Original Articles

Pulmonary Compliance During Anesthesia

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Dynamic pulmonary compliance was measured in adult patients, first awake and then during halothane anesthesia under various conditions. Patients were free from respiratory obstruction and excessive inflation of the lungs during all measurements. Compliance decreased approximately one-third during deep anesthesia. During light anesthesia and emergence when tidal exchange approximated control values, there was less decrease in compliance. The occurrence of pulmonary atelectasis during deep anesthesia in spontaneously breathing patients is suggested. This may be the primary reason for decreased compliance during anesthesia. Compliance decreased in the conscious state in changing from the sitting to supine position. Men had higher measurements both awake and anesthetized than women, and greater decreases during anesthesia. A thiopental induction was associated with more of a decreased compliance than an inhalation induction. Thin patients encountered little change during anesthesia compared with normal and obese patients. During positive-pressure breathing compliance was lower than measurements during spontaneous respiration.

MANY previous studies of compliance during anesthesia have dealt with *total* compliance, an expression of both pulmonary and chest wall compliance.[1-4] There is reason to believe that measurements of total compliance in conscious untrained subjects may be erroneous.[1] The present investigation dealt only with pulmonary compliance (C_L) in supine human beings immediately before, during, and in some instances immediately after anesthesia. This was a study of dynamic, not static compliance, in which measurements were made during a series of both spontaneous and positive-pressure respirations. The purpose of the investigation was to measure C_L during anesthesia in a controlled fashion and to evaluate those variables which influence it.

Received from the Department of Anesthesiology, University of Maryland School of Medicine, Baltimore. Accepted for publication November 30, 1964. This investigation was supported by Public Health Service Research Grant HE-06429 from the National Institutes of Health.

Experimental Method

Transpulmonary pressure was measured with a Statham PM-131TC differential transducer, the distal side of which was connected to a point in the airway between the mask or endotracheal tube and absorber (fig. 1). The proximal side was connected to a 10 cm. long esophageal balloon. This was inserted to the middle-third of the esophagus. The pressure-volume characteristics of each balloon were such that no pressure changes occurred when filled with 0.1 to 1.5 ml. of air. While in the esophagus the balloon contained less than 1 ml. of air and this volume was periodically checked. Gas flow was estimated by means of a No. 1 Fleisch pneumotachograph placed between the rebreathing bag and a carbon dioxide absorption canister. The pneumotachograph screen was heated by a 5-volt current and calibrated with a continuous flow of oxygen through two Fisher-Porter flowmeters, accurate to ± 1 per cent. Flows of oxygen were converted to the physical characteristics of the anesthetic mixture at 14.7 P.S.I.A. and 70° F. The pressure differential across the pneumotachograph screen was measured with a Statham PM-5 transducer. Tidal volumes were obtained by electronic integration of flow via an Electronics for Medicine Integrator/Relay/DC Amplifier, Model IRD-2. Transpulmonary pressure, gas flow and tidal volume, displayed on the oscilloscope, were permanently strip-printed with the aid of a Rapid Writer attachment.

All measurements in both the awake and anesthetized states were made with the use of either a tight-fitting face mask or an endotracheal tube. To minimize turbulence both the mask and endotracheal tube were connected to a large-lumen angle piece with a connection for pressure measurements in the

