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Research Article

THE COMPLIANCE OF THE HUMAN THORAX IN ANESTHETIZED PATIENTS

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In 1946, Rahn, Otis, Chadwick, and Fenn (1, 2) described a method for obtaining relaxation pressure-volume data for conscious subjects. Essentially the method requires that the subject inspire a measured volume, then close his mouth and nose and relax his respiratory muscles. During the period of relaxation, the pressure in the airway is measured by a manometer connected to a nasal tube; this pressure is assumed to equal alveolar pressure if the glottis is open and there is no airflow. Similar pressure measurements are made at the end of inspirations of different volume, and a relaxation pressure-volume curve plotted. Muscular relaxation is essential for this measurement if it is intended to give information about the balance between the elastic forces of the lungs and those of the remainder of the thorax, uninfluenced by active or reflex contraction or tonus of the respiratory muscles.

The method of Rahn, Otis, Chadwick, and Fenn (1) appeared to be a simple technique for determining the elastic properties of the thorax of patients with cardiopulmonary disease and accordingly we applied it to a group of normal subjects and patients. However, we had considerable difficulty in obtaining reproducible curves in many of these (Figure 1). Occasionally, this was due to the subject's inability to keep his glottis open but more often it appeared to be related to his inability to relax his respiratory muscles at end-inspiration. This led us to speculate whether even a cooperative and well trained subject, having inspired to certain volumes, could voluntarily relax all of his inspiratory and expiratory muscles and relax these completely at all lung volumes. To test this, we obtained pressure-volume data in 20 anesthetized patients made apneic either by hyperventilation or by the injection of neuromuscular blocking agents and compared these with the data of Rahn, Otis, Chadwick, and Fenn (1). We found that at a given volume-inflation of the lungs, the pressure was about two times as great in our anesthetized patients as in the conscious subjects. To eliminate the possibility that this finding was due to different physical characteristics of our subjects as compared with Rahn's, we studied a second group of six patients in whom pressure-volume curves were obtained when the patient was unanesthetized and "relaxed" and then again after the patient had been anesthetized. Again the thorax was less compliant when the subjects were anesthetized.

METHODS

The physical characteristics of the patients are presented in Table I. The patients were about to undergo surgical procedures under general anesthesia but all were free from clinical pulmonary disease except for patient No. 5 who had mitral stenosis and No. 20 who had a right apical lung cyst. All patients were anesthetized and studied in the supine position, with two exceptions (see Table I). In most cases, a cuffed endotracheal tube, nasopharyngeal tube or oral airway was introduced to insure an open airway. Just before the measurements of pressure and volume were made, apnea was produced by passive hyperventilation with high oxygen mixtures or by the injection of decamethonium bromide or succinyl choline chloride (Table I). Then one arm of a four-way metal tube (Figure 2) was attached to the anesthesia mask or endotracheal tube, a second arm to a Benedict-Roth spirometer writing on a rapid kymograph, a third arm to the anesthesia machine and the fourth to an anaeroid manometer. Hemostat B was closed, the lungs were inflated by pressure on the anesthesia bag and then hemostat A was also closed. After reading the pressure in the static mask-airway-lung system, hemostat B was removed, permitting the lungs to deflate passively to their resting expiratory level; the expired volume was recorded on a kymograph and corrected to B.T.P.S. Between measurements, the anesthetist employed controlled respiration in order to maintain anesthesia and/or produce adequate ventilation. Five to 20

