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Functional Residual Capacity in Anesthetized Children: Normal Values and Values in Children with Cardiac Anomalies

Adalbjörn Thorsteinsson, M.D., Christer Jonmarker, M.D., Ph.D.,† Anders Larsson, M.D., Ph.D.,† Carsten Vilstrup, M.D.,* Olof Werner, M.D., Ph.D.†*

To assess the increase in functional residual capacity (FRC) with growth, FRC was measured after induction of anesthesia in two groups of children. One group consisted of 74 children, 0.1–11.2 yr of age, without signs of cardiorespiratory disease (referred to here as "normal" children), and the other of 21 children, 0.2–6.9 yr of age, with cardiac malformations. Anesthesia was maintained with halothane in the normal children and with fentanyl, droperidol, and nitrous oxide in the children with cardiac anomalies. All patients were paralyzed, their tracheas intubated, and their lungs mechanically ventilated. FRC was measured with an automated tracer gas washout technique. In 70 patients the measurements were performed in duplicate with a mean coefficient of variation of 2.0%. FRC correlated significantly with height, weight, and age in both groups. Multiple regression analysis for both groups considered together indicated no significant improvement when factors for the sex of the child or for the presence of cardiac anomalies were incorporated into the model. In normal children the simple linear and nonlinear regression equations for FRC (in milliliters) *versus* height (in centimeters) were: FRC = −529 + 9.48 × height, r = 0.96; and FRC = 0.00175 × height$^{2.66}$, r = 0.97, respectively. The corresponding equations for FRC (in milliliters) *versus* weight (in kilograms) were: FRC = −92 + 29.9 × weight, r = 0.93; and FRC = 9.51 × weight$^{1.31}$, r = 0.95. The ratio of FRC to body weight was lower in normal infants (n = 21) than in normal children above 1 yr of age (n = 53): the values (mean ± SD) were 17 ± 4 and 24 ± 6 ml/kg, respectively ($P < 0.001$). It is concluded that FRC in anesthetized children whose tracheas are intubated can be predicted from height, weight, or age; that the ratio of FRC to body weight was lower in infants than in older children; and that FRC was not affected by the presence of cardiac anomalies. (Key words: Anesthesia: pediatric. Lung: functional residual capacity. Heart, Congenital heart disease.)

IN ANESTHETIZED CHILDREN, airway obstruction and apnea are associated with rapid development of hypoxemia. The smaller the child, the more rapid is the decrease in oxyhemoglobin saturation. Although factors such as the occurrence of intracardiac shunting or airway closure may contribute, the most important factor determining the speed with which hypoxemia develops in healthy children is probably the oxygen reserve contained in the lung and its relation to the oxygen consumption of the child. Knowledge of normal values for functional residual capacity (FRC) therefore is clinically useful. This paper presents results of FRC measurements with a tracer gas washout technique[1–3] in healthy children and in children with cardiac anomalies.

* Assistant Professor of Anesthesiology and Intensive Care.

† Associate Professor of Anesthesiology and Intensive Care.

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Address reprint requests to Dr. Jonmarker: Department of Anesthesiology, RN-10, University of Washington, Seattle, Washington 98195.

Methods

PATIENTS

After obtaining approval by the local Human Studies Committee and consent from the parents, 95 children were studied (table 1).

Seventy-four children, 30 girls and 44 boys, were candidates for lower abdominal or urologic procedures and had no evidence of cardiac or respiratory disease. They were regarded as "normal" for the purpose of this investigation.

