

## Comparison of the Single Breath and Volume Recruitment Techniques in the Measurement of Total Respiratory Compliance in Anesthetized Infants and Children

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Total respiratory compliance (Cr<sub>s</sub>) has not previously been measured from the static pressure-volume (P-V) curve during spontaneous breathing in anesthetized infants and children. A single breath test and a volume recruitment maneuver for measuring Cr<sub>s</sub> were applied to 18 infants and children breathing spontaneously during halothane anesthesia in order to determine the usefulness and reliability of these noninvasive tests for measuring static compliance during anesthesia. Cr<sub>s</sub> from the single breath test (Cr<sub>s,b</sub>) was determined from the mask pressure plateau (P) during a brief end-inspiratory airway occlusion and the lung volume (V) from the passive expiration following release of the occlusion. Cr<sub>s</sub> from the volume recruitment maneuver (Cr<sub>s,v</sub>) was determined from P and V during a series of expiratory occlusions at progressively higher lung volumes. The P-V curves fit a polynomial curve with the convexity toward the pressure axis in most patients, and Cr<sub>s,v</sub> was the tangent to the curve in the mid-tidal range. The tallest four patients did not show respiratory muscle relaxation during the occlusions with either test, and the single breath test could not be completed in an additional two patients. In the 12 patients (59–89 cm in height) in whom both tests were successful, Cr<sub>s,b</sub> correlated with, and was similar to, Cr<sub>s,v</sub>. The intrasubject coefficient of variation was less with the single breath test ( $9.4 \pm 6.7\%$ ) than with the volume recruitment maneuver ( $15.0 \pm 7.1\%$ ). The authors conclude that both tests are simple, reliable, and rapid and give similar results for Cr<sub>s</sub> in spontaneously breathing children (59–89 cm in height) anesthetized with halothane. (Key words: Anesthesia: pediatric. Anesthetics, volatile: halothane. Lung: compliance. Measurement techniques: compliance.)

TOTAL RESPIRATORY COMPLIANCE (Cr<sub>s</sub>) from static P-V curves in adult surgical patients decreases during induction of anesthesia<sup>1</sup> and may change rapidly thereafter during anesthesia and surgery.<sup>2</sup> A decrease in compliance may be associated with the development of hypoxemia in the anesthetized patient.<sup>3</sup> Lunn<sup>4</sup> has estimated that Cr<sub>s</sub> also decreases with the induction of anesthesia in children. However, static compliance has only been measured in anesthetized paralyzed children following tracheal intubation<sup>5</sup> using techniques unsuitable for spontaneously

breathing children. Measuring dynamic compliance using an esophageal balloon<sup>6</sup> would be suitable for this group, but the esophageal balloon is invasive and may not accurately reflect pleural pressures in infants.<sup>7</sup>

New, noninvasive tests for measuring passive respiratory mechanics in neonates have been developed recently, which may be suitable for use during anesthesia. LeSouef *et al.*<sup>8</sup> measured Cr<sub>s</sub> from a single breath by dividing the equilibrium airway pressure (P) developed during an end-inspiratory airway occlusion into the volume (V) of the post-occlusion expiration. Cr<sub>s</sub> by this method, termed the single breath test, correlated well with compliance measured using an esophageal balloon in puppies,<sup>9</sup> and by the multiple occlusion technique in infants and children.<sup>10</sup>

In an earlier report from our laboratory, Grunstein *et al.*<sup>11</sup> modified this test for infants using a unidirectional valve attached to a facemask. Occluding the expiratory port of this valve permitted inspiration but not expiration for four or five breaths. The infants then breathed at progressively higher lung volumes, and at each volume "step" the equilibrium occlusion airway pressure was measured. They then plotted a P-V curve with multiple points from each "volume recruitment" maneuver, and calculated Cr<sub>s</sub> from the curve. This technique has the advantage of a multiple point P-V curve for calculation of compliance including data points from volumes higher than the tidal volume range.

We applied the single breath test and the volume recruitment maneuver to measure Cr<sub>s</sub> in spontaneously breathing anesthetized infants and children in order to assess and compare the use of these tests during anesthesia.

### Methods

Eighteen ASA physical status I infants and children, from 3 months to 5 yr 5 months of age, 4.7–17.6 kg body weight, and 57–106 cm height, with normal birth histories and no subsequent respiratory problems, were studied. None had an upper respiratory illness within 2 weeks of the test and all were scheduled for elective general surgery for noncardiopulmonary diseases. Anthropometric data is presented in table 1. The protocol received the approval of the committee for human experimentation of this hospital and the parents of the patients gave informed consent prior to the study.

