Anesthesiology
78:251–259, 1993
© 1993 American Society of Anesthesiologists, Inc.
J. B. Lippincott Company, Philadelphia

Effect of Posture on Lung and Regional Chest Wall Mechanics

George M. Barnas, Ph.D., Michael D. Green, M.S.,† Colin F. Mackenzie, M.B.Ch.B., F.F.A.R.C.S.,‡ Simon J. Fletcher, M.B.Ch.B., F.F.A.R.C.S.,§ D. Neil Campbell, M.B.Ch.B., F.F.A.R.C.S.,§ Colin Runcie, M.B.Ch.B., F.F.A.R.C.S.,§ Gearin E. Broderick, M.D.‖*

Background: Little is known about the extent to which changes in postures in clinical situations affect respiratory mechanics, even in humans with healthy respiratory systems. This study tested the hypothesis that posture has only small effects on overall respiratory system mechanics in healthy subjects, despite changes in parts of the respiratory system in some postures.

Methods: Measurements were made of airway flow, airway and esophageal pressures, and rib cage and abdominal volume displacements (with inductance plethysmography) of awake, healthy subjects, relaxed at functional residual capacity, during external forcing at 0.2 Hz with a tidal volume of 8–10 ml/kg. From these measurements, discrete Fourier transform was used to calculate elastances (E) and resistances (R) of the total respiratory system, lungs, total chest wall, and compartments of the chest wall (rib cage, diaphragm-abdomen, and belly wall). Measurements were made while the subjects were in nine different postures: in six of these, the torso was straight; in three, the torso was bent or twisted.

Results: Although changes in mechanics of parts of the respiratory system were evident in certain postures, overall respiratory mechanics were not greatly affected by posture. Changing from sitting to supine decreased E and R of the diaphragm-abdomen about 50% ($P < .05$), but total chest wall E and R changed only slightly. Lung E increased 24% ($P < .05$), but total respiratory E did not change ($P < .05$). Lung and total respiratory R increased 40–50% ($P < .05$) with this same change in posture. As long as the torso was straight, however, changes in orientation of 30° from the horizontal or a shift to lateral posture resulted in only minor changes in the variables measured. Postures in which the torso was twisted or bent increased E of the total chest wall 20–30% compared to supine ($P < .05$), due to increases in E of one or more compartments. Respiratory system E also increased, at most 14%. Although lung R decreased 30–45% ($P < .05$) in these postures compared to supine with a straight torso, chest wall and total respiratory R generally were unchanged.

Conclusions: Changes in respiratory system mechanics over a wide range of postures that may be encountered clinically are relatively small in healthy awake subjects due to adaptability of total chest wall mechanical behavior. **(Key words: Lung, mechanics: compliance; elastance; position; resistance.)**

DURING anesthesia and surgery, the rib cage and abdomen are positioned to allow optimum access to the site of surgery, and the patient may be placed in various postures. Changes in respiratory mechanics, especially in patients with lung or chest wall pathologies, may hamper spontaneous breathing or the ability to ventilate. In other clinical situations, various postures often are employed to facilitate treatment and postoperative care. Although changes in respiratory mechanics in shifting from sitting to supine have been characterized,[1,2] the degree to which other posture changes affect chest wall and lung mechanics is less well known. Especially unclear is how mechanics change when the torso is not held straight. Additionally, since the chest wall consists of two major compartments in parallel, namely the rib cage and diaphragm-abdomen, it is not obvious how large changes in the mechanics of one of the compartments in a given situation (for example, increases in elastance [E]) will affect total chest wall mechanics. For example, in the sitting posture, strapping the abdominal wall has only slight effects on total chest wall mechanical impedance.[3] Furthermore, whether changes in mechanics of one or both compartments of the chest wall with posture will have significant effects on the mechanics of the lungs or total respiratory system can not be predicted easily.

Therefore, to understand the effects of some postures that are used in clinical situations, we simultaneously measured the mechanical properties of the total respi-

---

* Assistant Professor, Departments of Anesthesiology and Physiology.

† Research Engineer, Department of Anesthesiology.

‡ Professor, Department of Anesthesiology.

§ Visiting Assistant Professor, Department of Anesthesiology.

‖ Resident, Department of Anesthesiology.

Received from Anesthesiology Research Laboratories, University of Maryland School of Medicine, Baltimore, Maryland. Accepted for publication October 9, 1992. Supported by National Heart, Lung and Blood Institute grant HL-44128.

Address reprint requests to Dr. Barnas: Anesthesiology Research Laboratories, Room 534, MSTF Building, University of Maryland School of Medicine, 10 South Pine Street, Baltimore, Maryland 21201.

ratory system, lungs, total chest wall, and compartments of the chest wall in awake, voluntarily relaxed subjects in nine different postures. We tested the hypothesis that posture has only small effects on overall respiratory system mechanics in healthy subjects, despite changes in parts of the respiratory system in some postures. The results indicate the extent to which posture could interfere with care in healthy patients and act as control values to which future data in patients with respiratory pathologies may be compared.

