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Ventilatory consequences of the lateral position and thoracotomy in children

Functional residual capacity (FRC), breath-by-breath compliance of the respiratory system (C_{rs}) and arterial oxygen tension (PaO_2) were measured in ten children, two months to nine years of age, during anaesthesia for surgical correction of patent ductus arteriosus or coarctation of the aorta. The children were mechanically ventilated with halothane, nitrous oxide and oxygen. FIO_2 was kept constant in each child. After induction of anaesthesia, FRC was $17 \pm 7\ ml \cdot kg^{-1}$ (mean ± 1 SD), corresponding to 60 ± 22 per cent of a predicted awake value. FRC increased to $21 \pm 8\ ml \cdot kg^{-1}$ ($p = 0.0005$) when the child was turned to its right side and decreased to $13 \pm 5\ ml \cdot kg^{-1}$ ($p = 0.0003$) when the pleura was opened. No significant change in C_{rs} or PaO_2 occurred during these manoeuvres. Retraction of the upper lung to visualize the great vessels caused a significant decrease in FRC, C_{rs}, and PaO_2. The lowest PaO_2 observed during this stage was 70.0 mmHg. After surgery FRC and PaO_2 were about the same as before surgery while C_{rs} had decreased from 0.87 ± 0.18 preoperatively to $0.64 \pm 0.15\ ml \cdot cmH_2O^{-1} \cdot kg^{-1}$ ($p = 0.0069$). This study shows that FRC increases when mechanically ventilated children are placed in the lateral position, and that thoracotomy is associated with marked changes in FRC, C_{rs} and PaO_2.

Key words

PAEDIATRIC ANAESTHESIA: lateral position, thoracotomy; LUNG: functional residual capacity, compliance; MEASUREMENT TECHNIQUE: washout; VENTILATION: mechanical.

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In adults, turning from the supine to the lateral position results in an increase in functional residual capacity (FRC) irrespective of whether the patient is breathing spontaneously or is being mechanically ventilated.[1] In anaesthetized spontaneously breathing children, on the other hand, the lung volume does not seem to increase when the child is turned to its side.[2] The effect of lateral position in mechanically ventilated children has not been studied although the lateral position is often used for operations where positive pressure breathing is considered mandatory, e.g., surgery on the great intrathoracic vessels. During these operations several other manoeuvres affect lung function, e.g., opening the pleura and retracting the lung to expose the surgical field. The aim of the present study was to examine the effects of the right lateral position and thoracotomy on FRC, compliance of the respiratory system and arterial oxygenation.

Methods

Ten children, two months to nine years of age (median 17 months), undergoing elective surgery for patent ductus arteriosus or coarctation of the aorta were studied. Morphometric data and diagnosis for each child are shown in Table I. Informed consent was obtained from the parents and the study was approved by the local Human Studies Committee.

Anaesthesia was induced with halothane. Alcuronium was given in five cases and succinylcholine in one to facilitate intubation. Cuffed endotracheal tubes (Portex) were used. This is the recommended technique at our institution for intrathoracic surgery in children. Anaesthesia was maintained with halothane (1–2 per cent) in 50–70 per cent N_2O in oxygen, supplemented with fentanyl or meperidine in five children. FIO_2 was kept constant in each child. It was 0.3 in the older children and 0.4–0.5 in the others. The lungs were ventilated by a Servo ventilator 900 C (Siemens-Elema). The ventilator was set at 20–30 breaths/min. There were no spontaneous respiratory efforts during the measurements. The tidal volume was adjusted so that endtidal PCO_2 was about 30 mmHg (measured by a Siemens Elema CO_2-Analyzer 930). The resulting tidal volume ($12 \pm 2\ ml \cdot kg^{-1}$

TABLE I Patient characteristics and initial FRC

Patient number	*Age (months)*	*Height (cm)*	*Weight (kg)*	*Diagnosis*	*FRC-supine before surgery (ml)*
1	2	61	5	PDA	44
2	11	76	10	Coarc	101
3	13	71	9	PDA	101
4	13	74	8	PDA	127
5	14	79	9	PDA	110
6	20	83	13	Coarc	234
7	61	112	19	Coarc	595
8	81	116	24	PDA	424
9	81	120	23	Coarc	558
10	114	137	33	Coarc	703

PDA = Patent ductus arteriosus. Coarc = Coarctation of the aorta.

BTPS) (mean ± 1 SD) was kept unchanged after the initial adjustment. Arterial PCO_2 was 33 ± 3 mmHg and did not change significantly during the procedure. Insufflation time was 25–33 per cent and the end-inspiratory pause was 10 per cent of the breathing cycle. A breathing pattern with constant insufflation flow was used. End-expiratory pressure was zero. During the measurements the humidifier (Cascade, Bennet) was disconnected to reduce compliance of the respiratory tubing. After completion of the vascular repair the lungs were gently re-expanded until no atelectasis could be seen in the uppermost lung, a pleural drain was inserted and connected to 20 cmH_2O of negative pressure, and the chest was closed.