The patients received triclofos, 75–100 mg/kg body weight, preanesthetic sedation 1.5 h preinduction. Anes-

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TABLE 1. Anthropometric Data and Compliance from the Volume Recruitment Maneuver ( $Cr_{sv}$ ) and from the Single-Breath Test ( $Cr_{sb}$ )

Patient	Height (cm)	Weight (kg)	Age (months)	$Cr_{sv}$ (ml/cm H <sub>2</sub> O)	$Cr_{sb}$ (ml/cm H <sub>2</sub> O)
1	57	5.1	4	7.7*	Not obtained
2	59	6.3	3	4.7	4.7
3	61	5.3	3	4.8	3.8
4	62	4.7	4	4.5	4.3
5	63	6.3	4	3.4	3.3
6	64	6.4	6	5.8	5.3
7	66	7.2	7	8.4	10.1
8	73	8.7	13	11.1	10.2
9	74	8.8	8	8.0	8.1
10	83	10.1	16	14.4	13.9
11	87	13.3	35	15.6	11.9
12	88	11.5	28	10.1	10.0
13	89	13.0	33	22.1	18.3
14	90	14.1	36	24.6*	Not obtained
15	91	12.8	34	Not obtained	Not obtained
16	92	13.7	28	Not obtained	Not obtained
17	102	14.5	54	Not obtained	Not obtained
18	106	17.6	65	Not obtained	Not obtained

\*  $Cr_{sv}$  calculated without data from  $P = 0$ .

thetia was induced with halothane in oxygen by anesthetic mask *via* a Jackson-Rees modification of the Ayre's T-piece (Mapleson F circuit). The opening on the expiratory limb of the circuit was sufficiently large to permit free egress of gases without distention of the anesthetic bag, in order to avoid inadvertent administration of positive airway pressure in expiration. Once stable anesthesia was attained, there were no further changes in the inspired halothane concentration throughout the study period. Positive pressure ventilation was not used at any time before or during the study period. Monitoring included continuous ECG and oxygen saturation measurements throughout. The study was carried out following induction of anesthesia, but prior to commencing surgery.

The apparatus consisted of a firm Rendall-Baker mask sealed at the edges with silicon putty to prevent leaks. Attached to the mask was the proximal port of a screen pneumotachograph (Mercury Electronics, Scotland) the output of which was linear to a flow of 1.8 l/s. The an-

esthetic circuit was attached to the distal port of the pneumotachograph. The two pressure outputs from the pneumotachograph were connected to a differential pressure transducer (Validyne MP-45) whose signal was amplified (Hewlett-Packard 8805C) and integrated (Hewlett-Packard 8815A) and the resulting flow ( $\dot{V}$ ) and volume ( $V$ ) signals were displayed on an oscilloscope (Tektronix® T935A). The mask pressure ( $P_m$ ) signal was obtained *via* a small bore tubing placed underneath the mask and connected to a similar transducer and amplifier as above. The  $P_m$  signal was displayed on the oscilloscope, and all the signals were recorded on magnetic tape (Hewlett-Packard 3964A) for later analysis. Following the test procedures, the data were analyzed with the aid of a computer (PDP 11/23).

### SINGLE BREATH TEST

During quiet breathing, the anesthetic circuit was briefly disconnected from the pneumotachograph. The distal port of the pneumotachograph was manually occluded approximately at end inspiration and the occlusion was maintained until  $P_m$  was seen to plateau at pressure  $P$ . The occlusion was then released and the expiratory  $\dot{V}$ - $V$  curve was observed on the oscilloscope. Analysis of the maneuvers was similar to that outlined in an earlier report from our laboratory.<sup>12</sup> The least squares regression line of the linear portion of the relaxed  $V$ - $V$  curve was extrapolated to its intercept on the volume axis, which is the relaxed end-expiratory volume of the respiratory system ( $V_{rs}$ ).  $V$  is then the difference between end-inspiratory volume and  $V_{rs}$  and the compliance measured by this technique,  $Cr_{sb}$ , is  $V/P$ . The passive expiratory time constant ( $\tau$ ) was the inverse slope of the regression line of the linear portion of the expiratory  $V$ - $V$  curve. Five to ten "single breath" maneuvers were performed on each patient.