Twenty-one children, 9 girls and 12 boys, had congenital heart malformations. Six had isolated atrial or ventricular septal defects, and 15 had complex lesions (truncus arteriosus, transposition of the great arteries, double outlet right ventricle, pulmonary atresia, or tetralogy of Fallot). No child had clinical signs of obstructive pulmonary disease, and none required ventilatory support before surgery. The results obtained in 12 of the children with cardiac anomalies have been published previously.[4]

ANESTHETIC TECHNIQUE

In children without cardiac disease, anesthesia was induced with iv barbiturate (n = 59), with iv propofol (n = 2), or with halothane and nitrous oxide *via* face mask (n = 13). All of these children were paralyzed with vecuronium and their lungs ventilated with 1% halothane in air/oxygen (fractional inspired O_2 concentration [$F_{I_{O_2}}$] = 0.6).

In children with cardiac anomalies, anesthesia was induced with iv barbiturate (n = 1), with iv droperidol/fentanyl (n = 8), or with halothane and nitrous oxide *via* face mask (n = 12). Anesthesia was maintained with fentanyl/droperidol, and ventilation was with nitrous oxide/oxygen ($F_{I_{O_2}}$ = 0.35–0.5). Muscle paralysis was accomplished with alcuronium or pancuronium.

In all children, the trachea was intubated with a cuffed endotracheal tube. The cuff was inflated during measurements and the system was checked for leaks by auscultation. The lungs were ventilated with a Servo 900 C ventilator (Siemens-Elema, Sweden) set at volume-controlled ventilation with a constant inspiratory flow, a rate

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TABLE 1. Demographic Data

Patients	n	Age (yr)	Weight (kg)	Height (cm)
Normal children	74	2.6 (0.1–11.2)	14 (3.8–36)	92 (52–146)
Children with cardiac anomalies	21	1.5 (0.2–6.9)	8.7 (5.1–22.2)	74 (56–127)

Values are median and range (in parentheses).

of 20–30 breaths · min^{-1}, and a tidal volume of 8–16 ml · kg^{-1}, except in seven of the normal children. In these children the lungs were ventilated with a Mapleson D system, the expiratory limb of which was occluded manually during inspiration. Apparatus dead space varied from 8 ml in the youngest to 38 ml in the oldest, depending on the size of the pneumotachograph and on whether a heat–moisture exchanger was used or not.

MEASUREMENTS

FRC was measured with a multiple-breath washout technique with sulfur hexafluoride (SF_6) as tracer gas. The method has been described in detail previously[1–3]: the tracer gas concentration is measured in the apparatus deadspace with an infrared transducer placed over a cuvette with windows. SF_6 is washed in through a dispensing device, which mixes SF_6 in proportion to the instantaneous inspiratory flow. In this way, a uniform inspired concentration is achieved even with nonconstant inspiratory flow. Wash-in continues until a stable end-tidal concentration of approximately 0.5% is attained. SF_6 washout is started by stopping tracer gas delivery between two inspirations, and is considered complete when the mean expired concentration is less than 0.001%. Signals representing flow and SF_6 concentration are fed into a computer (PDP 11/23, Digital Equipment), which gives an on-line display of inspired and expired tidal volumes and of the tracer gas concentration in each breath, and calculates FRC when washout is complete. FRC is calculated as the volume of SF_6 washed out, divided by the alveolar concentration at the end of the wash-in period. The value is converted to BTPS conditions, and apparatus deadspace is subtracted.

Airway flow was measured with a heated Fleisch pneumotachograph size 00, 0, or 1 connected to a Validyne MP 45 differential pressure transducer (for normal children), or with the standard flowmeter of the ventilator (for children with cardiac anomalies). The pneumotachograph signal was zero-adjusted and calibrated before each measurement with a precision pump using air/oxygen (FI_{O_2} = 0.6). The flowmeter of the ventilator was calibrated against a wet gas meter (Flonic, Schlumberger) during ventilation with nitrous oxide/oxygen (FI_{O_2} = 0.35–0.5). Tidal volume was obtained by integration of the flow signal. The SF_6 analyzer is quite stable, and so daily calibrations of the concentration reading are not necessary. Both the system used in normal children and