Methods

Approval for the study was given by the University of Maryland Human Research Volunteers Committee. We studied seven healthy, nonsmoking adult subjects, one of them female, after obtaining informed consent from each. Table 1 lists the physical characteristics and pulmonary functions of each subject. The subjects lay on a standard clinical operating table (Amsco Surgical 2080, Erie, PA). Esophageal (P_{es}) and gastric (P_{ga}) pressures were measured using latex balloons attached to differential pressure transducers (Celesco LCVR, Canoga Park, CA, one port open to atmosphere) *via* polyethylene catheters. Placement of the P_{es} balloon was checked in each subject in each posture with a method described by Baydur *et al.*[4] Another Celesco LCVR transducer was used in differential mode to measure transpulmonary pressure, the difference between airway pressure (P_{aw}) and P_{es}. Chest wall surface displacements were measured with inductive plethysmograph belts (Respitrace, Ambulatory Monitoring, Ardsley, NY) around the rib cage and abdomen (nipple and umbilicus levels, respectively). The rib cage and abdominal signals, and their sum, were calibrated in each posture so that all three had the same sensitivity to volume changes.[5] Airway flow was measured with a pneumotachograph (Fleisch #2) and a differential pressure transducer (Celesco LCVR). P_{aw} was measured with a fifth Celesco LCVR transducer 2.0 cm from the mouth end of a rubber mouthpiece. We inserted a 2.5-cm inner diameter plastic tube inside most of the length of the mouthpiece to prevent mechanical distortion; resistance (R) of the measuring system was too small to be measured by our methods and was considered negligible.

Volume forcing with air was delivered from a servoventilator (Siemens-Elema, 900B, Englewood, CO) whose electronic circuitry was adjusted to allow it to be driven by a computer. In this way, we produced a flow waveform with an I:E ratio of 1:1 that was sinusoidal during inspiration while expiration was passive. The ventilator was set at a frequency of 0.2 Hz and a tidal volume of 8–10 ml/kg body weight. After two voluntary, deep inspirations, the subject breathed through the mouthpiece and relaxed his or her respiratory muscles. Pressure and flow waves were monitored continuously for indications of lack of relaxation, and measurements were not made unless the waveforms were smooth and reproducible. After at least five initial breaths at a given tidal volume, we measured three consecutive breaths with the subject's cheeks tightly compressed by a colleague to remove their variable contribution to the measurements. Measurements were repeated in each subject at least five times in each of the following postures: sitting, supine, head-up, head-down, lithotomy, lateral, torso twisted, "split table," and slouch (tables 2 and 3). Typically, two to four postures with a "straight torso" (table 2) were measured in a given day; postures with "torso not straight" (table 3), as well as a second set of supine measurements, were measured in a single day. There was no difference ($P > 0.1$) in any measured parameter (table 4) between the first and second set of supine measurements.

Measurements of the four pressures, airway flow, and inductance plethysmographic displacements from three successive breaths were digitized (sampling rate = 64 per breath) and computer averaged. We used discrete Fourier transform at the fundamental frequency (*i.e.*, 0.2 Hz) to calculate R and E as listed in table 4. We have shown previously that R and E calculated in this way, measured during the quasi-sinusoidal forcing used in the present experiments do not differ from values measured during pure sinusoidal forcing.[6,7] A detailed discussion of the limitations in interpreting R

Table 1. Physical Characteristics and Pulmonary Functions of the Subjects

Patient No.	Sex	Age (yr)	Height (cm)	Weight (kg)	Forced Vital Capacity (L)	Forced Expiratory Volume 1 s (L)
1	M	39	178	97	5.6 (112)	4.8 (118)
2	M	48	180	82	4.6 (91)	3.9 (97)
3	M	30	171	64	4.9 (99)	3.9 (98)
4	M	32	175	85	4.9 (95)	4.1 (100)
5	M	30	186	70	5.3 (90)	4.4 (97)
6	F	33	155	45	3.0 (89)	2.4 (90)
7	M	23	185	77	6.2 (104)	5.6 (119)

Values in parentheses are percent predicted.

Table 2. Postures Measured, with Torso Straight

Posture	Description	Some Clinical Applications
Supine	Arms at side	Clinical examination and many surgical procedures; postural drainage of anterior segments of upper lung lobes
30° head-up	Supine, table tilted 30° up from horizontal	Head and neck injury; laparoscopic cholecystectomy; nursing position after spinal cord injury; ophthalmologic surgery
30° head-down	Supine, table tilted 30° down from horizontal	Laparoscopic tubal ligation; postural drainage of anterior segments of lower lung lobes; hypovolemic hypotension; vasovagal attacks
Lithotomy	Supine with ankles held up in stirrups, knees bent	Pelvic examination; childbirth; urologic and gynecologic procedures
Lateral	On left side, head held horizontal with a pillow, arms held out forward and supported	Thoracotomy; auscultation of heart; hip surgery; routine side-to-side turning in comatose patients
Sitting	Back tilted slightly from vertical to facilitate relaxation	Clinical examination of respiratory and cardiovascular systems; postural drainage of apical segments of upper lobes; posterior fossa and cervical spine surgery

and E of the chest wall compartments has been presented elsewhere.[5] There was good agreement between flow derived from the sum of the rib cage and abdomen inductance plethysmograph signals and flow measured with the pneumotachograph. On the average, the former was 2% (±9% SD, n = 58) higher than pneumotachograph flow and led it by 0.9° (±1.5° SD). These differences in relative magnitude and phase were not affected by posture (paired *t* tests, $P > .05$), so we did not correct any values to account for discrepancies between the two types of flow measurements.

The data were analyzed with analysis of variance for repeated measures, and Fisher paired least significant difference was used to test for differences among the postures. $P < .05$ was the accepted level of significance.

Results

Postures with Straight Torso

Figure 1 and table 5 show that respiratory system E (E_{rs}) did not change among the six postures where the torso was straight (table 2). However, lung E (E_l) increased compared to sitting in the supine and lithotomy postures ($P < .05$). On the other hand, total chest wall E (E_{cw}) decreased compared to sitting in the head-up posture ($P < .05$). Rib cage E (E_{rc}) was not significantly changed except in the lateral posture, when it increased compared to sitting and supine ($P < .05$). Diaphragm-abdomen E (E_{da}) and belly wall E (E_{bw}) were lower compared to sitting in the five other postures ($P < .05$).