### VOLUME RECRUITMENT

During spontaneous breathing, a T-shaped apparatus was placed between the mask and the anesthetic circuit (fig. 1). Two internal valves allowed continuous one-way

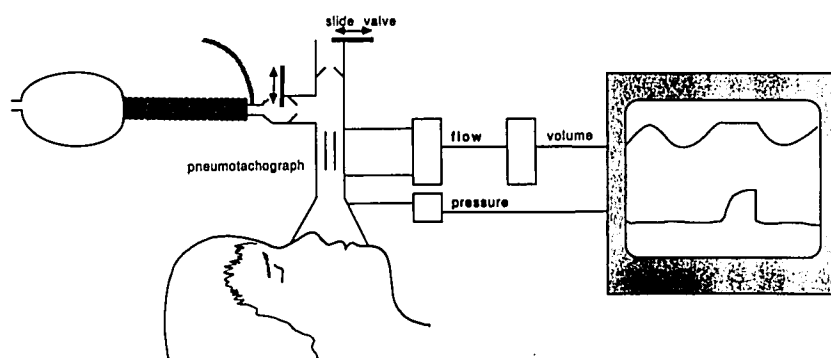


FIG. 1. Schematic diagram of the apparatus for the volume recruitment maneuver showing the position of the anesthesia circuit on the inspiratory limb of the T-shaped apparatus and two occluding valves.

flow of anesthetic gases and prevented reverse flow. During inspiration, the inspiratory and expiratory ports of the unidirectional valve were occluded with occlusion valves until a plateau on the  $P_m$  signal was noted. Then the inspiratory occlusion was released and only the expiratory port was occluded allowing inspiration of anesthetic gases but preventing expiration. During four or five respiratory cycles, the patient progressively recruited volume during inspiration and developed an equilibrium plateau  $P_m$  during each occluded expiration (fig. 2). The occlusion was then released and tidal breathing resumed. From five to ten volume recruitment maneuvers were carried out. Following completion of these maneuvers, a paralyzing dose of succinylcholine was administered iv to three patients from this study (patients 5, 10, and 11), prior to tracheal intubation. During controlled ventilation with oxygen *via* the anesthetic circuit and mask,  $\dot{V}$  and  $V$  signals from expiration during paralysis were recorded. Tracheal intubation was then carried out and the surgical procedure commenced.

In the computer-aided analysis,  $V$  was measured during each occluded expiration as the lung volume above functional residual capacity (FRC). FRC, labelled 0 in figure 2, was considered to be the end-expiratory position of the three tidal breaths preceding the maneuver. The plateau value of  $P_m$  during each occlusion,  $P$ , was accepted if it was 0.2 s or longer but plateaux as short as 0.1 s were accepted in one infant (patient 7).  $P$ - $V$  data from  $P = 0$  were obtained from the extrapolation of the linear segment of the relaxed  $\dot{V}$ - $V$  curves from the single breath test as above, and were included in subsequent analyses. The  $V$  and  $P$  data pairs pooled from all the volume recruitment maneuvers for each patient were then subjected to regression analysis (fig. 3) and linear, parabolic, exponential, and polynomial curves were fitted to the data for each patient. The curve which best fit the data was determined to be the curve with the highest correlation coefficient ( $r$ ). Total respiratory compliance by the volume recruitment maneuver ( $Cr_{s_{vr}}$ ) was calculated according to the regression equation.

The intrasubject coefficient of variation (CV) for the single-breath test was determined from the  $Cr_{s_{sb}}$  of the five to ten tests performed on each child. The CV for the volume recruitment test was determined by analyzing the  $P$ - $V$  curve from each volume recruitment maneuver by linear regression and the slope of the regression line is the compliance for that maneuver. In this way,  $Cr_{s_{vr}}$  was obtained from each of the five to ten volume recruitment maneuvers in each patient. The CV of these  $Cr_{s_{vr}}$  data for each patient was calculated. This calculation of  $Cr_{s_{vr}}$  for each individual maneuver also facilitated analysis of possible trends in  $Cr_{s_{vr}}$  during the course of the study by comparing the  $Cr_{s_{vr}}$  from the first maneuver in each patient to his last maneuver. The Wilcoxon signed rank test

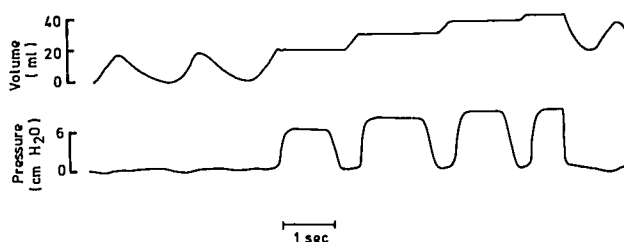


FIG. 2. Volume and pressure signals from the volume recruitment maneuver. After two tidal breaths, at end inspiration, expiration is occluded for four breaths and volume is progressively recruited with each subsequent inspiration. Then the occlusion is released and tidal breathing resumes.

was used to compare CV of the single breath test with that of the volume recruitment maneuver, and also to compare the first to last  $Cr_{s_{vr}}$  in the 14 patients in whom  $Cr_{s_{vr}}$  was measured.