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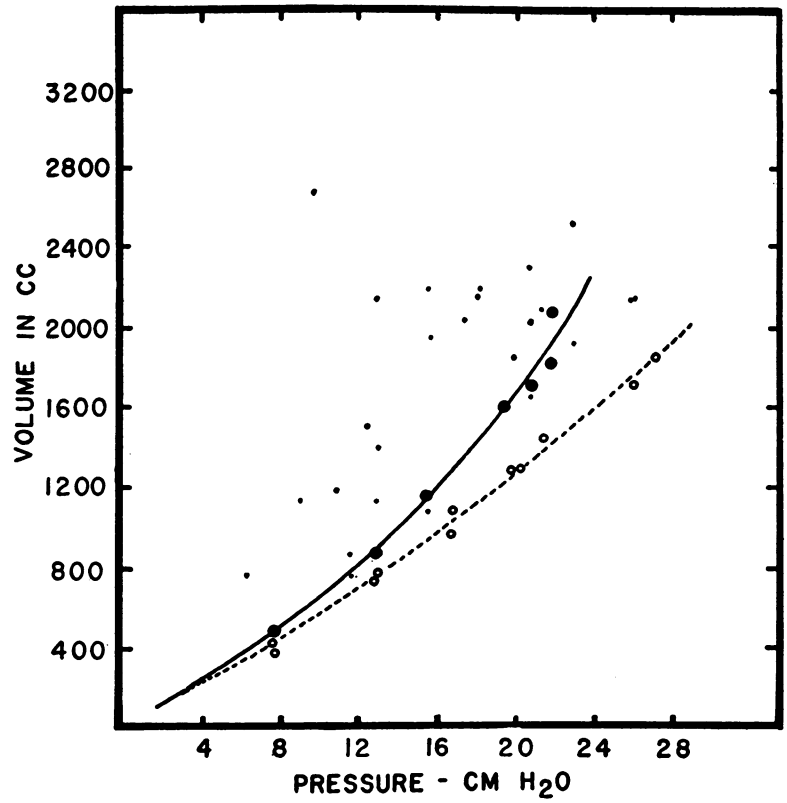

FIG. 1. COMPARISON OF PRESSURE-VOLUME CURVES IN THE CONSCIOUS AND IN THE ANESTHETIZED PATIENT

Small closed circles are the first points obtained in the conscious, relaxed state. Large closed dots represent the last seven values in the conscious, relaxed state after the patient had been trained. Open circles are values obtained after apnea was produced by anesthesia and succinyl choline.

measurements of various pressures (2 to 30 cm. H_2O) and the corresponding volumes were made over a five-minute period and pressure-volume curves were graphed (3). The scatter of points about free-hand drawn curves was small in all subjects. Because these were curves, no single value for compliance (cc. volume change per cm. H_2O pressure change) could be used to express the data. We decided arbitrarily to measure the volume increase at 20 cm. H_2O pressure in order to compare data in different individuals (Tables I and II).

In patients number 21 to 26, relaxation pressure measurements (method of Rahn) were also made before pre-anesthetic medication was given; measurements were repeated within three hours on the same patients in the anesthetized state.

RESULTS

The compliance of the thorax of anesthetized patients number 1 to 20 was found to be far less than that reported by Rahn for 10 conscious, relaxed, supine subjects. This was true whether the data were compared as per cent of vital capacity (Figure 3) or as volumes above the resting expiratory level (Figure 4). Our patients were predominantly female and their average age (42.5 years) was considerably greater than that of Rahn's subjects. However, the dissimilar physical characteristics of the two groups of subjects cannot explain these differences because patients number 21 to 26 (all female, average age 33 years) had pressure-volume data similar to those obtained by Rahn when they were studied in the conscious, "relaxed" state. Nevertheless, compliance decreased markedly when these six patients were anesthetized and made apneic by hyperventilation or succinyl choline (Table III).