Figure 2 and table 6 show that respiratory system R (R_{rs}) increased compared to sitting in the supine and head-down postures ($P < .05$). These increases were due to changes in lung R (R_l). During lithotomy, R_l increased and total chest wall R (R_{cw}) decreased compared to sitting ($P < .05$), so that R_{rs} did not change. Rib cage R (R_{rc}) was not significantly changed except in the lateral posture, when it increased compared to sitting and lithotomy ($P < .05$). Diaphragm-abdomen R (R_{da}) and belly wall R (R_{bw}) decreased compared to sitting in all of the other five postures ($P < .05$).

Table 3. Postures Measured, with Torso not Straight

Posture	Description	Some Clinnical Applications
Torso twisted	Lying on flat table, hips parallel with table while back supported so that shoulders perpendicular to table, *i.e.*, shoulders turned 90° compared with hips	Combined thoracoabdominal surgical procedures (*e.g.*, esophageal surgery)
Split table	As in lateral posture but with both ends of table sloping down from middle; subject positioned so center of table between lowest rib and hip	Nephrectomy and other renal surgical procedures
Slouch	Table at right angle in middle, subject positioned so that head and shoulders vertical while hips and legs horizontal	Craniotomy; posture often found in postoperative patients at bedside

Table 4. Measured Impedances

Complex Ratio	Impedance	Elastance (E)	Resistance (R)
$\Delta P_{aw}/\dot{V}_{aw}$	Total respiratory system (rs)	E_{rs}	R_{rs}
$\Delta(P_{aw} - P_{es})/\dot{V}_{aw}$	Lung (l)	E_l	R_l
$\Delta P_{es}/\dot{V}_{aw}$	Total chest wall (cw)	E_{cw}	R_{cw}
$\Delta P_{es}/\dot{V}_{rc}$	Rib cage (rc)	E_{rc}	R_{rc}
$\Delta P_{es}/\dot{V}_{bw}$	Diaphragm-abdomen (da)	E_{da}	R_{da}
$\Delta P_{ga}/\dot{V}_{bw}$	Belly wall plus some abdominal contents (bw)	E_{bw}	R_{bw}

P = pressure; aw = airway; es = esophageal; ga = gastric; $\dot{V}_{rc}$ = flow at rib cage surface; $\dot{V}_{bw}$ = flow at belly wall surface (anterior and lateral abdominal sources not apposed to rib cage).[5]

Postures with Torso not Straight

Compared to supine values, E_{rs} increased ($P < .05$) in the torso twist and slouch postures (fig. 3, table 5). E_{cw} increased during the three postures without a straight torso compared to supine ($P < .05$). During the torso twist, the increase in E_{cw} was primarily due to an increase in E_{rc} ($P < .05$), whereas during the slouch, E_{da} primarily increased ($P < .05$). E_{bw} increased during the slouch compared to the three other postures ($P < .05$), and also increased compared to supine during the split table posture ($P < .05$).

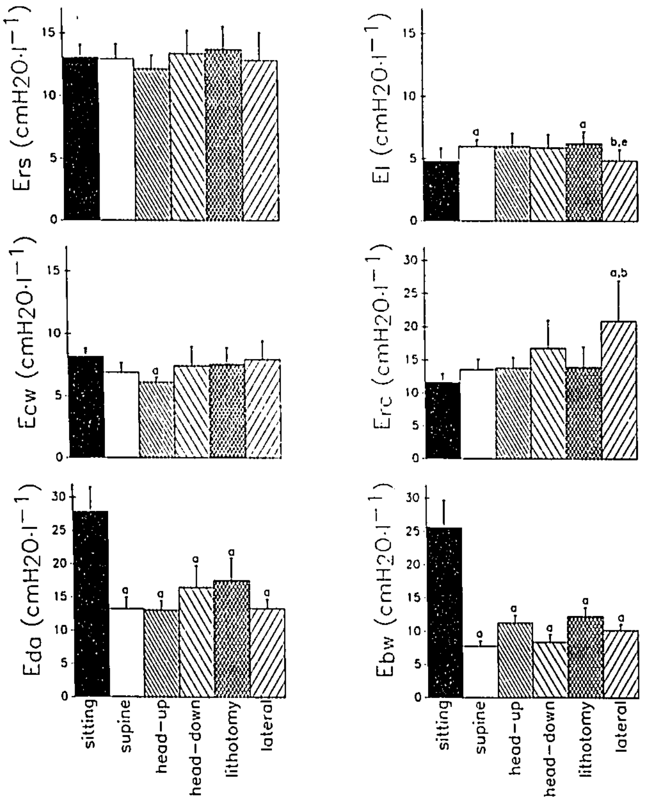

Fig. 1. Elastances of the total respiratory system (E_{rs}), lungs (E_l), total chest wall (E_{cw}), and parts of the chest wall (E_{rc}, E_{da}, and E_{bw}) of seven subjects in different postures with a straight torso. SE indicated by vertical bars. Results of analysis of variance ($P < .05$): a = different from sitting; b = different from supine; e = different from lithotomy.

Compared to supine values, R_{rs} was not different in the three postures with the torso not straight (fig. 4, table 6). However, R_l decreased ($P < .05$) compared to supine in these three postures. R_{cw} was higher during the split table than during the other postures ($P < .05$); the increase compared to supine was due to increases in both R_{rc} and R_{da} ($P < .05$). Although R_{da} increased greatly during the slouch compared to supine ($P < .05$), R_{cw} was not increased. R_{bw} increased during the slouch compared to the three other postures ($P < .05$).