The  $\dot{V}$  and  $V$  signals during paralyzed expiration were analyzed in a  $\dot{V}$ - $V$  format, similarly to the above analysis of the single breath test. The inverse slope of the linear regression (by least squares) of the linear portion of the expiratory  $\dot{V}$ - $V$  curve during paralyzed expiration was  $\tau_p$ .

## Results

From the 18 infants and children, acceptable  $P_m$  plateaux were obtained rarely or not at all in four patients,

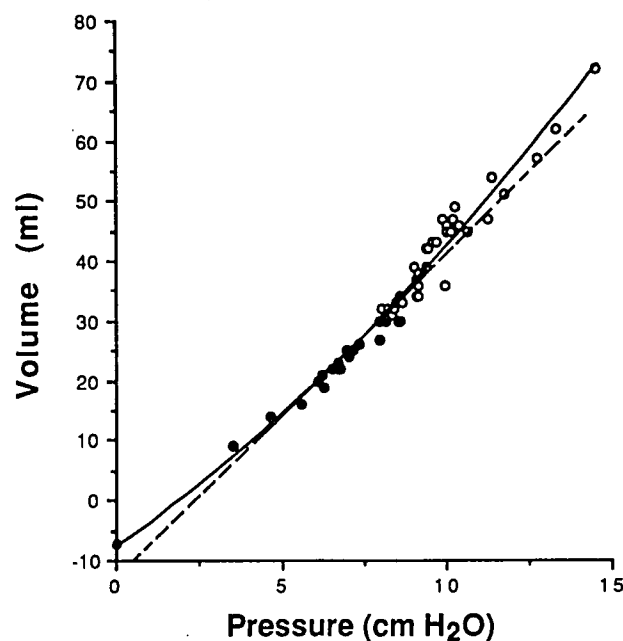


FIG. 3. Volume-pressure curve for one patient showing the fit of the data points to linear (---) and polynomial (—) equations. The filled circles represent data from within the tidal volume range and the open circles represent data from volumes greater than the tidal volume range.

TABLE 2. Comparison of Linear Regression Equation ( $y = ax + b$ ) and Polynomial Equation ( $y = ax^2 + bx + c$ ) for V-P Curve from the Volume Recruitment Maneuver in 12 Subjects

Patient	Linear			Polynomial			
	a	b	r	a	b	c	r
2	4.7	-8.0	0.99	-0.01	4.8	-8.1	0.99
3	4.9	-7.3	0.97	0.11*	3.9	-8.0	0.99
4	5.2	-12.5	0.96	0.17*	3.1	-9.1	0.96
5	4.5	-6.7	0.96	0.20*	1.8	-1.0	0.97
6	5.7	-7.4	0.94	-0.02	6.0	-7.9	0.94
7	8.5	-13.0	0.97	-0.14	9.5	-15.3	0.98
8	11.2	-43.1	1.00	0.06	10.6	-42.6	1.00
9	7.8	-17.6	1.00	-0.09	8.7	-17.8	1.00
10	14.6	-22.1	0.98	0.57*	9.8	-19.4	0.98
11	15.8	-13.7	0.91	1.27*	5.4	-7.2	0.93
12	12.1	-21.8	0.98	0.59*	5.4	-14.2	0.99
13	22.4	-47.8	0.98	0.60*	17.3	-43.1	0.98

\* Polynomial coefficient "a" is significantly different than 0 ( $P < 0.05$ ).

whose height ranged from 91 to 106 cm. We interpreted this to indicate that, in these larger children, their respiratory muscles did not relax during the airway occlusions, and these children were not included in subsequent analyses. In two of the remaining children, the single-breath test could not be completed, in patient 1 due to the rapidity of his breathing and difficulty timing the end inspiratory occlusion, and in patient 14 due to failure to relax during the occlusion. The volume recruitment maneuvers could be completed in all 14 patients with acceptable  $P_m$  plateaux at each occlusion. The 12 patients who had acceptable volume recruitment and single-breath studies were from 59 to 89 cm in height (table 1).