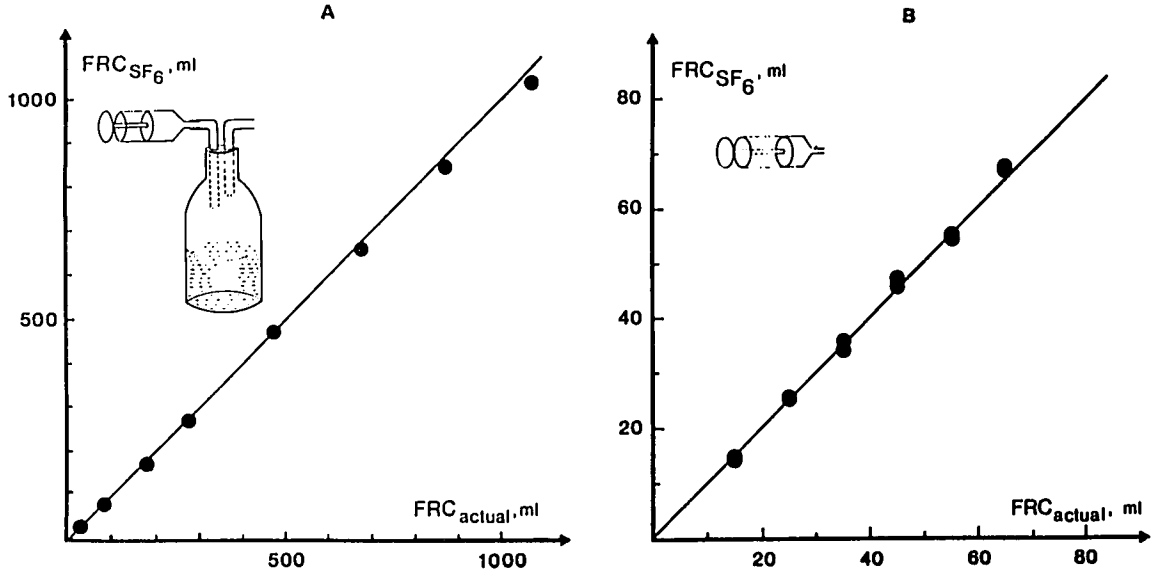

FIG. 1. Performance of the measurement system. (A) Results obtained in a model lung consisting of a 100-ml glass syringe connected to a bottle.[2] The model was ventilated by moving the plunger of the syringe at a rate of 20 min^{-1} and with a tidal volume of approximately 60 ml. (B) Results obtained in a model consisting only of the 100-ml glass syringe. FRC of the syringe was varied between 15 and 65 ml, and ventilation was accomplished by moving the plunger at a rate of 20–30 min^{-1} with a tidal volume of 15–35 ml. Each point represents a single determination. The lines of identity are shown. FRC_{SF_6} = FRC measured with SF_6 washout; FRC_{actual} = FRC of model lung.

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the system used in children with cardiac anomalies[4] give accurate measurements in pediatric-size lung models (fig. 1).

Procedure

FRC was measured approximately 15 min after induction of anesthesia in normal children and 30–45 min after induction in children with cardiac anomalies. The measurement was performed prior to surgery and with the patient in the supine position. To control the volume history of the lungs, a few deep breaths were given before wash-in in children whose lungs were manually ventilated, and in most children whose lungs were mechanically ventilated the lungs were expanded with 5 cmH_2O of positive end-expiratory pressure (PEEP) until 0.5–2 min before washout, when the ventilator setting was switched to zero end-expiratory pressure. To ascertain that zero end-expiratory pressure was present during measurement of FRC, flow and tracer gas signals were continuously recorded on paper, and the last expiration was prolonged before tracer gas washout was started.

