RESPIRATORY VOLUME-PRESSURE RELATIONSHIPS DURING ANAESTHESIA*

CHARLES L. WALTEMATH, M.D., NORMAN A. BERGMAN, M.D., AND DONALD D. PREUSS, M.D.

RESPIRATORY VOLUME-PRESSURE RELATIONSHIPS ($\Delta V/\Delta P$) are quantified in terms of compliance. The effect of general anaesthesia on the compliance of the total respiratory system (lungs plus chest wall) remains in dispute. Most workers have reported a reduction in compliance during anaesthesia.[1-8] However, others have reported compliance to be increased,[9] or unchanged.[10,11] One obstacle to the interpretation of these previous studies is that methods used to obtain control pre-anaesthetic measurements were different from those used in the anaesthetized subject. For example, measurements obtained by attempts at voluntary relaxation of respiratory muscles in conscious subjects have been compared with values obtained by passive inflation of the respiratory system in anaesthetized individuals. In this study, we have measured volume-pressure relationships for the total respiratory system in the conscious subject and again under several conditions following induction of general anaesthesia using identical methods under all circumstances. In addition, a new method for representation of respiratory volume-pressure data in logarithmic form is used to facilitate presentation, analysis and interpretation of results.

METHODS

Respiratory compliance was measured using the weighted spirometer technique of Cherniak and Brown.[12] The subjects of the study were 16 consenting adults scheduled for elective operations. All were free of systemic disease, did not smoke and ranged in age from 19 to 55 years. Seven were anaesthetized with halothane with oxygen and nine with neurolept-analgesia† with oxygen.

The experimental apparatus is represented in the diagram in Figure 1. All subjects were studied in the supine position and breathed either from a tightly fitting face mask or through a cuffed tracheal tube. Pressure within the airway relative to atmospheric was measured from the side-arm of the mask adapter using a Sanborn 270 transducer calibrated against a water manometer and recorded on a Sanborn 954 recorder. Respiratory volume changes were recorded on the spirometer kymograph (Collins, 9L). All volume changes were corrected for gas compression and water displacement in the spirometer circuit, and were converted to B.T.P.S.

In the halothane group, the subjects were studied in the conscious state and

*Department of Anesthesiology, University of Oregon Medical School, Portland, Oregon 97201.

Presented in part at the annual meeting of the American Society of Anesthesiologists, Atlanta, Georgia, October 1971.

†Innovar.

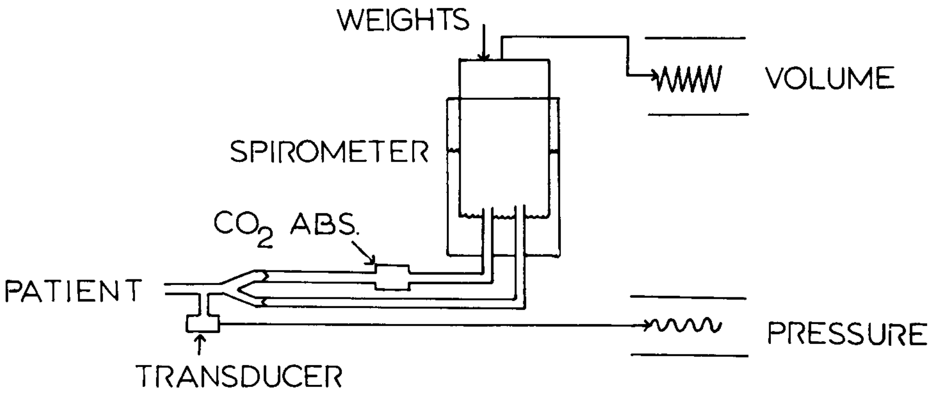

FIGURE 1. The experimental apparatus.

again following thiopentone sedation. At these times they breathed 100 per cent oxygen from the spirometer. Anaesthesia was then induced with halothane in oxygen. After a stable level of anaesthesia was obtained, the subjects were again studied while breathing halothane 1 per cent in oxygen from the spirometer. They were then given succinylcholine and studied during neuromuscular paralysis both with the mask and the tracheal tube. Several were then studied following return of spontaneous ventilation through a tracheal tube. Finally, all subjects were studied during neuromuscular paralysis with d-tubocurare through a tracheal tube. Ventilation of apnoeic subjects was performed between measurements by periodic manual depression of the spirometer bell.