$Crs_{sb}$  (ml/cm  $H_2O$ ) correlated with the height (cm) of the patients according to the equation:

$$Crs_{sb} = 1.3 \times 10^{-5} \times [\text{height}]^{3.1}, r = 0.87.$$

From the volume recruitment maneuver, the curves that fit the V-P data for each patient were best described by a polynomial function and were also well described by linear regression analysis (table 2; fig. 3). The curves derived from the polynomial functions in each patient are shown in figure 4. Since the V-P data were best described by a second order polynomial function,  $Crs_{vr}$  was calculated for each patient as the tangent to the polynomial curve in the mid-tidal volume range (see appendix), and  $Crs_{vr}$  is reported in table 1.  $Crs_{vr}$  (ml/cm  $H_2O$ ) correlated with height (cm) according to the equation:

$$Crs_{vr} = 5.3 \times 10^{-6} \times [\text{height}]^{3.3}, r = 0.90.$$

$Crs_{vr}$  was similar to compliance by the summary mean equation of Sharp *et al.*<sup>5</sup> (fig. 5) for anesthetized, paralyzed children measured by inflation of the lungs with a supersyringe.

$Crs_{sb}$  (ml/cm  $H_2O$ ) correlated with  $Crs_{vr}$  (ml/cm  $H_2O$ ) according to the following equation:

$$Crs_{vr} = 1.2 \times Crs_{sb} - 0.8, r = 0.97,$$

and the relationship is shown in figure 6.

The intrasubject CV for the single breath test was  $9.4 \pm 6.7\%$ , and for the volume recruitment maneuvers was  $15.0 \pm 7.1\%$ . This difference was significant at the  $P = 0.02$  level. There was a small but significant increase in  $Crs_{vr}$  on the last maneuver from each patient to that

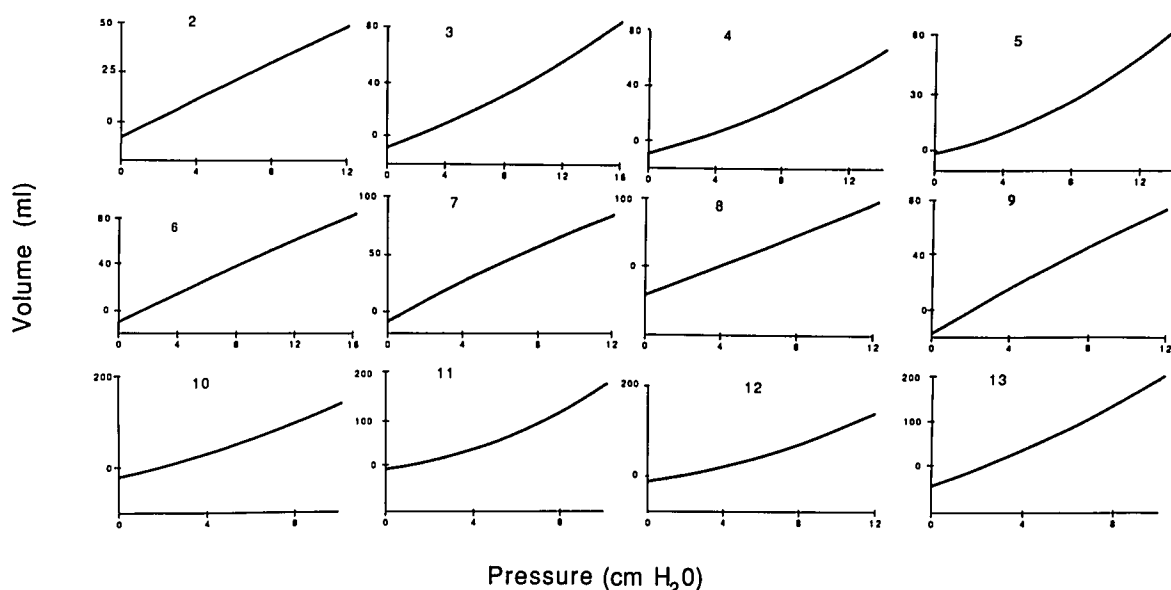


FIG. 4. V-P curves by polynomial analysis for 12 patients from the volume recruitment maneuver showing the direction of curvilinearity.

