Volume-Pressure Relations of the Respiratory System of Curarized Infants

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Static volume-pressure relations of the total respiratory system were measured in 34 healthy infants paralyzed by intravenous *d*-tubocurarine. The values reported are of practical interest when applied to anesthetic, therapeutic and resuscitation techniques used for infants. These values are not significantly different from the static total compliances measured in a comparable group of infants in a previous study, in which muscular paralysis was achieved with intramuscular succinylcholine.

Data are presented which demonstrate two parallel relationships in the infant between the static total compliance, measured in this study, and the dynamic lung compliance, reported by others. First, the similarity of the values for total compliance and lung compliance indicates that the infant's chest wall compliance, alone, is quite high. Second, the close relation observed here between total compliance and the third power of body height approximates the relationship reported for lung compliance and body height.

DURING the management of infant respiratory problems by total muscular relaxation and mechanical ventilation subtle changes in the distensibility of the lungs and chest wall often appear before other more obvious clinical signs of deterioration. Measurement of static volume-pressure relationships of the total respiratory system at intervals provides one means of evaluating certain important factors in therapy, such as the effectiveness of airway cleansing techniques, the need for short periods of manual pulmonary hyperexpansion, and the adjustments of the mechanical ventilator required to satisfy changes in lung distensibility.

The present study was undertaken to determine the static compliance of the respiratory system of healthy infants totally paralyzed by intravenous injections of *d*-tubocurarine. The data presented in this report provide a range of ideal, base-line values which are useful as guides for evaluating the severity and prognosis of conditions managed by the paralysis-ventilation technique, as well as for the construction and operation of automatic ventilators to suit the needs of the infant. In addition, these values are compared with those of similar total static compliance measurements previously reported for the infant during succinylcholine paralysis [1] and during the controlled breathing management of tetanus neonatorum.[2]

Method

The 34 infants selected for this study were less than six months of age and were scheduled mainly for elective inguinal hernioplasty or pyloroplasty. Five were females. None exhibited abdominal distention, and all appeared free of respiratory disease.

The apparatus (fig. 1) consisted of a source of oxygen, a pressure-selecting valve, a large-bore two-way stopcock, and a calibrated, low-inertia water spirometer of 1-liter capacity. These were connected by large-bore, smooth rubber tubing to permit inflation of the infant's lungs with oxygen through one limb of the stopcock, then rapid collection of the passively exhaled gas in the spirometer through the other limb. The distensibility of the rubber components of the system was negligible at the highest pressure.

All infants were studied just prior to operation. Preoperative medication consisted of atropine sulfate, 0.15 mg. given intramuscularly 20 to 120 minutes before the start of

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anesthesia. The infants were placed supine on the operating table, and a mixture of 40 per cent cyclopropane in oxygen administered until the movements ceased and *d*-tubocurarine could be given intravenously, usually within two to three minutes. The *d*-tubocurarine dosage was 0.33–0.55 mg./kg. for infants less than 30 days of age, and 0.55–0.84 mg./kg. for older infants.[3] Cyclopropane inhalation was discontinued as soon as the muscle relaxant had been injected, and as apnea developed over the next one to two minutes, breathing was assisted, then controlled with oxygen. Tracheal intubation was accomplished with a close-fitting tube within five minutes of the injection of *d*-tubocurarine.

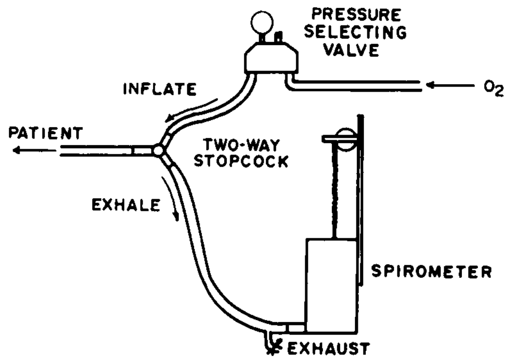

Fig. 1. Diagram of the apparatus used for measurements. The infant's lungs were inflated for 10 seconds at the selected airway pressure, then the stopcock was turned rapidly to collect his passively exhaled gas in the spirometer.