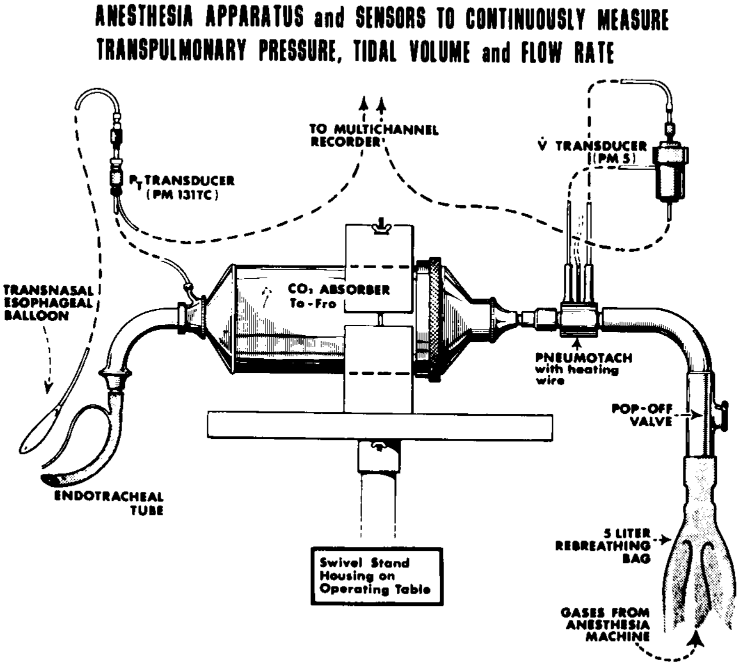

FIG. 1

airway. A 450 g. to-and-fro freshly-charged carbon dioxide absorption canister, the pneumotachograph, and a rebreathing bag completed this valveless breathing system and allowed for convenient clinical administration of anesthesia. The entire system was housed on a swivel stand attached to an operating table and adjusted to the correct height for each patient.

With zero flow rate as a reference, C_L, calculated as a ratio, was obtained by measuring simultaneous expiratory changes in tidal volume and transpulmonary pressure (fig. 2). In all instances mean compliances derived from individual series of 15 to 50 consecutive breaths (average 25) were analyzed for significance and standard error; in some instances analysis of variance was done.

The esophagus as a site for recording pressure is subject to error, especially in the supine position.[5] This disadvantage was accepted as part of the variation in the collected data. Since a large number of breaths was measured in each sequence, we did not use a mean or average of the cardiac oscillations in an attempt to minimize the pressure variations. A similar number of "low" and "high" pressure differentials resulted.

C_L was measured prior to operation in all patients in the awake state and then during general anesthesia under several conditions. To separate and study the effects of these conditions, chronologic plots from the time of induction of anesthesia to the termination of the study were constructed for each patient.

Premedication consisted of an appropriate dose of pentobarbital and scopolamine. All subjects lay on a standard operating table with a blood pressure cuff attached to the arm and an intravenous infusion of 5 per cent dextrose in water. The esophageal balloon was passed trans-nasally with 2 ml. of 4 per cent lidocaine for topical anesthesia. Prior to general anesthesia, sitting and supine C_L was measured. With the patient supine, the mean C_L served as his control. Depth of anesthesia was assessed from changes in tidal volume, EEG (fig. 2) and clinical signs.

The transducer-amplifying system and integrator were balanced before, during, and after anesthesia since the flow-volume signals in this closed, high moisture breathing system were particularly susceptible to drift. From the time of induction of anesthesia, a continuous trace of respiratory phenomena was printed until the patient was taken into the operating

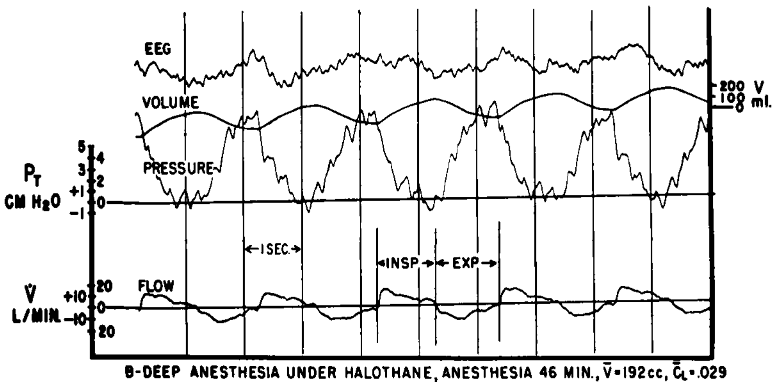

FIG. 2. Scalar trace with 1 second time lines of EEG and transpulmonary pressure, flow and tidal volume. Patient is deeply anesthetized with depressed tidal exchange and compliance.

room; the experimental run averaged 60 minutes. Five patients were studied postoperatively and allowed to awaken while similar measurements were being made.

C_L was measured in three ways:

(1) With mask, both without and with an oral airway, in that order. Data obtained during respiratory obstruction were discarded. Therefore, not all patients had C_L measured during anesthesia with a mask.

(2) With endotracheal tube: approximately 30 minutes after induction, 60 to 80 mg. of succinylcholine were administered. The lungs were then oxygenated and an effort made to approximate the patient's tidal volume to avoid the effect of excessive volumes on C_L. A cuffed endotracheal tube (9 to 10 mm. inside diameter) lubricated with 5 per cent lidocaine ointment was inserted. After spontaneous respirations returned, C_L was measured and the investigation proceeded with all parameters monitored as prior to intubation. It was believed important that no cough occur and both deep anesthesia and topical anesthesia were instrumental in effecting this.