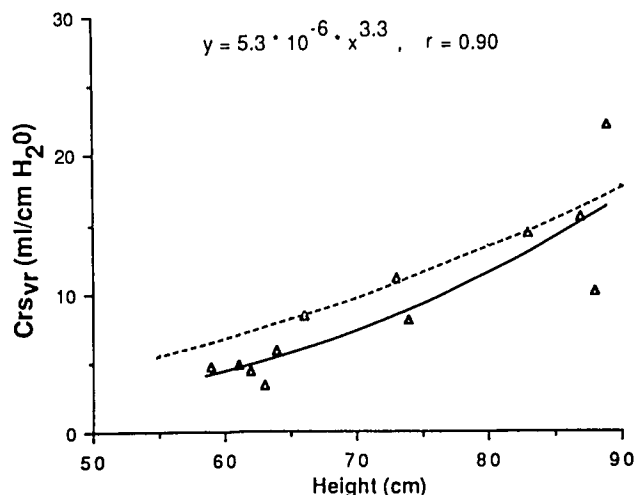


FIG. 5. Regression  $Crs_{vr}$  versus height for 12 patients is shown as a solid line. The equation of the regression is shown. The summary mean curve of compliance versus height from Sharp *et al.*<sup>5</sup> (---) is shown for comparison.

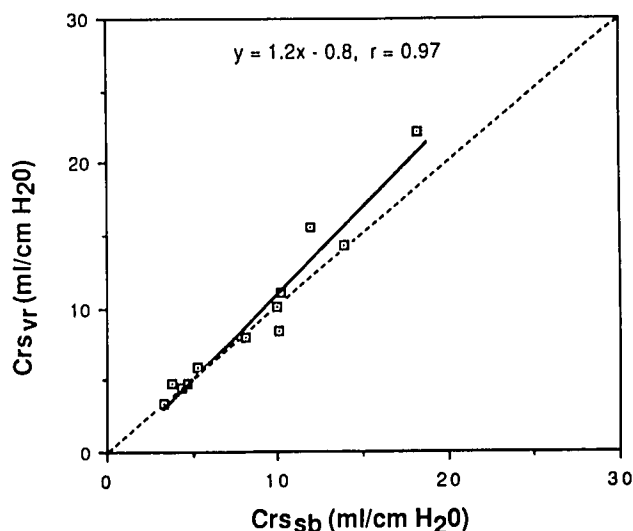


FIG. 6. Correlation between  $Crs_{vr}$  and  $Crs_{sb}$  for 12 patients is shown. The hatched line represents the line of identity.

measured from the first maneuver in that patient ( $P < 0.05$ ).

The passive expiratory time constant,  $\tau$ , was compared to the paralyzed expiratory time constant  $\tau_p$  in the three patients in whom  $\tau_p$  was measured, and the results are shown in table 3.

### Discussion

The single-breath test and the volume recruitment maneuver are recently described techniques for measuring passive respiratory compliance in children. In this study, they were found to be rapid, simple, and noninvasive, and these are highly desirable characteristics for tests to be applied to patients during anesthesia.

The single-breath test has previously been applied during anesthesia<sup>12</sup> and also to ill neonates and children,<sup>8</sup> including during mechanical ventilation. It is based on relaxation of the muscles of respiration generated by an end-inspiratory airway occlusion. Respiratory muscle relaxation is indicated by a plateau on the  $P_m$  signal and linearity of the  $\dot{V}$ - $V$  curve of the expiration following the release of the occlusion.<sup>12</sup> In order to verify respiratory muscle relaxation, the time constant of this expiration ( $\tau$ ) was compared to the time constant of expiration after pharmacological muscle paralysis ( $\tau_p$ ). The similarity of  $\tau$  and  $\tau_p$  in each subject (table 3) indicates that  $\tau$  was measured from an expiration that was unaffected by respiratory muscle activity. This supports the validity of the single breath test as a measure of the passive mechanical properties of the respiratory system.

The use of the single breath test in neonates is limited by the difficulty in timing the occlusion in the presence

of rapid breathing, and we were not able to complete this test in the smallest child (patient 1) in this study for this reason. As well, none of the patients greater than 89 cm in height (patients 14–18) achieved relaxation of the respiratory muscles during the occlusion, as seen from the constantly upsloping  $P_m$  signal. This problem has been noted in a small number of patients in previous studies using a similar test.<sup>13</sup> Therefore, use of the single breath test was limited to anesthetized children from 59 to 89 cm in height in whom we found constant airway pressure plateaux during occlusions.