TABLE I *, †

No.	Patient	Sex	Age	Ht. (*in.*)	Wt. (*lbs.*)	V.C.‡ (*cc.*)	B.P. (*mm. Hg*)	Type of airway‡	Anes.‡	Type of apnea‡	Thoracic compliance at 20 cm. H_2O (*cc./cm.* H_2O)
1	P. D.	F	41		101		120/70	O. M.	T.N.	H.V.	48
2	L. W.	F	47	65	136	(2,970)	140/100	E.	C.	H.V.	59
3	E. H.	F	32	69	189	(3,500)	150/80	N. M.	T.N.E.	D., H.V.	90
4	K. S.	F	20	65	110	(3,330)	130/70	N. M.	T.N.	D.	99
5	K. B.	F	36	62	119	(3,150)	110/80	E.	C.E.	H.V.	73
6	M. M.	F	49	65	145	(2,350)	185/110	E.	T.C.E.	H.V.	69
7	J. D.	M	42	74	240	4,250	120/80	E.	T.C.E.	H.V.	59
8	R. F.	F	41		120		120/80	E.	T.C.E.	H.V.	59
9	P. B.	F	21	64	111	(3,250)	90/20	N. M.	T.	D.	81
10	E. J.	F	50		225		140/80	N. M.	T.	D.	55
11	B. G.	F	44	59	125	(2,700)	240/130	E.	C.E.	H.V.	48
12	C. J.	F	58	67	160	(2,720)	110/70	E.	C.E.	H.V.	65
13	L. F.	M	45	70	105	3,760	125/70	E.	T.C.E.	H.V.	100
14	M. S.	M	51	66	145	(4,020)	70/60	E.	C.E.	H.V.	97
15	H. K.	F	29	62	135	(3,150)	130/80	O. M.	N.E.	H.V.	55
16	C. E.	F	66	61	136	(2,010)	140/100	E.	T.C.E.	D., H.V.	42
17	L. B.	F	29	63	123	(3,200)	120/70	O. M.	N.E.	H.V.	62
18	P. D.	F	62	66	190	1,710	140/80	E.	T.C.	H.V.	21
19	L. C.	M	43	70	164	2,940	140/90	E.	T.C.E.	H.V.	91
20	J. P.	M	44	64	165	(4,060)	100/60	E.	T.C.E.	H.V.	64
21	W. C.	F	30	61.5	116	1,840	90/50	M.	T.	S.	51
22	M. McC.	F	22	61.5	97	2,680	90/40	M.	T.	S.	75
23	B. B.	F	53	62.5	200	3,000	198/110	M.	T.	H.V.	57
24	C. W.	F	36	61	110	2,500	140/80	M.	T.	S.	54
25	M. B.	F	34	61	128	2,750	140/70	M.	T.	H.V.	63
26	D. W.	F	24	64	135	2,120	100/70	E. M.	T.N.C.	S., H.V.	63, 46

* All patients were supine except for No. 6 (left lateral nephrectomy position) and No. 20 (left lateral thoracotomy position).

† All patients received morphine preoperatively (with scopolamine or atropine) except for No. 5 (Demerol®+ atropine) and No. 26 (scopolamine alone).

‡ Parentheses around number means V.C. was calculated from physical data; otherwise V.C. = measured value. E = cuffed endotracheal tube; O = oral airway; N = naso-pharyngeal airway; M = mask. T = thiopental; N = $N_2O - O_2$; C = cyclopropane; E = ether. D = decamethonium bromide; S = succinyl choline; H.V. = hyperventilation.

DISCUSSION

The purpose of these experiments was to measure the elastic properties of the thorax of man, uninfluenced by contraction or tone of the respiratory muscles. In order to eliminate the effect of conscious muscular effort, the studies were done on anesthetized patients. Our experience with anesthetized animals (3) however, indicated that, because of interference by pulmonary reflexes, we would not obtain satisfactory pressure-volume curves unless the anesthesia was deepened to the point of respiratory failure. Since such deep anesthesia in man would neither be safe nor yield physiological data, we decided to eliminate rhythmic respiratory movements by (a) hyperventilat-

TABLE II

Values for compliance of human thorax

Method and investigator	Number of subjects: Male	Number of subjects: Female	Mean values (*cc./cm.* H_2O *at 20 cm.* H_2O *pressure*)
Conscious subject, relaxation pressures (1)	9	1	130
Conscious subject, relaxation pressures (2)	8	0	139
Conscious subject, relaxation pressures (present work)	3	9	111
Conscious subject in body respirator (4)	3	0	118
Conscious subject in body respirator (5)	2	0	115
Anesthetized, apneic subjects (present work)	5	2	62

