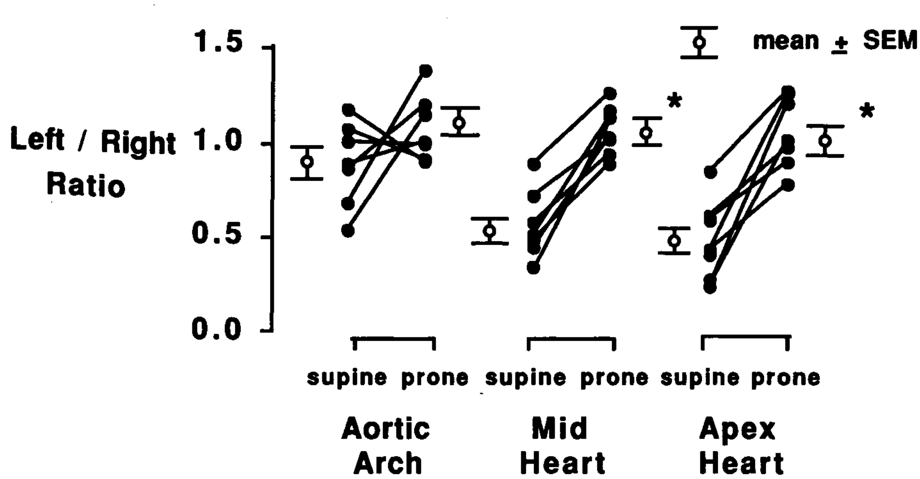

Fig. 5. Ratio of L/R peak counts per pixel at different thoracic levels in dorsal regions of patients with an enlarged heart. Note supine-prone differences in the mid-heart and cardiac apex regions. * = $p < 0.001$.

In the prone posture the heart moves ventrally and no longer compresses the lung. The mechanism of the reduction in ventilation remains to be determined but may involve airway closure or narrowing, or alveolar collapse.

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