A theoretical consideration in applying the single-breath test to nonintubated children is the possibility that the upper airway is partially obstructed or that the glottis is actively narrowed. Both circumstances would increase the passive expiratory time constant and thus  $V$  and  $Crs$  would be overestimated. This could occur even in the presence of a linear  $\dot{V}$ - $V$  curve.<sup>14</sup> We believe that there was no airway obstruction or glottic narrowing in the anesthetized children reported here for the following reasons: 1)  $V$  is measured during expiration in the single breath test and the expiratory  $\dot{V}$ - $V$  curve is less affected by variable upper airway obstruction than the inspiratory

TABLE 3. Comparison of the Mean  $\pm$  SD of the Passive Expiratory Time Constant,  $\tau$ , from the Single Breath Test to the Time Constant from Expiration during Pharmacological Paralysis,  $\tau_p$

Patient	$\tau$ (s)	$\tau_p$ (s)
5	$0.24 \pm 0.01$	$0.25 \pm 0.02$
10	$0.47 \pm 0.05$	$0.49 \pm 0.08$
11	$0.33 \pm 0.04$	$0.30 \pm 0.02$

$\dot{V}$ -V curve,<sup>15</sup> 2) the volume recruitment maneuver is a static maneuver and is not affected by changes in flow pattern; if airway obstruction was present, Crs would be overestimated by the single breath test only, and we would find that  $\text{Crs}_{\text{sb}} > \text{Crs}_{\text{vr}}$ , but this was not found in this study, 3) the variability of  $\text{Crs}_{\text{sb}}$  should be increased, reflecting the variable nature of upper airway obstruction; in fact, CV of  $\text{Crs}_{\text{sb}}$  was less than CV of  $\text{Crs}_{\text{vr}}$ , and 4) halothane depresses laryngeal reflexes.<sup>16</sup>

The volume recruitment maneuver was only slightly more successful in eliciting respiratory muscle relaxation than the single-breath test.  $\text{Crs}_{\text{vr}}$  for the youngest child could be adequately measured, since the occlusion of the expiratory port of the unidirectional valve may occur anytime throughout inspiration, eliminating the need for precise timing of the occlusion.  $\text{Crs}_{\text{vr}}$  could be determined in one other patient (patient 14) who could not be tested by the single-breath test. In this one patient, elevating lung volume above the tidal volume range may have facilitated muscle relaxation by eliciting the Hering Breuer reflex, which was not elicited by the end-inspiratory occlusion of the single-breath test. In all other patients, both tests were similar in their ability to measure Crs.

The volume recruitment maneuver was advantageous in providing information on compliance at lung volumes greater than the tidal volume range. The greater range of volume permitted a more flexible approach to analysis and may provide greater insight into respiratory mechanics during anesthesia. The polynomial regression was used to analyze the V-P curves from the volume recruitment maneuver, since this function provided the best correlation coefficient for the data. In addition, we could obtain a concept of the position of the anesthetized child on the normally sigmoid-shaped V-P curve (Appendix). This was assisted by incorporating data at volumes less than the tidal breathing range, by measuring the volume at  $P = 0$  from the single-breath test. Grunstein *et al.*<sup>11</sup> suggested this method of completing the V-P curve at the lower volume range, and, in our study, this improved the correlation coefficients for the polynomial analysis (mean  $r$  of  $0.98 \pm 0.02$  with the additional data at  $P = 0$ , versus mean  $r$  of  $0.92 \pm 0.06$  without this data).

The V-P curve of most patients was curvilinear with the convexity towards the pressure axis (fig. 4). Thus, tidal breathing occurred at the lower end of the normally sigmoid-shaped V-P curve, and this is similar to the finding of Sharp *et al.*<sup>5</sup> in anesthetized-paralyzed children. Compliance at the lower end of the V-P curve is less than that at the steep middle portion, indicating that compliance is not optimal during anesthesia. This is consistent with numerous investigations, summarized by Don,<sup>3</sup> which indicate that compliance decreases upon induction of anesthesia. The decrease in FRC on induction of anesthesia

would probably explain this position of the anesthetized patients' V-P curve.

The mean of the intrasubject  $\text{Crs}_{\text{vr}}$  was  $15.0 \pm 7.1\%$ , which is greater than mean intrasubject CV for  $\text{Crs}_{\text{sb}}$  of  $9.4 \pm 6.7\%$ . This difference was significant and indicates that the single breath test is reproducible in addition to its simplicity.