Discussion

Critique of Methods

Our method of passive, external forcing assumes no respiratory muscle activity is present in large enough magnitude to affect chest wall and total respiratory system properties. Our subjects were highly trained in relaxing during forcing, and we have found that relaxation is relatively easy to obtain with the type of forcing used. That is, the waveform, frequency, and tidal volume are all similar to normal breathing, although the minute ventilation is high to maintain a slight hyperventilation that facilitates suspension of active breathing movements. During measurements, even slight respiratory efforts are detectable as artifacts in the P_{es} and P_{aw} traces or differences in waveform of successive breaths. In fact, we found that measurements in the prone position on a flat table were not feasible due to lack of ability to completely relax. Although it is impossible to guarantee complete lack of respiratory muscle activity in the present series of experiments, it is unlikely that activity, when present, was large enough to affect the major findings.

Table 5. Elastances (E) of the Respiratory System in Different Postures

Posture	E_{rs}	E_l	E_{cw}	E_{rc}	E_{da}	E_{bw}
Supine	12.9 ± 1.2	6.0 ± 0.5	6.9 ± 0.8	13.6 ± 1.6	13.2 ± 1.7	7.7 ± 0.8
30° head-up	12.1 ± 1.1	6.0 ± 1.0	6.1 ± 0.4	13.8 ± 1.6	13.0 ± 1.4	11.3 ± 1.2
30° head-down	13.3 ± 1.9	5.9 ± 1.1	7.4 ± 1.5	16.8 ± 4.2	16.4 ± 3.3	8.4 ± 1.2
Lithotomy	13.7 ± 2.0	6.3 ± 0.9	7.6 ± 1.3	13.9 ± 3.1	17.5 ± 3.4	12.3 ± 1.3
Lateral	12.8 ± 2.3	4.9 ± 0.9	7.9 ± 1.5	20.9 ± 6.0	13.3 ± 1.3	10.2 ± 0.9
Sitting	13.0 ± 1.0	4.8 ± 1.0	8.2 ± 0.6	11.6 ± 1.3	27.8 ± 3.8	25.6 ± 4.0
Torso twisted	14.4 ± 0.8	4.3 ± 0.4	10.1 ± 0.7	23.8 ± 1.3	17.6 ± 2.7	11.3 ± 1.7
Split table	13.5 ± 0.6	4.3 ± 0.3	9.2 ± 0.5	20.5 ± 1.9	17.5 ± 2.5	14.4 ± 2.8
Slouch	14.7 ± 0.6	5.3 ± 0.8	9.4 ± 0.6	14.1 ± 0.4	28.9 ± 6.9	21.6 ± 3.8

Values are mean ± SE (cmH_2O/L); n = 7 except in the last three postures, where n = 4.

Statistical differences are shown in figures 1 and 3.

rs = respiratory system: l = lungs; cw = total chest wall; rc = rib cage; da = diaphragm-abdomen; bw = belly wall.

Since our results were measured during passive, mechanical ventilation, we cannot directly apply them to spontaneous breathing. However, the passive regional properties of the chest wall seem to be important in determining patterns of spontaneous breathing. For example, several studies have shown that the proportion of a tidal volume during spontaneous breathing that is expressed at the rib cage surface decreases when supine.[2,8,9] This is consistent with the observed decrease in E_{da} in the supine posture compared to sitting: when the diaphragm contracts, the relative displacements of the rib cage and diaphragm-abdomen are at least partly determined by the relative E of the two parallel compartments. It is probable that spontaneous breathing patterns in healthy subjects in other postures also will be determined, to a certain extent, by changes in E_{rc} and E_{da}. Regional chest wall mechanics, in turn, may affect regional intrapulmonary gas distribution. For example, it has been shown that distribution of ventilation in awake healthy patients changes among the sitting, supine, and lateral postures,[10,11] and these changes are not due solely to differences in functional residual capacity (FRC) with posture.[10]

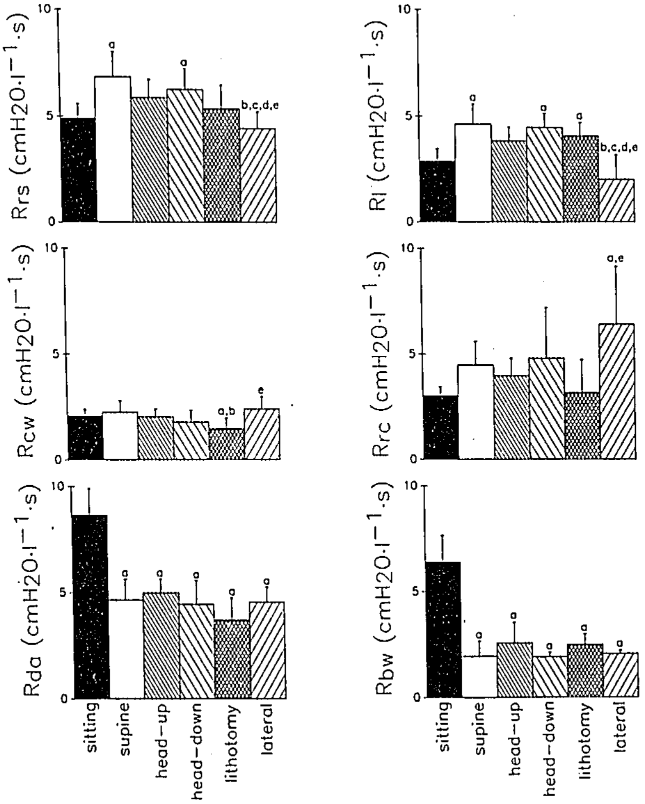

Fig. 2. Resistances of the total respiratory system (R_{rs}), lungs (R_l), total chest wall (R_{cw}), and parts of the chest wall (R_{rc}, R_{da}, and R_{bw}) of seven subjects in different postures with a straight torso. SE indicated by vertical bars. Results of analysis of variance ($P < .05$): a = different from sitting; b = different from supine; c = different from head-up; d = different from head-down; e = different from lithotomy.