In the neurolept anaesthesia group, induction was carried out by intravenous injection of 1 ml of Innovar per 15 pounds body weight. These patients were then studied during spontaneous ventilation and during succinylcholine paralysis.

One of the subjects was studied with both tracheal and bronchial intubation. This allows comparison of compliance after acute reduction in lung volume.

In all study situations, after a stable base line for end-expiratory pressure and volume had been obtained, four different weights in varying sequence were placed on the bell of the spirometer. This results in movement of gas from the spirometer into the subject and a shift in the end-expiratory volume and pressure base lines. The volume and pressure changes were derived by comparing the end-expiratory readings with and without weighting of the spirometer. This technique was used both in conscious subjects and in spontaneously breathing and apnoeic anaesthetized subjects. Figure 2 is a representative tracing from subject five of the halothane group.

All volume changes were expressed as a percentage of the patient's calculated vital capacity.[13] These volumes were then related to their corresponding transthoracic pressure changes on logarithmic coordinates. The basis for this method of presentation of data, the derivation of the volume-pressure curve, its slope and relationship to elasticity of the respiratory system are discussed in the appendix. The logarithmic plot results in a linear relationship between volume and pressure (Figure 3b). The slope of the line reflects the change in volume per unit change in

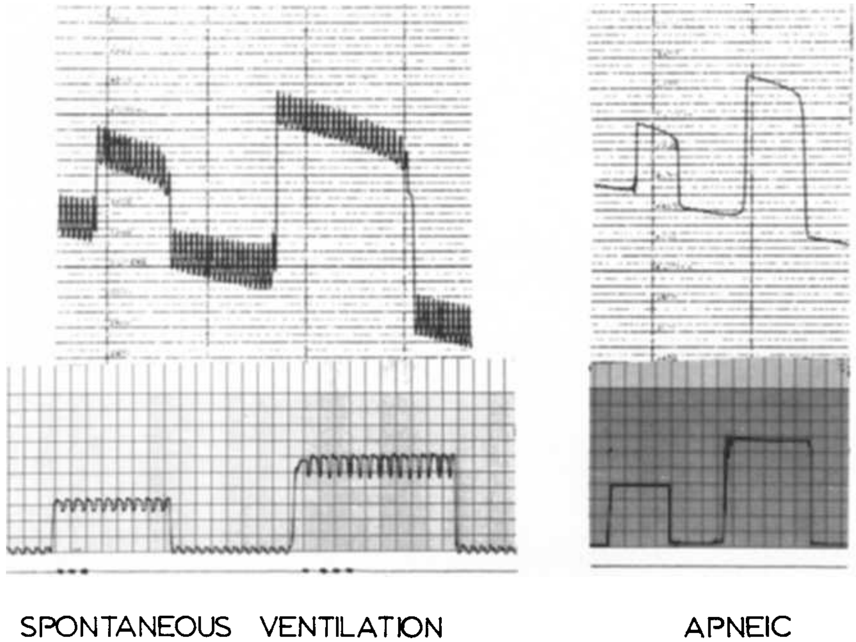

FIGURE 2. Representative tracings from a subject anaesthetized with halothane through a tracheal tube. The volume change due to weighting the spirometer is the difference between the end-expiratory points on each volume base line. The technique is useful in spontaneously breathing subjects and during apnoea.

pressure ($\Delta V/\Delta P$) and reflects the elasticity of the system. A larger value would be associated with increased compliance.

Statistical analysis of the difference in slope between the study conditions was done by paired "t" test.

RESULTS

All data are tabulated as the value of the slope of the volume-pressure curve. Individual data for all subjects under all study conditions are presented in Table I and Table II. In each case, the relationship between the logarithm of volume and the logarithm of pressure was linear with a coefficient of correlation (r) between the two variables of 0.91. For graphic comparison, the data for subjects awake and then anaesthetized with halothane through a tracheal tube and paralyzed with curare are presented in Figure 3.