(3) During and after IPPB. C_L was measured during controlled respirations (manually or with a Mörch piston ventilator). In addition, some patients breathing spontaneously were alternately manually assisted so that the effects of IPPB on C_L could be simultaneously compared with C_L during spontaneous respirations. At the end of the experiment all patients were brought to the operating room for the scheduled operation.

Thirty-seven patients received halothane as the primary anesthetic agent; nitrous oxide, oxygen were used as carrier gases. Thiopental was employed for induction in 25 patients (table 1). No other agents or drugs were given during the experiment except succinylcholine for intubation. There were 22 female and 15 male patients with a mean age of 39 years, a mean weight of 163 pounds and mean height of 66 inches.

Results

The Awake and Anesthetized States. C_L and tidal volume data are listed in table 1. With the exception of C_L obtained immediately after intermittent positive-pressure breathing (IPPB), C_L decreased during anesthesia when compared to the awake state. C_L fell from a control value of 0.12 liter/cm. of water to 0.08 liter/cm. of water during anesthesia with the endotracheal tube ($P < .002$), a mean decrease of 33 per cent during relatively deep anesthesia. During light anesthesia patients demonstrated a lesser decrease in C_L (table 2) than during deep anesthesia (18 per cent versus 33 per cent).

In figure 3, simultaneous C_L and tidal volume data are plotted for 1 anesthetized patient. Change in C_L is expressed as percentage deviation from conscious control. Depression or increase of both parameters proceeded in the same direction.

Sitting and Supine Positions in the Conscious State. Thirty conscious patients, first in the sitting and then supine positions, demonstrated values for compliance of 0.140 and 0.120 liter/cm. of water, respectively, a decrease of 17 per cent.

The Influence of Sex. In male patients C_L was significantly higher than in female patients

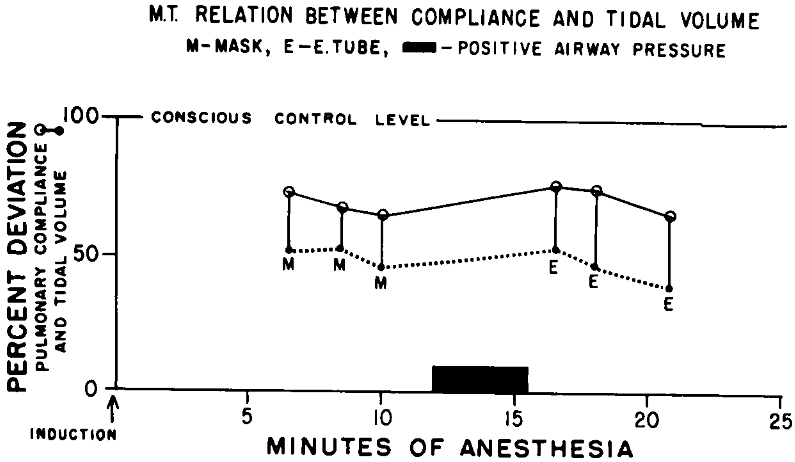

FIG. 3. Chronologic plot in one patient of simultaneous compliances and tidal volumes expressed as per cent deviation from control.

in both the awake and anesthetized states (tables 3A, 3B). Decreases in C_L from awake to anesthetized states in both men and women were similar, 37 per cent and 34 per cent, respectively ($P < 0.001$).

The difference between men and women in the decreased C_L was examined by means of analysis of variance. Results indicated a significant influence of sex on the decrease in C_L during anesthesia. That is, men apparently have not only a higher C_L, awake and anesthetized, but a greater reduction in compliance when anesthetized.

The Influence of Thiopental Induction. In the 25 patients given thiopental, an average conscious C_L of 0.11 fell to 0.06 liter/cm. of water during halothane anesthesia, a reduction of 45 per cent ($P < 0.001$). In the 12 patients who did not receive thiopental, C_L decreased from 0.13 to 0.10 liter/cm. of water, a fall of 23 per cent ($P < 0.005$).

Changes in C_L in both groups were analyzed by analysis of variance and revealed no significant influence of thiopental induction on compliance.