Estimates of absolute pleural pressure with an esophageal balloon are prone to artifact in supine subjects, and possibly, in other postures. However, the likelihood that such artifacts were significant in our study is small since our calculations are based on the validity of changes in P_{es}, not absolute values, in a relatively small range of the vital capacity. We tested the P_{es} balloon placement in each posture by comparing P_{aw} and P_{es} changes during voluntary inspiratory efforts with a closed airway. When the changes are nearly equal and in phase, then estimates of overall pleural pressure changes should be valid.[4] Examples of the test for balloon placement in one subject are shown in figure 5 in the sitting posture, where artifact should be minimum, and in the head-down posture, where one might

Table 6. Resistances (R) of the Respiratory System in Different Postures

Posture	R_{rs}	R_l	R_{cw}	R_{rc}	R_{da}	R_{bw}
Supine	6.8 ± 0.7	4.6 ± 0.9	2.2 ± 0.5	4.5 ± 1.1	4.6 ± 1.0	1.9 ± 0.4
30° head-up	5.9 ± 0.9	3.8 ± 0.7	2.0 ± 0.4	4.0 ± 0.8	5.0 ± 0.6	2.6 ± 0.4
30° head-down	6.3 ± 1.0	4.6 ± 0.8	1.8 ± 0.6	4.8 ± 2.4	4.4 ± 1.1	1.9 ± 0.2
Lithotomy	5.4 ± 1.1	4.1 ± 0.6	1.5 ± 0.5	3.2 ± 1.6	3.7 ± 1.1	2.5 ± 0.5
Lateral	4.4 ± 0.8	2.0 ± 0.3	2.4 ± 0.6	6.5 ± 2.7	4.5 ± 0.7	2.1 ± 0.2
Sitting	4.9 ± 0.7	2.9 ± 0.6	2.1 ± 0.3	3.0 ± 0.4	8.6 ± 1.3	6.4 ± 1.3
Torso twisted	5.1 ± 0.7	3.3 ± 0.6	1.8 ± 0.2	3.7 ± 0.6	3.5 ± 0.9	2.2 ± 0.3
Split table	5.4 ± 1.1	2.6 ± 0.6	2.8 ± 0.7	6.4 ± 1.6	5.7 ± 1.4	2.3 ± 0.3
Slouch	4.7 ± 0.8	3.0 ± 0.5	1.7 ± 0.3	2.5 ± 0.5	6.7 ± 2.5	4.9 ± 0.4

Values are mean ± SE ($cmH_2O \cdot L^{-1} \cdot s$); n = 7 except in the last three postures, where n = 4.

Statistical differences are shown in figures 2 and 4.

rs = respiratory system: l = lungs; cw = total chest wall; rc = rib cage; da = diaphragm-abdomen; bw = belly wall.

expect the largest artifact due to the weight of tissues in intrathoracic structures on the balloon. We found no consistent difference with the test among the postures. There is evidence from studies in rabbits and dogs[12] that regional pleural pressure changes may not be homogeneous throughout the lung. It is possible that such nonuniformities are significant even in healthy humans, particularly in certain postures. If so, our calculations of R and E may be, to some extent, oversimplifications. Despite these reservations, P_{es} remains a useful measurement in estimating lung and chest wall properties in humans. However, in patients with lung or chest wall pathologies, nonuniformity in regional P_{es} changes may be enhanced and the usefulness of measurements limited.

Changes from Sitting to Supine

The static pressure/volume characteristic of the abdominal wall is nonlinear:[13,14] at high degrees of stretch, its E increases. While seated, the weight of the abdominal contents distends the abdominal wall, and we found E_{da} and E_{bw} to be high (fig. 1). Conversely, in the supine posture, they were much lower. These results are similar to those from static measurements by Estenne *et al.*,[1] who found that E_{da} decreased in the supine compared to the sitting posture. Despite the large decreases in E_{da} when shifting from sitting to supine, corresponding changes in E_{cw} were small. This is due, for the most part, simply to the parallel arrangement of the rib cage and diaphragm-abdomen compartments with respect to pleural pressure. Because of this, $1/E_{cw} = 1/E_{rc} + 1/E_{da}$. Therefore, large changes in one of the compartments will be mitigated by a constancy in the other, especially if, as with the chest wall, the E of the changing compartment is much higher than the other.

The increase in E_l we found when shifting from sitting to supine (fig. 1) is similar to analogous increases in static or dynamic E_l reported by others.[15–18] However, since $E_{rs} = E_{cw} + E_l$, and E_{rs} does not change[19,20] (fig. 1) from sitting to supine, E_{cw} would be expected to decrease with the same change. This is consistent with the slight decrease in E_{cw} we found in the supine posture, although the tendency was not significant.

The increases in R_l, and therefore in R_{rs}, in the supine posture (fig. 2) were probably due to the well documented finding that FRC decreases in the supine posture compared to sitting.[8,14–17,21,22] This would result in decreased mean airway diameter and an increase in the airways component of R_l. Additionally, the tissue component of R_l also may increase at low FRC, although this has not been studied. Analogous to our discussion of E_{cw} above, R_{cw} showed only minor differences between sitting and supine despite large decreases in R_{da} in the supine posture. Again, this is primarily due to the parallel nature of the two chest wall compartments.