There were no significant differences in the slope of the volume-pressure lines among the various conditions studied. In all cases $p > 0.5$ in the halothane group and $p > 0.1$ in the neurolept group. This is interpreted as indicating that none of the factors associated with anaesthesia with or without neuromuscular paralysis influences the elasticity of the respiratory system.

The data from the patient studied during bronchial intubation are presented in Figure 4. The slope values are: tracheal tube 1.21 and bronchial tube 1.43. If the data are plotted on conventional rectangular coordinates (Figure 4a), a reduction

TABLE I

COMPOSITE DATA FOR SUBJECTS IN THE HALOTHANE GROUP
(SDC = succinylcholine; d-tc = curare)

Subject	Age	Height (cm)	Predicted V.C.	Conscious	Thiopentone	Halothane (mask)	Halothane, SDC (mask)	Halothane (tube)	Halothane, SDC (tube)	Halothane, d-Tc (tube)
1	55	157	3460	1.18	1.21	1.21	1.36	1.28	1.28	1.73
2	46	157	3460	1.46	1.35			1.36	1.17	1.28
3	23	157	3460	1.26	1.13	1.14	1.00	.90	1.33	1.24
4	29	160	3526	1.08	1.23	1.31	1.47	1.34		1.46
5	19	178	4904	1.02	1.34	1.23	1.25	1.26	1.18	1.28
6	23	178	4904	1.61	1.32	1.49	1.24	1.49	1.33	1.51
7	45	180	4960	1.37	1.18	1.27		.97		1.15
Mean				1.28	1.26	1.28	1.26	1.23	1.26	1.38
S.D.				.21	.09	.12	.17	.21	.08	.20

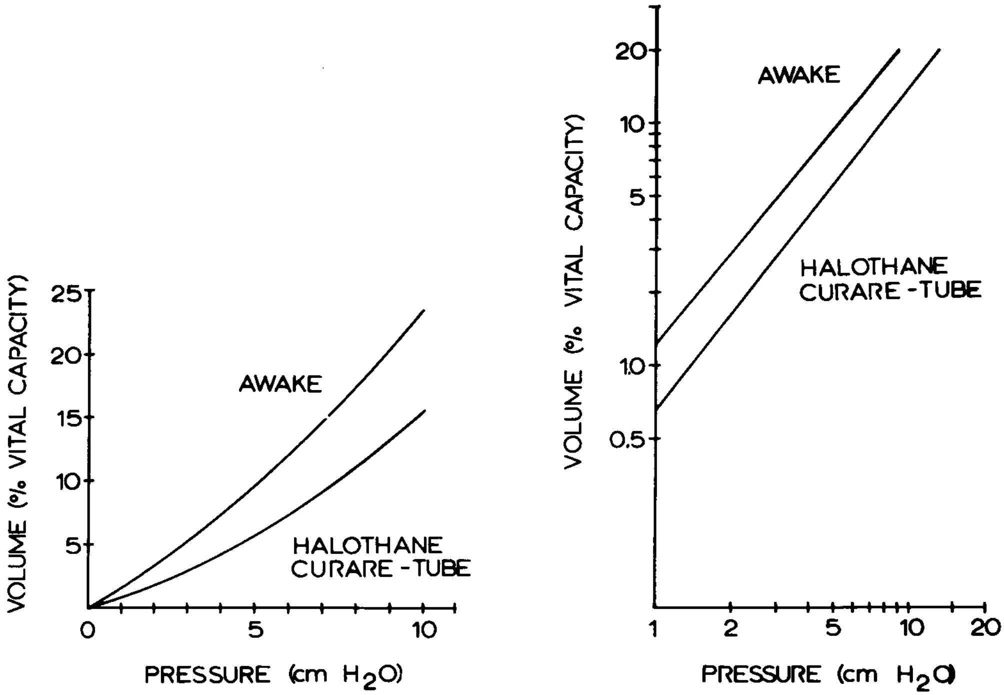

FIGURE 3. Compliance curves plotted from the mean data for all patients awake and then anaesthetized with halothane through a tracheal tube and paralyzed with curare. In (a) the data is plotted on conventional rectangular coordinates. A difference in compliance between the two situations is apparent. In (b) the data are plotted on logarithmic coordinates. The parallel slopes of the lines indicate no real difference in the elasticity of the system (see text).