Table 1

Pt. No.	Age (days)	Weight (kg.)	Height (cm.)	*d*-TC Dose (mg./kg.)	Volume/Pressure (ml./cm. H_2O)				
					At 6.8 cm. H_2O	At 13.6 cm. H_2O	At 20.4 cm. H_2O	At 27.2 cm. H_2O	At 34.0 cm. H_2O
1	2	2.9	48.2	0.33	1.9	2.8	3.7	3.3	2.8
2	36	3.0	49.5	0.55	4.1	3.9	3.8	3.5	3.4
3	13	2.6	50.8	0.44	1.9	4.1	4.2	3.5	—
4	40	4.5	53.3	0.55	6.3	7.0	5.8	5.1	4.4
5	74	4.6	53.3	0.66	3.7	4.6	4.1	3.7	3.4
6	19	3.2	54.6	0.55	5.9	6.5	5.6	5.0	4.4
7	23	3.9	54.6	0.55	6.7	7.4	6.2	5.6	4.9
8	53	3.9	54.6	0.51	4.1	5.9	5.2	4.6	4.2
9	24	4.0	55.8	0.51	7.5	7.3	6.0	5.1	4.4
10	32	4.4	55.8	0.55	5.1	6.9	5.7	5.1	4.6
11	44	3.7	55.8	0.66	4.3	6.1	5.3	4.8	4.3
12	66	4.4	55.8	0.66	4.9	5.6	5.5	5.0	4.5
13	32	3.5	56.5	0.49	7.3	8.1	6.9	5.8	5.2
14	50	5.5	58.3	0.66	5.9	7.0	6.5	5.9	5.6
15	68	5.4	58.3	0.66	6.8	7.9	7.0	6.0	5.5
16	85	4.4	58.3	0.66	7.4	8.8	7.4	6.1	5.4
17	86	5.2	59.7	0.66	5.9	7.1	6.0	5.4	4.8
18	91	5.0	59.7	0.66	4.5	6.2	6.2	6.3	5.6
19	106	5.4	59.7	0.66	5.2	7.2	7.1	6.4	5.8
20	66	5.4	60.9	0.66	5.9	7.5	6.8	6.3	5.7
21	109	5.4	60.9	0.66	4.5	6.8	6.5	6.0	5.5
22	82	7.0	61.6	0.77	4.2	5.9	6.4	5.8	5.3
23	60	5.0	61.8	0.66	5.1	6.2	6.0	6.2	6.0
24	56	5.6	63.4	0.66	9.5	10.1	8.3	7.1	6.2
25	71	6.2	63.4	0.66	7.4	9.7	9.3	8.3	7.4
26	75	5.4	63.4	0.66	7.1	8.2	8.0	7.2	6.5
27	110	5.9	65.4	0.77	7.6	9.6	9.7	8.6	7.5
28	168	6.7	66.7	0.66	7.4	10.5	11.2	10.6	9.2
29	109	6.7	67.3	0.66	7.4	10.4	11.4	10.8	9.4
30	146	7.6	67.3	0.66	10.1	13.0	12.5	11.2	9.6
31	112	6.1	67.9	0.84	9.0	11.4	10.5	9.4	8.3
32	157	7.5	71.7	0.80	13.8	15.8	14.0	12.0	10.5
33	162	7.5	72.3	0.73	12.5	15.6	14.9	14.0	12.2
34	172	7.7	73.6	0.66	7.4	11.1	12.1	10.7	9.7

TABLE 2

Source	Average Total Static Compliance (ml./cm. H_2O)				
	At 6.8 cm. H_2O	At 13.6 cm. H_2O	At 20.4 cm. H_2O	At 27.2 cm. H_2O	At 34.0 cm. H_2O
Richards & Bachman, 1961 (20 infants)	5.2 ± 1.0	6.2 ± 0.9	5.4 ± 0.9	4.9 ± 0.8	4.7 ± 0.6
Present study (15 infants)	5.1 ± 1.7	6.1 ± 1.4	5.4 ± 1.2	4.8 ± 0.9	4.4 ± 0.7
	$P > 0.5$	$P > 0.5$	$P < 0.5$	$P > 0.5$	$P > 0.1$

Immediately thereafter, a gastric catheter was passed to assure deflation of the stomach.