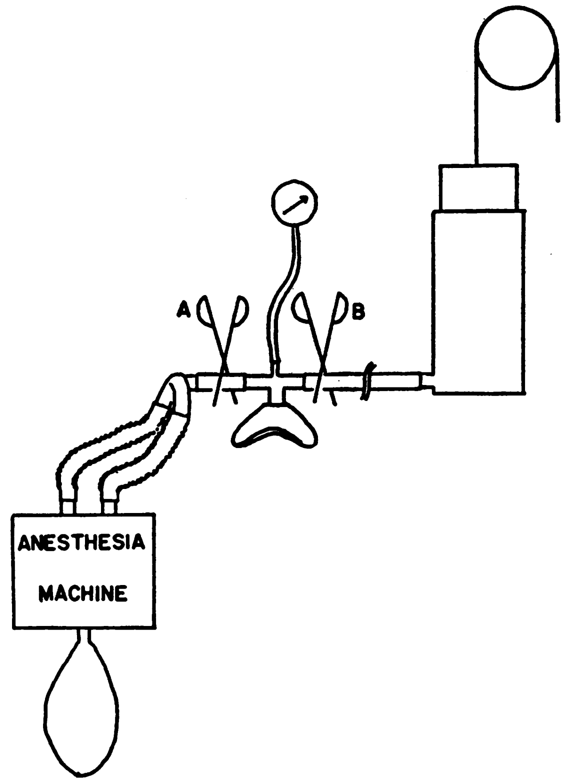

FIG. 2. APPARATUS USED THROUGHOUT THE STUDY
For details of use, see text.

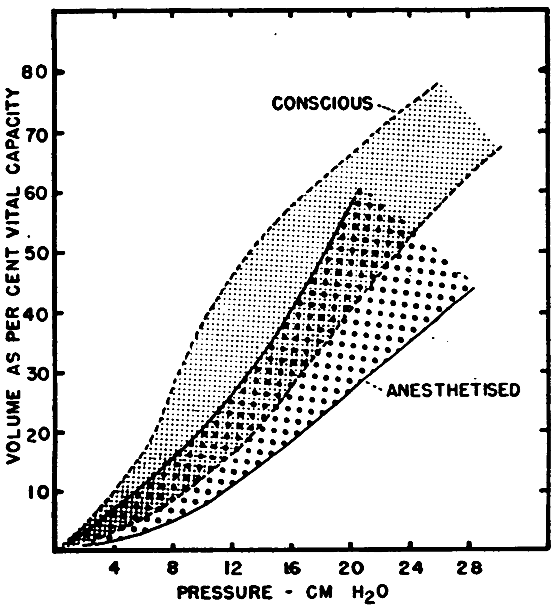

FIG. 3. COMPARISON OF DATA FOR COMPLIANCE IN TEN CONSCIOUS RELAXED PATIENTS (DATA OF RAHN, OTIS, CHADWICK, AND FENN (1) AND IN 20 ANESTHETIZED PATIENTS USED IN THIS STUDY

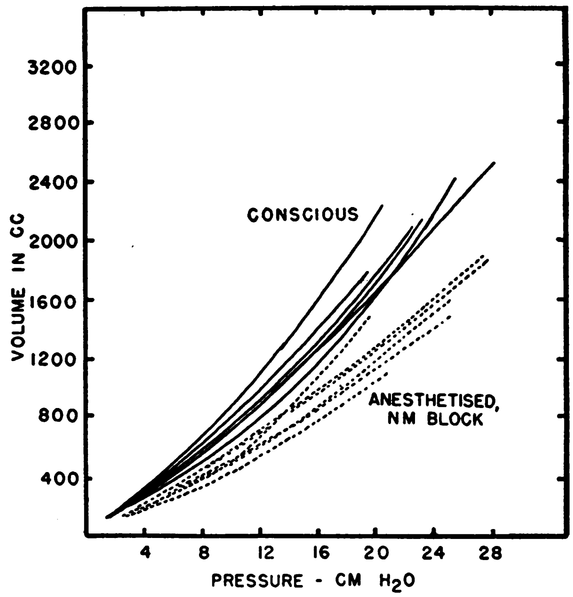

FIG. 4. COMPARISON OF VALUES FOR COMPLIANCE IN SIX PATIENTS IN THE CONSCIOUS, RELAXED STATE AND AFTER APNEA INDUCED BY SUCCINYL CHOLINE AND ANESTHESIA