Statistics

The coefficient of variation for duplicate FRC determinations was obtained as: SD/m, where SD is the standard deviation and m the mean. With FRC as the dependent variable, linear and nonlinear regression equations were calculated for FRC *versus* weight, FRC *versus* height, and FRC *versus* age. Multiple regression analysis was used to assess whether adding factors for the sex of the child or for the existence of cardiac anomalies improved the model. Because log FRC values seemed to be normally distributed and had similar variation around the regression line for different values for the independent variable, this model was used for performing the multiple regression analysis and for testing whether slopes or intercepts were different in children with and without cardiac anomalies. *P* values less than 0.05 were considered statistically significant. Data are presented as mean ± SD unless otherwise indicated.

Results

In 70 of the 95 patients the measurements were performed in duplicate. Duplicate measurements had a mean coefficient of variation of 2.4% (range 0–5.1%) in infants, and 1.9% (range 0–8.5%) in children more than 1 yr of age, giving a mean coefficient of variation of 2.0% for both groups considered together. There was no significant difference between the first and second FRC measurements. The correlation coefficient between the two measurements was 0.999; the slope of the regression line was close to 1.0 (1.002); and the intercept with the y-axis was close to zero (1.25 ml). The 95% confidence limits for individual second determinations were 96.2–106.6 and 498–507, if the first measurements were 100 and 500 ml, respectively.

Normal Children

There was a close correlation between FRC and height, weight, and age (table 2 and fig. 2). As indicated by the

Table 2. Regression Analysis of the Relation of FRC (ml) to Height, Weight, and Age

Relationship	Normal Children, n = 74			Children with Cardiac Anomalies, n = 21		
	A	B	r	A	B	r
X = height (cm)						
FRC = A + BX	−529	9.48	0.96	−289	6.50	0.95
±SEE	34	0.34		40	0.47	
Log FRC = A + BX	1.27	0.012	0.96	1.38	0.011	0.93
±SEE	0.04	0.0004		0.09	0.001	
Log FRC = A + B·logX	−2.76	2.66	0.97	−2.00	2.27	0.94
±SEE	0.15	0.08		0.36	0.19	
X = weight (kg)						
FRC = A + BX	−92	29.9	0.93	−20	24.2	0.93
±SEE	24	1.4		27	2.1	
Log FRC = A + BX	1.85	0.039	0.93	1.86	0.042	0.90
±SEE	0.03	0.002		0.06	0.005	
Log FRC = A + B·logX	0.978	1.31	0.95	1.21	1.12	0.92
±SEE	0.06	0.05		0.11	0.11	
X = age (yr)						
FRC = A + BX	78	83.1	0.96	102	61.4	0.92
±SEE	13	2.6		20	6.0	
Log FRC = A + BX	2.08	0.10	0.94	2.07	0.11	0.88
±SEE	0.02	0.005		0.04	0.10	
Log FRC = A + B·logX	2.27	0.60	0.94	2.26	0.45	0.89
±SEE	0.02	0.03		0.03	0.05	

r = coefficient of correlation; SEE = standard error of estimate.

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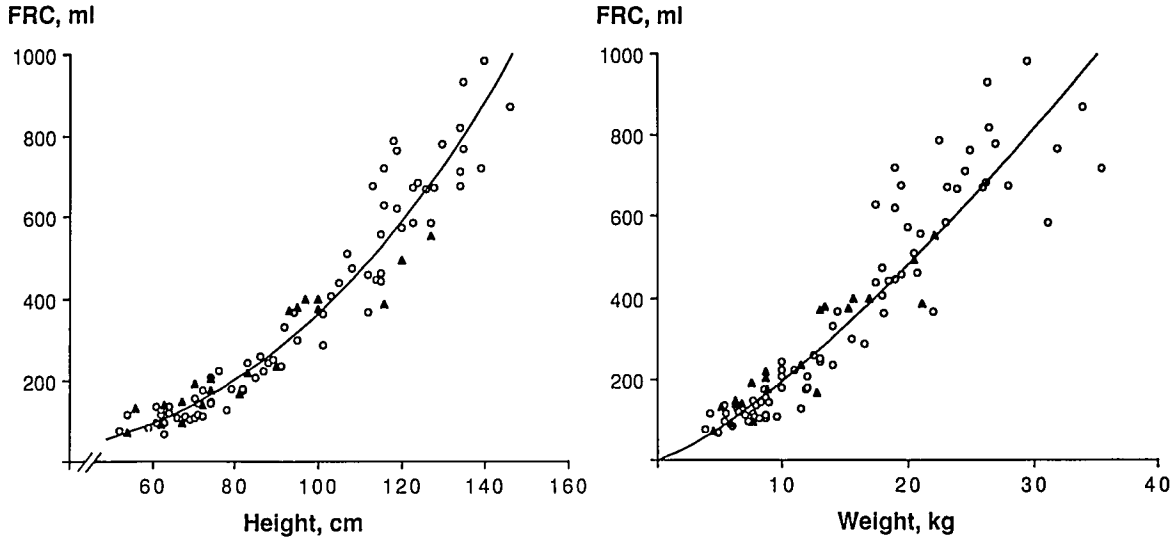