In summary, when shifting from the sitting to supine posture in healthy subjects, there are large changes in mechanics in the diaphragm-abdomen, but changes in total chest wall behavior are small. An increase occurs in E_l that is not enough to cause a significant increase in E_{rs}. R_{rs} is increased slightly by changes in the lung. The relatively small magnitude of the changes in overall respiratory mechanics imply that such changes in posture will have only minor clinical importance in patients unless accompanying respiratory pathology or other disorders are present. However, the importance of changes in mechanics of shifting from sitting to supine when other contributing factors are involved needs to be studied more systematically. For example, R_l seems to increase much more in the supine posture compared to sitting in patients with congestive heart

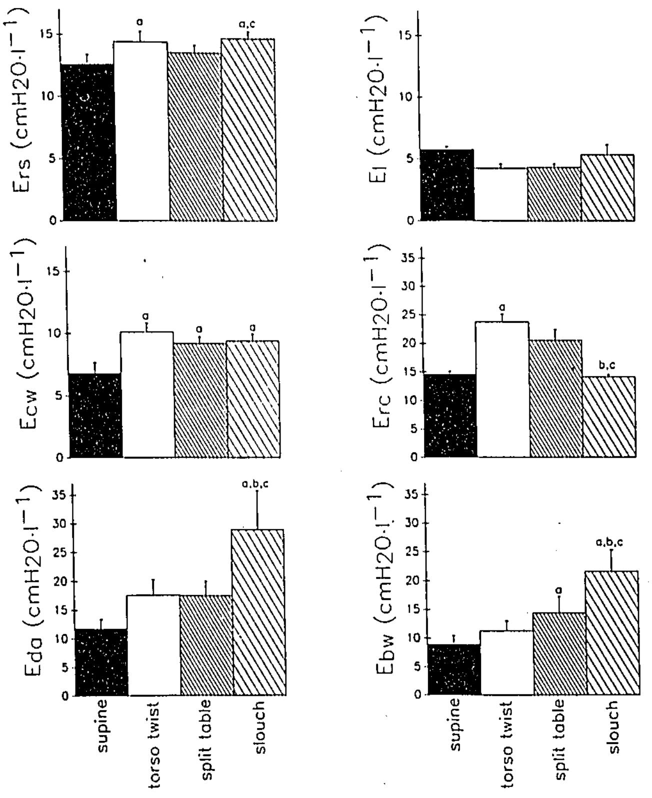

Fig. 3. Elastances of the total respiratory system (E_{rs}), lungs (E_l), total chest wall (E_{cw}), and parts of the chest wall (E_{rc}, E_{da}, and E_{bw}) of four subjects in different postures with the torso not straight. SE indicated by vertical bars. Results of analysis of variance ($P < .05$): a = different from supine; b = different from torso twist; c = different from split table.

failure than in normal patients.[23] It is observed also that ventilation in obese patients generally deteriorates in certain postures,[24] although the extent to which changes in respiratory mechanics contribute to this is not clear. The lack of effect on overall chest wall behavior despite the large changes in E_{da} and R_{da} illustrate that the chest wall essentially acts as a system comprising two parallel compartments. The clinical relevance of this parallel arrangement is that procedures and conditions that severely increase the stiffness of the abdomen, for example, tight dressings on an abdominal wound or ascites, may not affect overall chest wall and total respiratory mechanics unless the procedure also changes FRC.

Head-up and Head-down Postures

There were only small differences between the supine and 30° head-up and 30° head-down postures (figs. 1 and 2). It is easy to observe by direct palpation that the tension on the abdominal wall does not obviously change when the subject is tilted up or down. Changes in FRC are small with tilting: compared to the completely horizontal posture, FRC increases at most only 20% when a subject is tilted 30° up or down.[14,22] This is appreciably less than the 35% changes that usually are seen when going from supine to sitting.[25] Thus, those factors that cause changes in lung and chest wall mechanics between the sitting and supine postures (*i.e.*, abdominal wall tension and FRC) do not seem to differ widely among the supine, head-up, and head-down postures in healthy subjects. In short, tilting a healthy patient up or down 30° will have no large effect on respiratory mechanics. Of course, this may not apply to patients with respiratory disease or obese patients. In the latter, chest wall mechanics may be affected more greatly by tilting due to large changes in the hydrostatic pressure exerted on the diaphragm by the abdominal contents. Especially in the head-down posture, the diaphragm may be stretched, leading to a decrease in FRC.

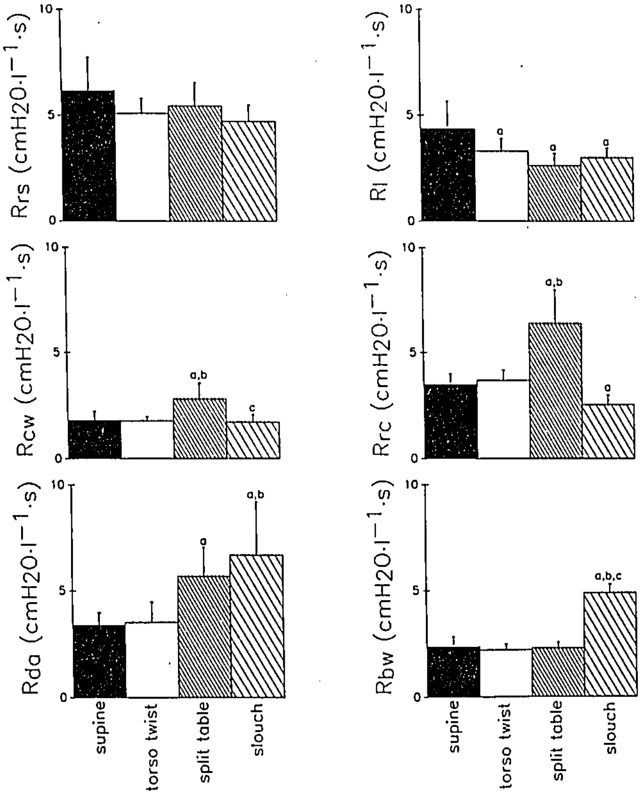

Fig. 4. Resistances of the total respiratory system (R_{rs}), lungs (R_l), total chest wall (R_{cw}), and parts of the chest wall (R_{rc}, R_{da}, and R_{bw}) of four subjects in different postures with the torso not straight. SE indicated by vertical bars. Results of analysis of variance ($P < .05$): a = different from supine; b = different from torso twist; c = different from split table.