ing patients under surgical anesthesia with high oxygen mixtures or (b) supplementing the anesthesia with neuromuscular blocking agents. Adequate amounts of the latter agents probably eliminate all contractions and tone of the respiratory muscles. There is no assurance that hyperventilation abolishes tone; however, increase in arterial Pco_2 increases inspiratory tone in the apneustic animal (6) and presumably a decrease in arterial Pco_2 has the opposite effect.

There is no doubt from the experiments in which each patient was used as her own control

TABLE III

Compliance of thorax at 20 cm. H_2O pressure (increase in volume above F.R.C.)

Patient No.	Conscious "relaxed"	Anesthetized +Succinyl choline	Anesthetized +Hyperventilation
21	2,120	1,010	—
22	2,360	1,490	—
23	1,800	—	1,140
24	1,700	1,080	—
25	2,380	—	1,260
26	1,590	1,260	920
Mean	1,992	1,210	1,107

that the thorax was less compliant when the patient was anesthetized and apneic than when she was conscious and "relaxed." One might conclude from this that "relaxation" pressure curves in conscious subjects do not in fact provide a true measure of elastic forces because inspiratory tone still exists and creates a larger thorax than in the truly relaxed state. This conclusion is strengthened by the studies of Gordon, Fainer, and Ivy (7) who found that manual methods of artificial respiration always produced a greater tidal exchange when the subject was conscious and "voluntarily suspended" his breathing than when the same subject was anesthetized and curarized; they attributed this to the inability of subjects to suppress completely "normal respiratory mechanisms and the desire to breathe."

However, before such a conclusion can be accepted, it must be shown that the anesthesia, hyperventilation or neuromuscular blocking agents have not produced changes in the properties of the lungs and other thoracic structures other than the suppression of muscular contraction and tone. Some of these alterations might be:

(a) *Bronchial obstruction.* It is possible that anesthesia, hyperventilation, the use of drugs, or the insertion of an endotracheal tube, may lead to bronchial obstruction by constriction of bronchiolar smooth muscle, mucosal edema or congestion or the secretion of mucus. It is known that bronchiolar obstruction may decrease lung compliance [3] by reducing the lung volume in communication with the ambient air (8) and possibly also by a "stiffening" of lung tissue; indeed, intense bronchiolar constriction may result in a pressure-volume curve that is essentially that for the tracheal-bronchial tree (9). We were unable to measure absolute values for F.R.C. in the operating room and we have no certain way of knowing whether the airways to some alveoli were occluded completely. However, if the changes in compliance were due to this factor alone, approximately 40 per cent of the airways must have been completely occluded.

(b) *Pulmonary congestion.* Price, Conner, and Dripps (10) have found that prolonged deep anesthesia with cyclopropane may lead to changes suggestive of pulmonary congestion; anesthesia with Pentothal® does not produce similar effects. We did not use Price, Conner, and Dripps' technique and cannot be sure that pulmonary congestion did not occur as a result of the use of anesthesia or neuromuscular blocking agents. However, the change in compliance noted in our studies occurred in patients anesthetized with ether, thiopental, and nitrous oxide as well as with cyclopropane and occurred whether anesthesia was deep or light (apnea produced by neuromuscular blocking agents).