The Effect of Body Configuration. Patients were divided into three groups according to body configuration in the following fashion: asthenic men weighed 140 pounds or less and were 66 inches or more tall; women

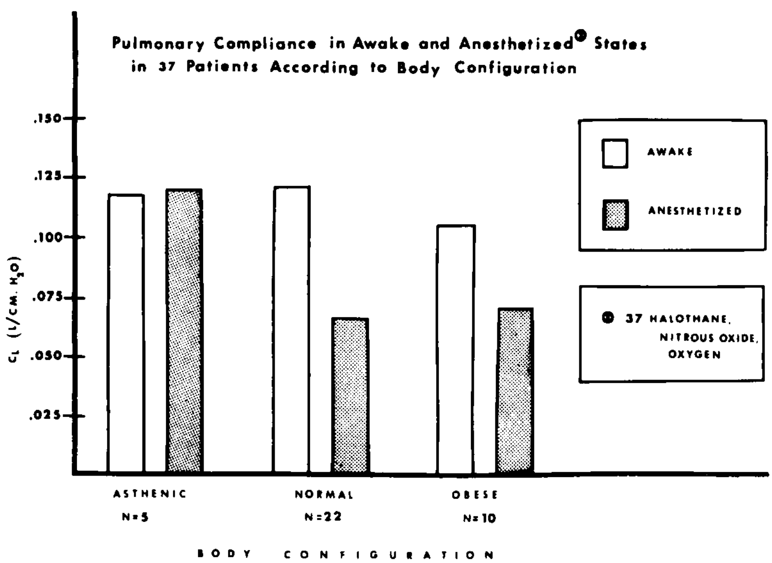

FIG. 4. Relation between body configuration and pulmonary compliance during awake and anesthetized states.

weighed 120 pounds or less and were 64 inches or more in height. Obese men weighed 200 pounds or more and were 67 inches tall or less; obese women weighed 170 pounds or more and were 66 inches tall or less. Normals included all other patients. The expression of body configuration and its extremes for example, is overtly morphological although attempts have been made to define it which are extremely complicated.[6]

The asthenic group was the only one in which C_L was not influenced by anesthesia

TABLE 1. Mean Dynamic Pulmonary Compliance (C_L) and Tidal Volume (TV) in 37 Supine Patients in the Awake State and During Halothane-N_2O-O_2 Anesthesia

Patient	Sex	Age	Weight (pounds)	Height (inches)	C_L (liter/cm. H_2O)		TV (ml.)		Thiopental Induction (mg.)
					Awake	Anesthetized	Awake	Anesthetized	
1	M	24	150	70	0.20	0.11	480	160	—
2	M	20	140	68	0.16	0.15	350	200	150
3	F	34	189	67	0.10	0.15	375	140	—
4	M	58	146	66	0.25	0.19	525	275	—
5	M	38	172	60	0.13	0.09	500	175	—
6	F	31	168	59	0.13	0.04	470	110	250
7	F	52	140	64	0.09	0.07	440	130	200
8	M	30	176	68	0.16	0.09	410	250	—
9	M	33	165	69	0.21	0.09	590	300	300
10	F	37	140	62	0.07	0.03	475	375	200
11	M	47	175	68	0.09	0.04	400	200	450
12	M	30	190	73	0.10	0.04	300	220	250
13	F	48	180	64	0.15	0.08	460	270	—
14	F	39	230	68	0.11	0.03	370	275	500
15	M	34	190	66	0.08	0.05	250	135	250
16	M	19	140	73	0.09	0.10	570	260	—
17	F	29	170	64	0.10	0.05	275	150	100
18	F	32	118	60	0.14	0.15	440	403	100
19	F	35	186	65	0.07	0.05	476	200	250
20	M	52	210	71	0.09	0.05	594	280	450
21	M	29	168	70	0.06	0.06	574	300	350
22	M	57	156	71	0.15	0.08	701	150	250
23	F	33	182	64	0.12	0.10	414	300	—
24	F	33	190	70	0.11	0.13	355	246	400
25	F	38	143	64	0.06	0.02	347	190	50
26	F	49	160	64	0.08	0.03	468	220	—
27	F	35	137	62	0.14	0.09	648	160	250
28	F	59	140	64	0.10	0.05	576	252	—
29	M	25	141	72	0.15	0.14	542	378	—
30	F	46	160	64	0.05	0.03	447	240	150
31	F	40	133	66	0.04	0.04	241	255	—
32	F	44	128	62	0.05	0.06	540	310	100
33	F	29	180	66	0.11	0.05	356	193	300
34	F	52	160	65	0.08	0.06	406	230	225
35	M	58	159	69	0.33	0.13	632	301	250
36	F	47	134	59	0.08	0.04	627	227	200
37	F	49	172	62	0.09	0.02	517	136	225
Range		19–59	118–230	59–73	.04–0.33	.02–0.19	241–701	110–403	50–500
Mean		39	163	66	0.12	0.08	463	232	248
Mean % decrease						33.3		50.0	
Significance						$P<0.002$		$P<0.001$	