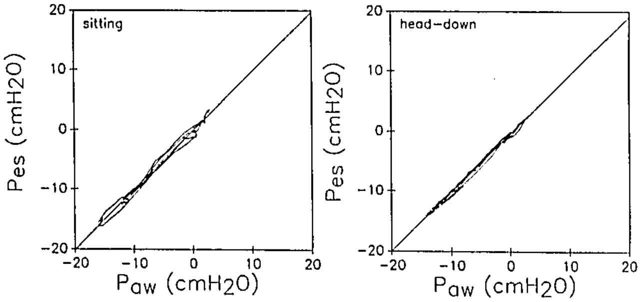

Fig. 5. Examples of test to check placement of the esophageal balloon in one subject in two different postures. Several breathing efforts are made against an occluded mouthpiece and changes in esophageal pressure are plotted against those in airways pressure. Changes should be equal in magnitude.

Lithotomy Posture

As with the head-up and head-down postures, there were only small differences between the supine and lithotomy postures, the only significant difference being a slight decrease in R_{cw} during the lithotomy (fig. 2). Apparently, raising the legs in the lithotomy position affects respiratory mechanics very little.

Lateral Posture

Compared to the four other horizontal postures with a straight torso, R_l and R_{rs} in the lateral posture were less (fig. 2). This would seem consistent with the observations[15,17] that FRC is greater in the lateral than in the supine posture, and therefore mean airway diameter should be larger. Indeed, Linderholm[17] found that R_l in four subjects measured during panting in a body plethysmograph was 3.1 $cmH_2O \cdot l^{-1} \cdot s$ while supine and 2.2 $cmH_2O \cdot l^{-1} \cdot s$ in the lateral posture. However, Behrakis *et al.*[15] found no difference in R_l measured during spontaneous breathing between supine and lateral postures despite differences in FRC. They attributed this surprising finding to increases in upper airway R in the lateral posture due to changes in geometry of the upper airways and/or aperture of the glottis. If this were the case, perhaps the passive external forcing used in our experiments minimized such presumed changes. Similar to the findings of Behrakis *et al.*[15] in 10 subjects and of Linderholm[17] in 3 subjects, we found E_l also to be less in the lateral than in the supine posture (fig. 1). We have found previously that, like R_l, E_l measured during forced sinusoidal oscillations is slightly less when mean lung volume is increased only a few hundred milliliters above FRC.[26] It is possible that the change in E_l in the lateral posture results from the slight increase in FRC.

Despite large increases in E_{rc} and R_{rc} (figs. 1 and 2), there were no changes in overall chest wall properties in the lateral posture compared to supine. This again illustrates how the parallel arrangement of the rib cage and diaphragm-abdomen is able to mitigate overall changes in the chest wall. Simply speaking, if the rib cage becomes stiff, volume changes can be expressed at the abdominal wall almost as easily as in a normal chest wall.

Torso Twist

Although, as discussed above, changes in posture have little effect on E_{rs} in healthy subjects if the torso is straight, our findings show that postures with the torso not straight (table 3) can significantly change regional and overall chest wall mechanical properties. The increases in E_{cw} if the torso is turned 90° compared to supine with a straight torso are large enough to increase E_{rs} (fig. 3). This increase in E_{cw} is largely due to changes in E_{rc}. These results during the torso twist while horizontal were similar to those we have reported previously for the twisted torso in the seated position.[3] A simplistic explanation is that, when certain muscle groups in the chest wall become stretched compared to resting position with a straight torso, they are stiffer. Furthermore, lessening the stretch of other muscles does not compensate for stiffening elsewhere. In the case of the rib cage, stretching of ligaments and tendons must be considered also. Chest wall pathology, such as obesity, could possibly exaggerate the increases in E_{cw} that occur when the torso is bent or twisted. Such changes in E_{cw} may be clinically relevant and need to be tested.

An intriguing result is that R_l decreased slightly during the torso twist compared to supine (fig. 4); E_l also tended to decrease, although not significantly. Will these effects be larger in some types of patients? If so, changes in chest wall configuration due to posture may serve to optimize lung function in some conditions by decreasing lung impedance. Of course, one also must consider possible deleterious effects, such as alterations in ventilation/perfusion distribution, that may outweigh any salutary effects of posture.

Split Table

As during the torso twist, E_{cw} was increased in the split table posture compared to supine with a straight torso, although not enough to significantly affect E_{rs} (fig. 3). R_{cw} also increases, but since R_l is less, R_{rs} does not change (fig. 4). Surprisingly then, the split table posture, which severely distorts the chest wall, has only minimal effects on the total respiratory system mechanics. Of course, our measurements do not address issues such as patient comfort or efficiency of breathing. However, the data suggest that the split table posture could be considered a way to decrease R_l.