Volume-pressure measurements were begun within three minutes after tracheal intubation; each study required between five and ten minutes for completion. The procedure consisted of inflating the infant's lungs with oxygen for at least ten seconds at each of five different airway pressures and collecting the passively exhaled gas in the spirometer. The lungs and chest wall thus relaxed to the resting expiratory level after each volume measurement and were reinflated from this level during the succeeding application of pressure. The pressures chosen were 6.8, 13.6, 20.4, 27.2 and 34.0 cm. of water, corresponding to 5, 10, 15, 20 and 25 mm. of mercury, respectively. Measurements were made by starting at the highest pressure and progressing to the lowest pressure; the series was repeated to obtain two volume determinations for each airway pressure. Pulmonary relaxation volumes for each infant should have remained reasonably constant under these conditions. Spirometer collection times at each pressure were five seconds or more, ample time to insure no further gas flow from the lungs. Expired volumes were corrected to BTPS.

Results

Static volume-pressure relationships of the total respiratory system, for each airway pressure applied, are listed in table 1. Each value represents an average of two measurements and is expressed as the ratio of the volume of gas expired (ml.) to the airway pressure applied (cm. of water) immediately preceding expiration.

The group was not believed to be sufficiently homogeneous in age or physical measurements to permit averaging the values in each column. However, the first 15 subjects were similar in age (less than 75 days), weight (less than 12.5 pounds) and height (less than 60 cm.) to the 20 infants studied during complete muscular relaxation by intramuscular succinylcholine, as reported by Richards and Bachman.[1] Data are presented in table 2 to compare the total static compliance averages of the descending series of inflation pressures from the earlier study with the compliance averages for the first 15 infants of the present study, also measured in a descending order of airway pressures. No significant difference in the static volume-pressure relations of the infant's total respiratory system is observed whether muscular paralysis is achieved by intramuscular succinylcholine or intravenous *d*-tubocurarine.

Comparisons of data from individual infants, with respect to age, weight and height, were made using the volume/pressure ratio obtained at 20.4 cm. of water airway pressure. This is an arbitrary comparison point, used in the previous study as well as by other investigators,[4] and selected here for two reasons. This was the midpoint of the pressure range used and, therefore, should have been less affected by variables that might appear at either extreme of the pressure range. Also, there was a sufficiently wide spread of values at this pressure to show correlation between total static compliance and physical characteristics, if such a relationship existed.

The best correlation for total compliance values at 20.4 cm. of water airway pressure appeared to be a non-linear relationship with the height measurement (fig. 2). A log-log plot of the data from figure 2 discloses a regression line with a slope of about 3.2 (fig. 3). The correlation coefficient for this line is 0.94, with a high degree of significance ($P < .001$), indicating a close relation between the total static compliance and body height.

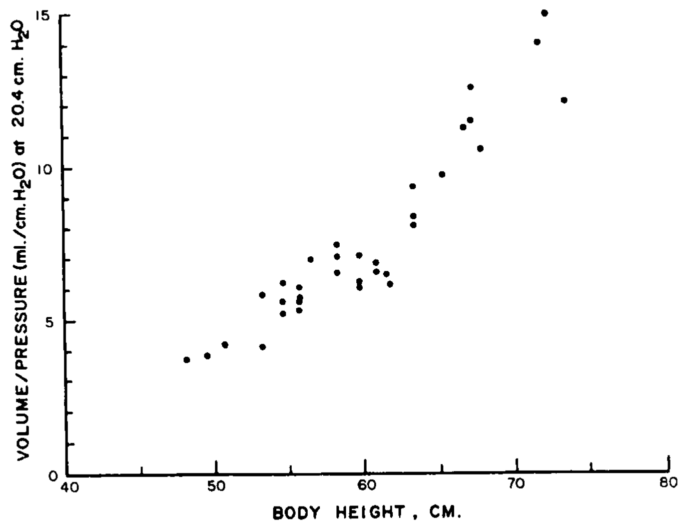

FIG. 2. Relation between height (cm.) and the total static compliance (ml./cm. of water) at 20.4 cm. of water airway pressure.

Discussion

One purpose of these experiments was to detect any difference in the ability to inflate an infant's lungs and thorax with various airway pressures when the infant was totally paralyzed by either succinylcholine or *d*-tubocurarine. Safar and Bachman [5] had demonstrated a 50 per cent reduction in the distensibility of the lungs and thorax of adult dogs during total muscular relaxation by *d*-tubocurarine as compared with succinylcholine. The possibility that the infant might respond in a similar fashion was suggested when Smythe [2] reported an average total static compliance of 2.5 ml./cm. of water for 11 infants with tetanus neonatorum being managed by mechanical ventilation and total muscular paralysis with *d*-tubocurarine. Smythe's values, measured in infants with normal alveolar P_{CO_2} and showing no evidence of pulmonary collapse, were about half those determined by Richards and Bachman [1] in a group of healthy infants of comparable age and size during succinylcholine paralysis. However, comparison of data from the present study with data obtained previously during succinylcholine paralysis by an identical technique reveals no significant difference in the total static compliance whether complete muscular paralysis is achieved by succinylcholine or by *d*-tubocurarine, as long as the conditions of measurement are the same and the variables limited.