TABLE 2. Pulmonary Compliance (C_L) in Liter/Cm. of Water in 13 Patients Awake and During Light Halothane Anesthesia*

	C_L Awake	C_L Anesthetized	Average % Change
Mean	0.107	0.088	−17.7**
Range	0.04–0.33	0.05–0.16	

* Average of 5–10 minutes after induction, no airway, unobstructed.
** Mean Difference ± $SE_{\bar{x}}$ = .021 ± .002
This is not significant at the 5 per cent level.

(fig. 4). All others showed a significant drop in C_L from the awake to anesthetized states.

The Influence of Intermittent Positive-Pressure Breathing (IPPB). In 20 patients there were 55 instances wherein C_L was measured during IPPB as compared with C_L during spontaneous breathing beforehand. Mean C_L fell from a control value of 0.083 liter/cm. water during spontaneous breathing to 0.063 liter/cm. of water with positive-pressure breathing, a decrease of 24 per cent ($P < 0.001$).

In addition, assisted respirations were alternated with spontaneous respirations during anesthesia. In 15 instances in 8 patients, mean C_L during spontaneous breathing was 0.079 liter/cm. of water. Those obtained during assisted respirations were 0.061 liter/cm. of water, a decrease of 23 per cent ($P > 0.05$).

Discussion

There are certain objections to previous studies of compliance performed during anesthesia. Conclusions have been drawn from studies lacking controls in the conscious state or employing small numbers of controls.[1, 2, 7, 8] Values from conscious patients in the sitting position have also been used as a basis of comparison.[1, 7, 8] With total compliance, subjects may be unable to relax their respiratory muscles thereby providing a measure of "assistance" by inspiratory muscles. This results in control compliances that are too high.[1] This investigation of pulmonary compliance included a control period for each patient studied in the conscious state. Total compliance as a composite of both chest wall and lung compliance is influenced by more variables than either alone. For example, a surgeon leaning on the chest wall would influence total compliance primarily by decreasing chest wall compliance. However, changes in compliance during anesthesia appear to be more closely related to pulmonary rather than total compliance.[7, 8] Previous investigations have employed single breath measurements or a few breaths. Such measurements might vary widely and present considerable aberration from the normal. This has been obviated in the present study with the use of a series of consecutive breaths (average 25) and a calculation of means—an effective way of approximating a steady state.

The present investigation indicated that a decrease in compliance occurred during anesthesia and is in agreement with previous studies.[1, 2, 7, 8, 9] During spontaneous breathing, it appeared that decrease in C_L was directly related to decreased tidal volume. There was greater decrease in C_L with prolonged or deep anesthesia than during induction or light anesthesia, or during emergence from anesthesia, when tidal exchange approximated control levels. Wu, Miller and Luhn demonstrated maximal depression of both spontaneous respirations and C_L two hours after induction of anesthesia when compared with controls.[9] Mead and Collier showed little change in C_L early in anesthesia.[10] There is, therefore, evidence that it is not depth of anesthesia but some factor at work during anesthesia related to tidal exchange which influenced compliance. That decreased C_L was predictably increased by IPPB with augmented tidal volume was shown by Mead and Collier and corroborated by our own experience.[10]

Decreased C_L in conscious man during quiet breathing has been recognized and explained on the basis of either closure of lung units (atelectasis) or alteration of surface tension forces.[11] The role of decreased volume of thoracic gas or functional residual capacity (FRC) has been assessed in conscious subjects and anesthetized animals,[10] but not during the present study nor in anesthetized man; it is suspected of being highly significant. When McIlroy and workers reduced FRC by one liter by means of chest compression in normal sitting volunteers, not only did C_L decrease by approximately 50 per cent but it failed to return to normal with release of chest compression, and did so only when the subjects inhaled deeply.[12] Although conclusive evidence is not available, it is reasonable to assume that some form of atelectasis occurred as general anesthesia deepened.[3]

The supine position is most frequently employed during surgical anesthesia, but since the majority of conscious C_L data is derived from sitting patients, investigation of the differences in C_L in the two positions was performed with conscious patients prior to induction of anesthesia. An average decrease of 17 per cent in C_L occurred with a change from the sitting to supine position. This agrees with a previous report.[13]

Male patients demonstrated significantly higher C_L in both awake and anesthetized states. The decrease in C_L from awake to anesthetized states was also greater. It should be realized, however, that lung volume data were not included; men in this study probably had higher lung volumes than female patients and while this may be the reason for higher absolute compliances in men than women it does not explain the greater decrease in compliance from the awake to anesthetized states in men. A higher incidence of respiratory complications in men after anesthesia and operation has been demonstrated.[14] In addition, a higher incidence of bronchospasm in asthmatics has been shown in men during anesthesia.[15] There may be a relation between this difference in pulmonary mechanics between the sexes and the incidence of respiratory complications.