FIG. 2. FRC *versus* height and weight in normal children (circles, n = 74) and children with cardiac anomalies (triangles, n = 21). The regression curves which best fitted the data in normal children are shown (FRC [ml] = 0.00175 × height$^{2.66}$ [cm] and FRC [ml] = 9.51 × weight$^{1.31}$ [kg]).

coefficients of correlation, the increase in FRC with growth was best described by a logarithmic model with height as the independent variable: log FRC = −2.76 + 2.66 × log height, or expressed differently, FRC = 0.00175 × height$^{2.66}$ (where FRC is expressed in milliliters and height in centimeters). Multiple regression analysis indicated no significant improvement when factors for weight or age were incorporated into this model. The simple regression model that best described the increase in FRC with weight also was a logarithmic model (table 2). Thus, the ratio of FRC to body weight increased with age (fig. 3). FRC was 17 ± 4 ml/kg in infants (n = 21), whereas the value in children more than 1 yr of age (n = 53) was 24 ± 6 ml/kg ($P < 0.001$).

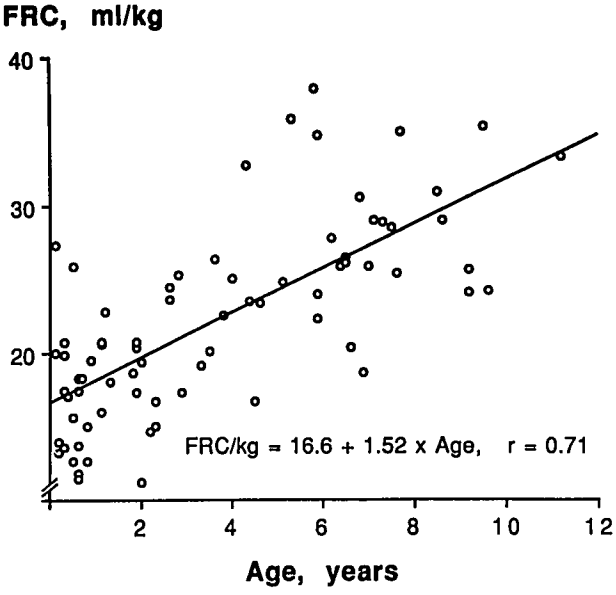

FIG. 3. FRC/bodyweight *versus* age in normal children (n = 74). The equation of the linear regression line is shown.

CHILDREN WITH CARDIAC ANOMALIES

The results are shown in table 2 and figure 2. The increase in FRC with growth was best described by a simple linear regression model: FRC = −289 + 6.5 × height (where FRC is expressed in milliliters and height in centimeters). When using multiple regression analysis for both groups considered together (n = 95), the addition of factors for cardiac disease or for the sex of the child had no significant influence on the regression model. Neither slopes nor intercepts for the regression equations relating log FRC to height, weight, or age in children with cardiac anomalies were significantly different from those in normal children (table 2).