TABLE II

COMPOSITE DATA FOR SUBJECTS IN THE NEUROLEPT ANAESTHESIA GROUP
(SDC = succinylcholine)

Subject	Age	Height (cm)	Predicted V.C.	Conscious	Neurolept Anaesthesia	Anaesthesia and SDC
1	20	156	3416	1.26	1.48	1.48
2	21	160	3526	1.27	1.54	
3	25	160	3526	1.32	.99	1.26
4	30	161	3548	1.37	1.97	1.22
5	33	160	3526	1.42	1.47	
6	35	170	3747	1.09	1.30	1.03
7	37	162	3555	1.45	1.28	1.31
8	45	154	3394	1.29	1.41	1.37
9	25	168	4628	1.32	1.79	1.26
Mean				1.31	1.47	1.28
S.D.				.11	.29	.14

in compliance is evident. However, if the data are plotted on logarithmic coordinates (Figure 4b), it can be seen that the slopes of the volume-pressure curves are almost parallel. The absence of effect of the volume change on the slope is easily appreciated. We interpret this to indicate that the elasticity of the total respiratory system and of the hemi-thorax are essentially the same, and the apparent change in compliance is due to the volume change.

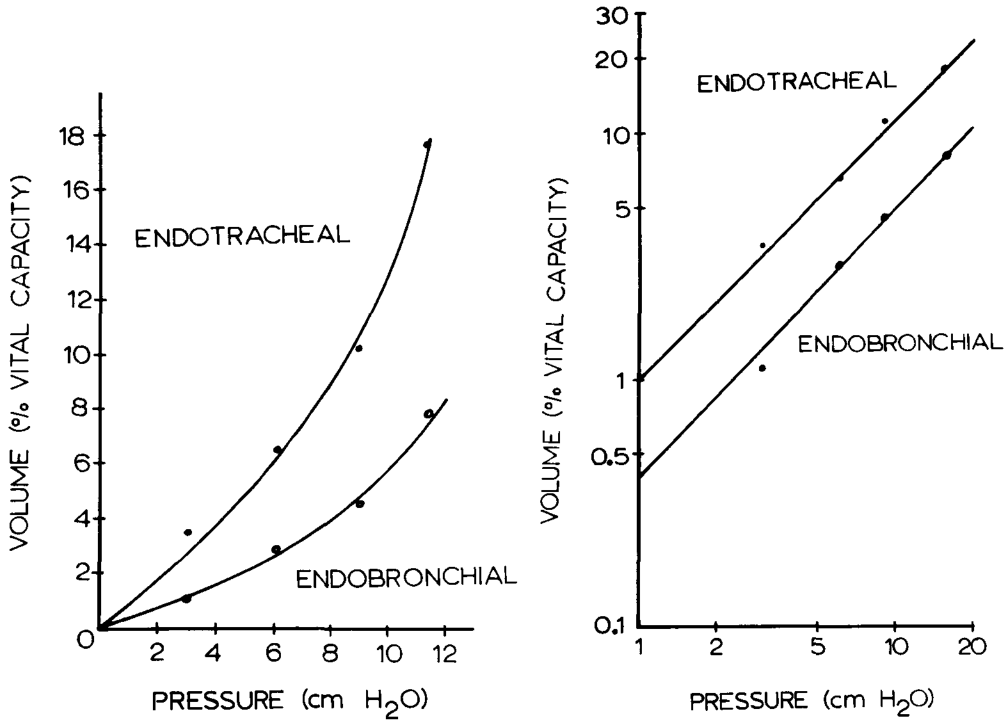

FIGURE 4. Compliance curves for both the total respiratory system and the right hemithorax in a patient anaesthetized with halothane. Plotted on rectangular coordinates (a), the difference in compliance is evident. Plotted on logarithmic coordinates (b), the parallel slopes indicate no real difference in elasticity of the system (see text).