Reduction of C_L in the patients given a thiopental induction was greater than in those patients who received the inhalation induction.

Body configuration apparently influences C_L during anesthesia. The majority of patients belonged to the "normal" and obese groups and had decreased C_L during deep anesthesia. Asthenic individuals did not. There is little in the literature relating body configuration to C_L changes during anesthesia. Conscious obese subjects have decreased total compliance primarily because of lowered chest wall, not pulmonary compliance.[16] It is possible that the thin patients in this study were able to maintain a normal FRC during anesthesia while the "normal" and obese subjects did not. The weight of a thick chest wall in those who were not asthenic and the effect of gravity in the supine position may have a bearing on this phenomenon.

TABLE 3A. Pulmonary Compliance (C_L) in Liter/Cm. of Water in 15 Male Patients Awake and During Halothane Anesthesia

	C_L Awake	C_L Anesthetized	Average % Change
Mean	0.150	0.094	−37*
Range	0.06 − 0.33	0.04 − 0.19	

* Mean Difference ± $SE_{\bar{x}}$ = .056 ± 0.014. This is significant at the 0.1 per cent level.

TABLE 3B. Pulmonary Compliance (C_L) in Liter/Cm. of Water in 22 Female Patients Awake and During Halothane Anesthesia

	C_L Awake	C_L Anesthetized	Average % Change
Mean	0.094	0.062	−34*
Range	0.04 − 0.15	0.02 − 0.15	

* Mean Difference ± $SE_{\bar{x}}$ = 0.032 ± 0.008. This is significant at the 0.1 per cent level.

The last variable studied was intermittent positive-pressure breathing (IPPB). Our results agreed with previously reported studies in conscious and anesthetized subjects, demonstrating a reduction in compliance during IPPB when compared with measurements during spontaneous breathing.[7,8,17] The converse has also been reported.[10,18] A second approach to the problem was made with assisted respirations alternating with spontaneous breathing during anesthesia. Again C_L decreased during IPPB. Regardless of the change in compliance, since the patient was not using his own respiratory muscles during IPPB, his work of breathing did not increase.

Summary

Dynamic pulmonary compliance was measured in 37 patients prior to operation in the awake and anesthetized states during various conditions. In spontaneously breathing patients during halothane anesthesia, data were obtained free from the influence of both respiratory obstruction and excessive tidal vol-

umes. Compliance decreased approximately one-third from the awake to the deeply anesthetized state. However, during light anesthesia when tidal exchange approximated control values, C_L was not significantly depressed. An apparent relation existed between tidal exchange and compliance such that during deep anesthesia with decreased tidal exchange compliance also decreased. There was no direct evidence that the state of anesthesia or depth of anesthesia *per se* influenced compliance. The possibility was suggested that the volume of thoracic gas decreased during depressed spontaneous respirations which accompany deep anesthesia in the supine position; this led to atelectasis and subsequently decreased FRC. Therefore, the lung volume history directly influenced C_L.

In the conscious patient C_L decreased from the sitting to the supine position.

Compliances in men were higher in both the awake and anesthetized states while the decrease in compliance was significantly higher in male patients.

Patients with either halothane or thiopental induction demonstrated decreased compliance, but thiopental was associated with a greater decrease.

Body configuration influenced C_L during anesthesia. While normal and obese patients underwent significant C_L changes during anesthesia, thin patients did not.

During intermittent positive-pressure breathing, C_L was decreased when compared with C_L obtained in spontaneously breathing patients during general anesthesia. The same fall occurred during assisted respirations imposed alternately with spontaneous breaths.

The following individuals contributed significantly to this investigation: Holcombe Hurt, Jr., M.D., Michael Ashman, M.D., Lillian Chambliss, A.B., Barbara Eerligh, R.N., Martin Quinn, Augustin Gombart, A. B. The statistical analyses in this study were provided by Dr. William Reinke.

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