$\text{Crs}_{\text{vr}}$  correlated well with  $\text{Crs}_{\text{sb}}$  (fig. 6). In two of the taller children,  $\text{Crs}_{\text{vr}}$  was approximately 25% greater than  $\text{Crs}_{\text{sb}}$  and the linear regression of  $\text{Crs}_{\text{vr}}$  versus  $\text{Crs}_{\text{sb}}$  therefore had a slope of 1.2. There may be minor differences due to the technique of measuring Crs in that  $\text{Crs}_{\text{sb}}$  is measured after a shorter occlusion, which may not allow sufficient time for stress relaxation to occur, resulting in lower apparent compliance values. However, this is a small effect, as may be seen from the  $P_m$  plateaux in figure 2, and stress relaxation probably does not influence  $P$  to a significant degree, especially at lower lung volumes.<sup>17</sup> In addition, this minor effect would be offset by loss in lung volume during gas exchange in the alveolus during the longer breath hold of the volume recruitment maneuver, an effect which decreases  $\text{Crs}_{\text{vr}}$  more than  $\text{Crs}_{\text{sb}}$ . Therefore, we would expect  $\text{Crs}_{\text{vr}}$  to be similar to  $\text{Crs}_{\text{sb}}$ , and this was confirmed in this study.

In summary, we have shown that the single-breath test of LeSouef *et al.*<sup>8</sup> and the volume recruitment maneuver of Grunstein *et al.*<sup>11</sup> could be applied readily to unintubated anesthetized infants or children, from 59 to 89 cm in height, for measurement of Crs. Within this height range, the single-breath test was rapid and reproducible, and could be used to study Crs serially at various stages of anesthesia and surgery. The volume recruitment maneuver provided data for the V-P curve within and outside the tidal breathing range, and may be useful for comparison of Crs at different lung volumes. The single breath test could be applied only to children 59–89 cm in height, and the volume recruitment maneuver could be applied to only two additional patients outside this height range. In the 12 children in whom both tests were applied,  $\text{Crs}_{\text{vr}}$  correlated with, and was similar to,  $\text{Crs}_{\text{sb}}$ . There was no marked advantage of one maneuver over the other for inducing respiratory muscle relaxation, and the comparison of coefficients of variation suggests greater reproducibility of the single-breath test.

## Appendix

For analysis of the V-P curves from the volume recruitment maneuver, we used the polynomial equation of the form:

$$V = aP^2 + bP + c \quad (1)$$

The index "a" describes the curvilinearity of the function, "b" describes its steepness, and "c" is the intercept of the curve on the volume axis.<sup>11</sup> The polynomial curves were convex to the

pressure axis in eight patients and appeared concave to the pressure axis in four patients (fig. 4) as indicated by the sign of the index "a" from equation 1. Grunstein *et al.*<sup>11</sup> also found that V-P data from infants without respiratory disease fit a polynomial regression with the convexity of the curve toward the pressure axis. In the present investigation, mean "a" was  $0.28 \pm 0.12 \text{ ml} \cdot \text{cm H}_2\text{O}^{-2}$ , indicating that the direction of the convexity of the curve was toward the pressure axis. However, in five patients (patients 2, 6, 7, 8, and 9) "a" was not significant by Student's *t* test ( $P < 0.05$ ) (table 2), indicating that the equation which best fit the P-V data in these patients was linear. Thus, in all the patients from the present study, the P-V curves were either convex to the pressure axis or were linear.

Compliance can be calculated as the slope of the line tangent to a point on the polynomial curve. To determine the tangent compliance at any given pressure, equation 1 was differentiated with respect to P:

$$dV/dP = 2aP + b, \quad (2)$$

and the tangent compliance was calculated from equation 2. We chose to report  $\text{Cr}_{s_{\text{vr}}}$  as tangent compliance in the mid-tidal range in order to compare it to  $\text{Cr}_{s_{\text{sb}}}$ , which is measured throughout the tidal range. The mid-tidal range is represented by one-half tidal volume or one-half of the pressure developed at end-tidal inspiration. Mean P at end-inspiration was  $8.0 \pm 1.4 \text{ cm H}_2\text{O}$  from the single-breath test, and thus 4 cm H<sub>2</sub>O represents the pressure developed during occlusion at mid-tidal range. In this study, we report  $\text{Cr}_{s_{\text{vr}}}$  measured at 4 cm H<sub>2</sub>O, representing approximately mid-tidal range, and compare it with  $\text{Cr}_{s_{\text{sb}}}$ , which represents the compliance throughout the tidal range.

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