DISCUSSION

Pulmonary volume-pressure relationships are usually expressed as "compliance" and quantitated as volume of gas moved per unit of pressure change. The usual parameters are liters/cm H_2O. Two factors combine to produce the compliance measurement; the elasticity of the system and the volume of the system just prior to measurement.[14]

Measurement of compliance is usually made just above the Functional Residual Capacity (F.R.C.). This method has two pitfalls. First, conventional compliance curves are not linear in this area and the data obtained at F.R.C. cannot be applied throughout the entire inflation volume. Secondly, F.R.C. is known to change during anaesthesia[15,16] and data from awake subjects cannot be compared with data gathered during anaesthesia unless the change in volume is accounted for.

We believe our method of presenting the respiratory volume-pressure data overcomes both of these problems. The logarithmic plot linearizes the curves, and the slope of the curve does not seem to be affected by changes in lung volume (Figure 4).

We found no change in the elastic properties of the respiratory system as a result of sedation, halothane or neurolept-anaesthesia, muscle paralysis or tracheal intubation. Thus, changes in compliance during anaesthesia can be reasonably attributed to changes in lung volume, or perhaps in central blood volume.

An interesting additional observation during this study was confirmation of the absence of the Hering-Breuer reflex in conscious and in anaesthetized man. In Figure 2, it may be seen that application of pressure with a corresponding thoracic inflation did not inhibit spontaneous ventilation in an anaesthetized subject. This has been reported previously by Paskin, *et al.*[17]

Summary

The effect of anaesthesia on respiratory system compliance is not settled. We have studied compliance in subjects awake and then anaesthetized with either halothane or neurolept anaesthesia, both with and without muscle paralysis.

A new method of data analysis is also presented. The changes in respiratory volume and pressure are related logarithmically. On the basis of comparison of data in which lung volume is acutely changed during study, the slope of the volume-pressure line is interpreted to represent the elasticity of the system.

We found no change in elasticity of the respiratory system resulting from induction of anaesthesia or muscle paralysis. From this we conclude that changes in respiratory compliance during anaesthesia are probably due to the changes in lung volume which are known to occur.

Résumé

L'effet de l'anesthésie sur la compliance du système respiratoire ne réunit pas encore toutes les opinions. Nous avons étudié la compliance de sujets à l'état de veille puis anesthésiés soit avec de l'halothane ou la neuroleptanesthésie et, dans les deux cas avec ou sans paralysie musculaire.

Nous présentons également une nouvelle méthode d'analyse des données. Les changements dans le volume et la pression pulmonaire ont une relation logarithmique. Sur la base de la comparaison des données qui démontrent que le volume pulmonaire subit des changements rapides durant l'étude, l'allure de la courbe volume-pression est interprété comme représentant l'élasticité du système.

Nous n'avons pas trouvé de changement dans l'élasticité du système respiratoire à la suite de l'induction de l'anesthésie ou de la paralysie de la musculature. Cela nous permet de conclure que les changements de la compliance respiratoire durant l'anesthésie sont probablement attribuables aux changements de volumes pulmonaires qui surviennent, comme chacun le sait.

Appendix

We made the empirical observation that a linear relationship was obtained when the logarithm of respiratory volume was plotted as a function of the logarithm of transthoracic pressure in the range zero to about 15 cm H_2O. The general form for the equation fitting this plot is:

(1) $\log Vp = \log V_{1.0} + x \log P$

where: Vp is the respiratory volume at pressure P
$V_{1.0}$ is the volume at $P = 1.0$ cm H_2O
x is the slope of the line

This equation may be rearranged to a power function :[18]

(2) $Vp = V_{1.0} P^x$

Mathematical manipulation of these equations indicates that the exponent (x) is a measure of distensibility and thus reflects the elasticity of the respiratory system. Alterations in the value of $V_{1.0}$ appear to be related to changes in the volume of the system being measured. The comparison of respiratory volume-pressure relationships obtained during anaesthesia both with tracheal and bronchial intubation (Figure 4) are compatible with the interpretation that parallel shifts of volume-pressure lines plotted on logarithmic coordinates signify alteration in the volume of the system being measured, with no change in elasticity. However, we have been unable to correlate observed changes in $V_{1.0}$ with the magnitude of previously reported reproductions in F.R.C. during anaesthesia.[15,16]

It is not likely that the hysteresis of the respiratory system need be considered with this technique, as all measurements are made at end-expiration (resting lung volume).