Discussion

METHODOLOGY

The measurement system used is highly automated, gives accurate measurements in lung models (fig. 1), and has been shown to yield values in good agreement with nitrogen washout and body plethysmographic techniques in older children and adults.[1,2] Because the method is based on gas dilution, underestimation may occur in patients who have obstructive pulmonary disease and who have lung units that fill and empty slowly. However, none

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of the patients in the current study had such disease. To avoid leaks, the trachea was sealed by the tracheal tube cuff during measurements, and inspired and expired volumes were recorded and compared breath-by-breath in each measurement before it was accepted.

PEEP was applied or a few deep breaths were given before tracer gas washout in order to standardize the volume history of the lungs and to avoid a possible influence of progressive atelectasis. Because of the compliance of the respiratory system of small children, even a small PEEP may increase end-expiratory lung volume markedly; static compliance curves indicate that in a 1-yr-old child, only a few cmH_2O of PEEP may increase FRC by up to 25%.[5] Care therefore was taken to ascertain that the PEEP effect had disappeared and that the last expiration was complete before washout was started. Comparison of inspired and expired tidal volumes in children whose lungs were mechanically ventilated verified previous findings in adults, in whom the increase in lung volume caused by PEEP is usually gone within five breaths.[6] Hence it is unlikely that the use of PEEP shortly before measurements caused an overestimation of FRC. The clinical circumstances did not always allow measurements to be performed in duplicate, but the mean coefficient of variation observed in the current study was only 2.0%, which compares favorably with previous studies in children where nitrogen washout (3.9%)[7] and helium dilution (5.5%)[8] were used. We therefore decided to accept FRC values based on single measurements.

Normal Children

The children without cardiac disease were anesthetized with halothane and paralyzed with vecuronium, and their tracheas were intubated and their lungs ventilated. Previous findings indicate that during halothane anesthesia and tracheal intubation, FRC in children whose lungs are mechanically ventilated is similar to that in children who are spontaneously breathing,[9] but other anesthetic techniques may affect FRC differently. Thus, Dobbinson *et al.* found that FRC in older children was significantly lower after induction of anesthesia with methoxyflurane and intubation than before induction,[10] whereas Shulman *et al.* observed that FRC did not change during induction of anesthesia with ketamine in children who breathed air/oxygen *via* a face mask.[11] Although it seems likely that FRC in children anesthetized with isoflurane or enflurane, for example, would be similar to the values observed in the current study, caution should be exercised in making any further extrapolation.

The regression model that best described the increase in FRC with growth in normal children was a power curve relating FRC to height. To our knowledge, no other group has reported FRC values in relation to weight and height in anesthetized children in whom the trachea is

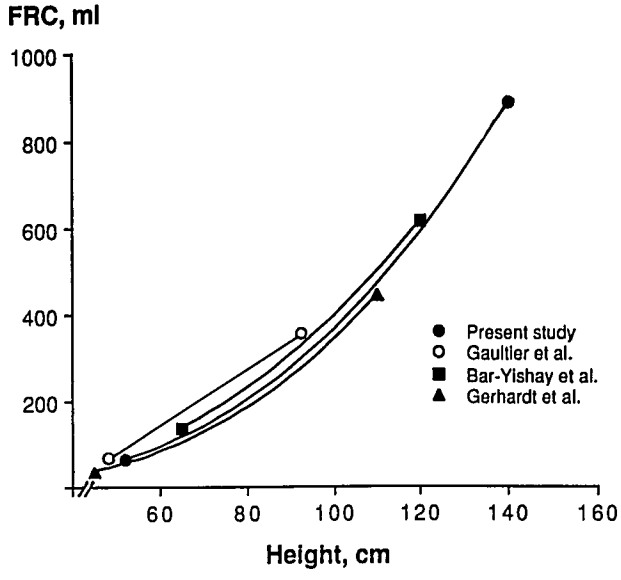

FIG. 4. Regression lines for FRC *versus* height obtained by others in awake/sedated‡,[7] or awake/ketamine-anesthetized children,[8] as compared to the present findings in normal children (FRC [ml] = $0.00175 \times \text{height}^{2.66}$ [cm]).