Slouch

The abdominal wall becomes much stiffer in the slouch posture than supine with a straight torso, as evidenced by increases in E_{bw}, E_{da}, R_{bw}, and R_{da} (figs. 3 and 4). These changes are enough to increase overall E_{cw}, despite near constancy in the rib cage. The change in the chest wall in a slouching patient, in turn, will increase E_{rs} although E_l does not seem to change. On the other hand, R_l is less with a slouch, an observation that warrants further investigation of the use of this posture to mitigate breathing problems under certain conditions. Of course, one also must consider possible deleterious effects of posture.

Although we have measured a limited number of postures, we are struck by the relative constancy of overall respiratory system mechanics in healthy subjects despite occasionally large changes in some of its constituents. Overall, chest wall behavior shows remarkable adaptability to posture changes, and resulting effects on the lung are relatively small. Our results show that, at least in healthy awake patients, posture has relatively small effects on E_{rs} and R_{rs}. This may not be true in patients with pathologic respiratory function, and indeed, large changes in E_{rs} and R_{rs} with posture may be a marker of some types of respiratory abnormality.

The authors thank Peter Zdandkiewicz for his technical assistance.

References

1. Estenne M, Yernault JC, DeTroyer A: Rib cage and diaphragm-abdomen compliance in humans: Effects of age and posture. J Appl Physiol 59:1842–1848, 1985

2. Vellody VP, Nassery N, Druz WS, Sharp JT: Effects of body position change on thoracoabdominal motion. J Appl Physiol 45:581–589, 1978

3. Barnas GM, Mills PJ, Mackenzie CF, Skacel M, Smalley AJ, Watson RJN, Loring SH: Regional chest wall impedance during non-respiratory maneuvers. J Appl Physiol 70:92–96, 1990

4. Baydur A, Behrakis PK, Zin WA, Jaeger M, Milic-Emili J: A simple method for assessing the validity of the esophageal balloon technique. Am Rev Respir Dis 126:788–791, 1982

5. Barnas GM, Yoshino K, Stamenovic D, Kikuchi Y, Loring SH, Mead J: Chest wall impedance partitioned into rib cage and diaphragm-abdominal pathways. J Appl Physiol 66:350–359, 1989

6. Barnas GM, Mackenzie CF, Skacel M, Hempleman S, Wicke K, Skacel C, Loring SH: Amplitude dependency of rib cage and diaphragm-abdominal resistance and elastance at normal breathing frequencies. Am Rev Respir Dis 140:25–30, 1989

7. Barnas GM, Ho G, Green MD, Smalley AJ, Campbell DN, Mendham JE: Effects of analysis method and forcing waveform on measurement of respiratory system mechanics. Respir Physiol 89:273–285, 1992

8. Lumb AB, Nunn JF: Respiratory function and ribcage contribution to ventilation in body positions commonly used during anesthesia. Anesth Analg 73:422–426, 1991

9. Mannix SE, Bye P, Hughes JMB, Cover D, Davies EE: Effect of posture on ventilatory response to steady-state hypoxia and hypercapnia. Respir Physiol 58:87–99, 1984

10. Jones HA, Davies EE, Hughes JMB: Modification of pulmonary gas mixing by postural changes. J Appl Physiol 61:75–80, 1986

11. Rehder K, Sessler AD, Rodarte JR: Regional intrapulmonary gas distribution in awake and anesthetized-paralyzed man. J Appl Physiol 42:391–402, 1977

12. Agostoni E, Miserocchi G: Vertical gradient of transpulmonary pressure with active and artificial expansion. J Appl Physiol 29:705–712, 1970

13. Smith JC, Loring SH: Passive mechanical properties of the chest wall, Handbook of Physiology: The Respiratory System, section 3, vol 3. Edited by Macklem PT, Mead J. Bethesda, American Physiological Society, 1986, pp 429–442

14. Agostoni E, Hyatt RE: Static behavior of the respiratory system, Handbook of Physiology: The Respiratory System, section 3, vol 3. Edited by Macklem PT, Mead J. Bethesda, American Physiological Society, 1986, pp 113–130

15. Behrakis PK, Baydur A, Jaeger MJ, Milic-Emili J: Lung mechanics in sitting and horizontal body positions. Chest 83:643–646, 1983

16. Lim TP, Luft UC: Alterations in lung compliance and functional residual capacity with posture. J Appl Physiol 14:164–166, 1959

17. Linderholm H: Lung mechanics in sitting and horizontal postures studied by body plethysmographic methods. Am J Physiol 204:85–91, 1963

18. Sasaki H, Hida W, Takishima T: Influence of body position on dynamic compliance in young subjects. J Appl Physiol 42:706–710, 1977

19. Berger R, Burki NK: The effects of posture on total respiratory compliance. Am Rev Respir Dis 125:262–263, 1982

20. Hodgkins JE, Petroff PA, Hyatt RE: Evaluation of methods of determining chest wall compliance in normal subjects. Am Rev Respir Dis 105:1015–1016, 1972

21. Moreno F, Lyons HA: Effect of body posture on lung volumes. J Appl Physiol 16:27–29, 1961

22. Nunn JF: Elastic forces and lung volumes, Applied Respiratory Physiology. London, Butterworths, 1987, pp 23–45

23. Cherniack RM, Cuddy TE, Armstrong JB: Significance of pulmonary elastic and viscous resistance in orthopnea. Circulation 15:859–864, 1957

24. Fisher A, Waterhouse TD, Adams AP: Obesity: Its relation to anaesthesia. Anaesthesia 30:633–647, 1975

25. Ibanez J, Raurick JM: Normal values of functional residual capacity in the sitting and supine positions. Intensive Care Med 8:173–177, 1982

26. Barnas GM, Campbell DN, Mackenzie CF, Mendham JE, Fahy B, Runcie C, Mendham GE: Lung, chest wall and total respiratory system resistances and elastances in the normal range of breathing. Am Rev Respir Dis 145:110–113, 1992