(c) *Change in skeletal muscle tone.* It is possible that hyperventilation, by a reduction in arterial P_{CO_2}, may lead to a decrease in inspiratory and an increase in expiratory tone of the respiratory muscles and that this may lead to a further decrease in compliance. However, neuromuscular blocking agents are believed to paralyze both the inspiratory and expiratory muscles of respiration. The resting expiratory level was recorded in six additional patients during the administration of succinyl choline and indicated that a mean *increase* in F.R.C. of 257 cc. occurred. This rules out contracture of the expiratory muscles but does not eliminate the possibility of a contracture of the inspiratory muscles. Both decamethonium and succinyl choline are capable of causing contracture of skeletal muscle in some species but, in man, they generally lead to transient fasciculation followed by flaccid paralysis. In our studies, decamethonium and succinyl choline were administered until complete apnea developed.

(d) *Changes in vagal reflexes.* Certain anesthetic agents sensitize vagal stretch receptors and lead to rapid shallow respiration (11); although these effects would not be apparent in an apneic patient, they might be reflected in an increased tone of respiratory muscles. Culver and Rahn (12) and Van Liew (13) have shown that va-

[3] The term "lung compliance" is used in this paper to mean the increase in *lung* volume per unit pressure change. The term "thoracic compliance" is used to denote the increase in *thoracic* volume per unit pressure change applied to the airway; "thoracic compliance" includes compliance of the lung plus that of the chest wall and its muscles, the diaphragm and intrathoracic structures displaced by inflation of the lungs. "*True* thoracic compliance" is used to denote the increase in thoracic volume per unit pressure change applied to the airway when no voluntary or involuntary skeletal muscle contraction or contracture assists or resists the volume change.

gotomy is followed by increased thoracic compliance [8] in anesthetized dogs. From this, it appears that the vagi carry tonic impulses which contribute to decreased thoracic compliance, possibly to prevent overdistention of pulmonary tissues. Nevertheless, afferent vagal impulses should not be able to exert any influence after complete neuromuscular block has been produced, as in these studies.

(e) *Artefacts.* Rahn measured inspired volume whereas we measured the volume expired after lung inflation. The positive intrapulmonary pressure used in our studies may reduce pulmonary blood volume, thus allowing more room for air; however, correction for this factor would yield still lower values for compliance in our anesthetized patients.

CONCLUSIONS

We have no certain way of determining whether the true value for compliance of the thorax,[8] uninfluenced by contraction or tone of the muscles of respiration, is that obtained in conscious, "relaxed" man or in anesthetized, apneic patients. We suspect that the value obtained in conscious man is too high because man may be unable voluntarily to suppress completely the tone of his inspiratory muscles. However, we have not been able to prove that the only important change in our apneic patients is the production of flaccid paralysis or to rule out, by direct means, the possibility that compliance is abnormally low because of changes produced by anesthesia, intubation, drugs or hyperventilation.

Regardless of which values are closer to the normal, the data obtained by us in anesthetized patients are certain to be closer to the true values for compliance in narcotized or apneic patients in need of artificial respiration (14) and these values, rather than those obtained in conscious persons, should be the ones used in the design of apparatus for artificial respiration. It is also important for the anesthetist, using controlled respiration, to realize that anesthetized patients have decreased thoracic compliance, compared to "normal" values in the literature.

The method used in this study requires no special apparatus and could be used routinely by anesthesiologists to determine changes in compliance and the effectiveness of controlled respiration in terms of tidal volume.

SUMMARY

1. Pressure volume data for the thorax were obtained in 26 patients, under surgical anesthesia, made apneic by passive hyperventilation or by the injection of decamethonium bromide or succinyl choline. In six of these patients, relaxation pressure-volume data were also obtained in the conscious state shortly before anesthesia was induced.

2. The compliance of the thorax (cc. volume change per cm. H_2O pressure change) was greater in the conscious, "relaxed" state than in the anesthetized patients with complete apnea.

3. Reasons are given for considering that conscious individuals may not be able to relax completely their respiratory muscles and that values for compliance in the conscious "relaxed" state may include not only a measure of the elastic forces of the thorax but also a measure of "assistance" by the tone of the inspiratory muscles. Values obtained in patients with neuromuscular block may be closer to true values for compliance of the thorax, uninfluenced by muscle tone or contraction.

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