intubated. The shape of the regression curve found in the current study, however, is similar to that observed in previous studies in which gas dilution techniques and a tight-fitting face mask were used to measure FRC (fig. 4). With the exception of the study of Bar-Yishay *et al.*,[8] in which 21 of the 41 children were anesthetized with ketamine, the patients in these studies were either awake or sedated. Bar-Yishay *et al.*[8] and Gerhardt *et al.*[7] studied children 0–8 and 0–5 yr of age, respectively, and found that the increase in FRC with growth was well described by the log FRC to log height relationship shown in figure 4. Gaultier *et al.*‡ studied younger children (0–3 yr) and found a better fit with a linear regression model, with weight as the independent variable. When comparing FRC values predicted by the nonlinear regression equation in the current study (FRC = $0.00175 \times \text{height}^{2.66}$) to those predicted by the equation of Bar-Yishay *et al.* (FRC = $0.0052 \times \text{height}^{2.44}$), who studied a similar age group (only five of our normal children were more than 8 yr of age), our values tended to be somewhat lower, especially in infants. Although it is possible that this difference may be because induction of anesthesia and intubation cause a relatively greater decrease in FRC in infants, as previously suggested by Motoyama *et al.*,§ fur-

‡ Gaultier C, Boulé M, Allaire Y, Clément A, Girard F: Growth of lung volumes during the first three years of life. Bull Europ Physiopath Respir 15:1103–1116, 1979

§ Motoyama EK, Brinkmeyer SD, Mutich RL, Walczak SA: Reduced FRC in anesthetized infants: Effect of low PEEP. (Abstract) ANESTHESIOLOGY 57:A418, 1982

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ther studies in which the same technique is used to measure FRC before and after induction of anesthesia in young children are needed to test this hypothesis. The current finding that FRC values are similar in boys and girls confirms the findings of Bar-Yishay *et al.*[8]

The nonlinear increase in FRC with growth is also apparent when FRC is normalized to body weight (fig. 3). Thus, infants had significantly lower FRC-to-body weight ratios than did older children. This may be of some clinical interest because initial lung volume has been shown to be the most important determinant of hypoxemia during apnea. Findley *et al.*[12] found that apnea of 30 s duration at low lung volumes was accompanied by severe arterial oxyhemoglobin desaturation in awake, healthy adults. At lung volumes below 3,000 ml, corresponding to about 40 $ml \cdot kg^{-1}$, the oxyhemoglobin saturation at 30 s decreased linearly with the decrease in lung volume.[12] Because oxygen consumption in relation to weight decreases with age,[13] while the ratio of FRC to body weight increases with age, it is perhaps not surprising that hypoxemia can occur more rapidly in infants than in older children.

Children with Cardiac Anomalies

Previous studies in awake children[14,15] and in older children during anesthesia[10] indicate that the presence of cardiac anomalies has little effect on FRC if the child does not have congestive heart failure. This seems to be true both for anomalies with and anomalies without increased pulmonary circulation.[4,14,15] Although the current findings appear to confirm that cardiac disease usually does not affect FRC, it should be noted that different anesthetic agents were used in the two groups studied. Also, the measurements in children with cardiac disease were obtained a somewhat longer time after induction of anesthesia, as compared to measurements in normal children.

In conclusion, FRC in anesthetized infants and children in whom the trachea was intubated could be predicted from the weight and height of the child. The prediction did not seem to be affected by presence of cardiac anomalies. When normalized to weight, infants had a lower FRC (in milliliters per kilogram) than older children.

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