We did not determine the limits of our $\Delta V/\Delta P$ curves since the patients were studied only within the usual range of pressures and volumes seen during clinical anaesthesia. It is likely that the linearity would not be maintained below resting lung volume and at the elastic limit of the respiratory system. Thus, this method of data analysis is probably not applicable throughout the total lung volume. However, it should be useful in the area from resting lung volume to about 30 per cent of the vital capacity above this point.

ACKNOWLEDGEMENTS

This study was supported by Veterans Administration Project 9–70, by a grant from the Medical Research Foundation of Oregon and by the Selling Research Fund of the University of Oregon.

REFERENCES

1. REHDER, K., HATCH, D.J., SESSLER, A.D., MARSH, H.M., & FOWLER, W.S. Effects of general anesthesia, muscle paralysis, and mechanical ventilation on pulmonary nitrogen clearance. Anesthesiology *35*: 591 (1971).
2. MEAD, J. & COLLIER, C. Relation of volume history of lungs to respiratory mechanics in anesthetized dogs. J. Appl. Physiol. *14*: 669 (1959).
3. NIMS, R.G., CONNER, E.H., & COMROE, J.H., JR. The compliance of the human thorax in anesthetized patients. J. Clin. Invest. *34*: 744 (1955).
4. HOWELL, J.B.L. & PECKETT, B.W. Studies of elastic properties of the thorax of supine anesthetized paralyzed human subjects. J. Physiol. *136*: 1 (1957).
5. EMERSON, P.A., TORRES, G.E., & LYONS, H.A. The effect of intermittent positive pressure breathing on the lung compliance and intrapulmonary mixing of gases. Thorax *15*: 124 (1960).
6. BUTLER, J. & SMITH, B.H. Pressure-volume relationships of the chest in the completely relaxed anaesthetized patient. Clin. Sci. *16*: 125 (1957).
7. GOLD, M.I. & HELRICH, M. Pulmonary compliance during anesthesia. Anesthesiology *26*: 281 (1965).
8. LOUZADA, N.L. & TROP, D. Lung mechanics and blood gases during anaesthesia with spontaneous respiration. Can. Anaesth. Soc. J. *17*: 370 (1970).

9. Van Lith, P., Johnson, F.N. & Sharp, J.T. Respiratory elastances in relaxed and paralyzed states in normal and abnormal men. J. Appl. Physiol. *23*: 475 (1967).
10. Foster, C.A., Heaf, P.J.D. & Semple, S.J.G. Compliance of the lung in anesthetized paralyzed subjects. J. Appl. Physiol. *11*: 383 (1957).
11. Bromage, P.R. Total respiratory compliance in anaesthetized subjects and modifications produced by noxious stimuli. Clin. Sci. *17*: 217 (1958).
12. Cherniak, R.M. & Brown, E. A simple method for measuring total respiratory compliance: normal values for males. J. Appl. Physiol. *20*: 87 (1965).
13. West, H.F. Clinical studies of the respiration. VI: A comparison of the various studies for the normal capacity of the lungs. Arch. Int. Med. *25*: 306 (1920).
14. Mead, J. & Collier, C. Relation of volume history of lungs to respiratory mechanics in anesthetized dogs. J. Appl. Physiol. *14*: 669 (1959).
15. Don, H.F., Wahba, M., Cuadrado, L., & Kelkar, K. The effects of anesthesia and 100 per cent oxygen on the functional residual capacity of the lungs. Anesthesiology *32*: 521 (1970).
16. Don, H.F., Wahba, W.M., & Craig, D.B. Airway closure, gas trapping, and the functional residual capacity during anesthesia. Anesthesiology *36*: 533 (1972).
17. Paskin, S., Skovsted, P., & Smith, T.C. Failure of the Hering-Breuer reflex to account for tachypnea in anesthetized man: A survey of halothane, fluroxene, methoxyflurane and cyclopropane. Anesthesiology *29*: 550 (1968).
18. Brownlee, K.A. Statistical theory and methodology in science and engineering, 2nd Ed., New York: Wiley (1965).