Smythe's observations of a decreased distensibility of the infant's lungs and thorax during *d*-tubocurarine paralysis are not related to the muscle relaxant drug but can be attributed to several other factors. Prolonged intermittent positive-pressure breathing is accompanied by a progressively decreasing compliance,[6] and Smythe's determinations were made over a period of 10 to 17 days in infants who required constant mechanical ventilation. In addition, Smythe recorded airway pressures in an ascending series of incremental air injections from 10 ml. to a total of 40 ml., with-

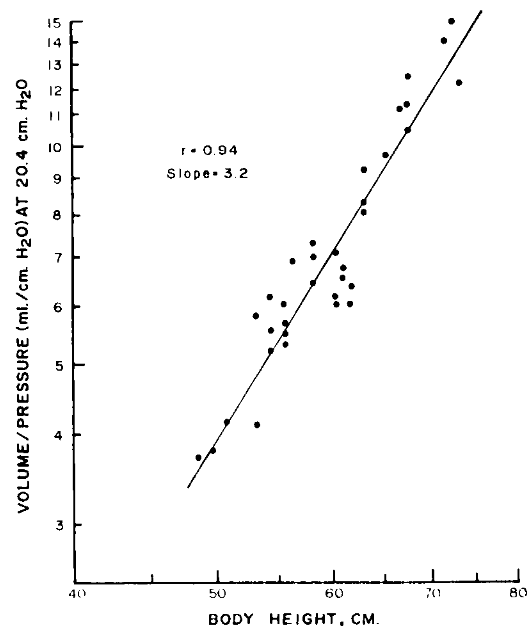

FIG. 3. Log-log plot of the data from figure 2.

out prior inflation of the lungs at a pressure greater than the ventilator had been giving. Others[1,7] have shown that total static compliance is greater, for a given pressure, when progression is from high toward the lower pressure-volume measurements.

It is interesting to compare values for total static compliance, measured during complete muscular paralysis, with lung compliance values obtained during spontaneous breathing. Cook and his associates[8] found an average lung compliance of 5.2 ml./cm. of water during quiet breathing in 18 infants, and Swyer, Reiman and Wright[9] measured a lung compliance of 4.9 ml./cm. of water in 15 sleeping infants. The average total static compliance for the first 15 infants of table 1 was 5.1 ± 1.7 ml./cm. of water at 6.8 cm. of water inflation pressure, the positive pressure which most closely approximates the negative change in esophageal pressure observed during spontaneous breathing. The similarity between the values for lung compliance and total static compliance confirms the impression that the compliance of the chest wall, alone, is high in infants.[10] Although the mechanical disadvantages inherent in the structure of the infant's thorax render him poorly able to expand his rib cage during spontaneous breathing, the high chest wall compliance permits free thoracic expansion during even gentle positive-pressure breathing.

Of several physical parameters which are easily measured, the one which correlates most closely with lung compliance is body height. Both Krieger[11] and Cook, Helliesen and Agathon[12] report a relationship of lung compliance to approximately the third power of body height. Our data disclose a correlation of similar degree between body height and the static compliance of the total respiratory system at 20.4 cm. of water inflation pressure, in a relatively small group of infants less than six months of age. This mid-range volume/pressure ratio actually varied with height to the 3.21 power, with a regression equation of $1.40 \times \text{height}^{3.21} \times 10^{-5}$.

Summary

The total static compliance of 34 normal infants paralyzed with *d*-tubocurarine has been determined at various airway pressures to provide baseline values useful during anesthetic or therapeutic controlled ventilation techniques.

Data from 15 infants in this study were compared with data from 20 infants, of comparable age and physical characteristics, in a previous study in which paralysis was produced by intramuscular succinylcholine. No significant difference was noted in the static volume-pressure relationships of the infant's total respiratory system whether succinylcholine or *d*-tubocurarine was used to achieve muscular relaxation.

Total static compliance, at 20.4 cm. of water airway pressure, showed a close relationship to the third power of the body height.

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