Functional residual capacity (FRC), breath-by-breath compliance, and arterial oxygen tension (PaO_2) were measured at seven occasions during anaesthesia: (1) before surgery, supine position; (2) before surgery, left side up; (3) after opening the pleura, lung untouched; (4) during dissection of the vessels, with the upper lung retracted; (5) after re-expanding the lung; (6) after closure of the thoracotomy, left side up; (7) after surgery, supine position. Surgery was discontinued during the measurements of stage 3 and stage 5.

FRC was measured with a multiple breath washout technique using sulphur hexafluoride (SF_6) as tracer gas.[3] The tracer gas concentration was measured with an infrared analyzer insensitive to the anaesthetic gases used and to CO_2. The transducer of the analyzer was placed over a cuvette with windows in the ventilator tubing (Figure 1). SF_6 was washed in through a catheter until the alveolar concentration was about 0.5 per cent. SF_6 washout was continued until the concentration was 0.001 per cent. Signals representing expired flow and SF_6 concentration were fed into a computer (PDP-11/23, Digital Equipment), which calculated FRC as the volume of SF_6 washed out divided by the alveolar concentration at the end of washin. Apparatus dead space was subtracted and the volume was converted to BTPS conditions. All FRC measurements were done in duplicate. The method gives accurate results in adults[3] and in paediatric size model lungs.[4]

The airway pressure and the expiratory flow were measured with the standard manometer and expiratory flowmeter of the ventilator. The airway manometer was calibrated against a mercury manometer and the flowmeter was calibrated against a wet gas meter (Flonic, Schlumberger) during ventilation with 50 per cent N_2O in O_2. The expired flow and airway pressure signals were transmitted to the computer which calculated breath-by-breath compliance of the respiratory system (C_{rs}) as: $C_{rs} = V_T/(P_{pause} - P_{endexp})$, where V_T equals the expiratory tidal volume (BTPS), P_{pause} the airway pressure at the end of the end-inspiratory pause, and P_{endexp} the airway pressure at the end of expiration. The latter was obtained by using the "end-expiratory hold" facility of the ventilator which closes both the inspiratory and expiratory valves. This function was activated for about 1 s. The end-inspiratory pause was 0.2–0.35 s which was judged sufficient to obtain a well-defined plateau in the pressure curve.[4] Compliance of the tubing ($0.5\ ml \cdot cmH_2O^{-1}$) was subtracted from the obtained compliance value.

PaO_2 was measured in nine children. The samples were collected from the right radial artery, i.e., preductally, and were assessed within five minutes on a blood gas analyzer (ABL2, Radiometer), at 37°C.

Statistics

Overall changes in FRC, PaO_2, and C_{rs} were examined by two-way analysis of variance. Probability values below 0.05 were considered to indicate statistical significance. If a significant variation was found, paired comparisons were performed with the t-test. Since seven comparisons were made, the Bonferroni method was

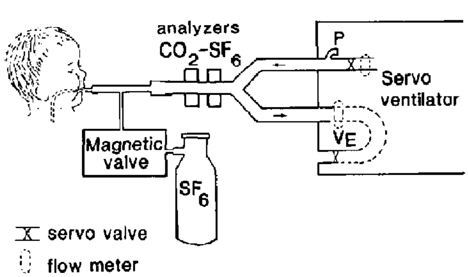

FIGURE 1 The measurement system. P = tube to pressure transducer, VE = expiratory flow meter.

used for adjustment of the significance levels. Thus, probability values below $1 - (1-0.05)^{1/7}$ (= 0.0073) were considered to indicate statistical significance by the t-test. The p-values for each comparison are shown in Table II. The data are given as mean ± 1 SD when not otherwise indicated. Regression lines were obtained by the method of least squares. The t-test was also used to assess whether intercepts were different from zero.

Results

Functional residual capacity (Figure 2)
The individual values obtained with the child in the supine position before surgery are shown in Table I. The correlation to height was: FRC (ml) = −554 + 9.27 × height (cm), r = 0.97 and the correlation to weight was: FRC (ml) = −90.1 + 25.4 × weight (kg), r = 0.94. The latter intercept was not significantly different from zero. The data are therefore reported as FRC/kg body weight. When the child was turned to its side FRC increased from 17 ± 7 $ml \cdot kg^{-1}$ to 21 ± 8 $ml \cdot kg^{-1}$ (p = 0.0005). FRC decreased markedly when the pleura was opened, to 13 ± 5 $ml \cdot kg^{-1}$, and when the upper lung was retracted during the vascular repair, to 9 ± 4 $ml \cdot kg^{-1}$. The FRC values obtained after re-expanding the lung,

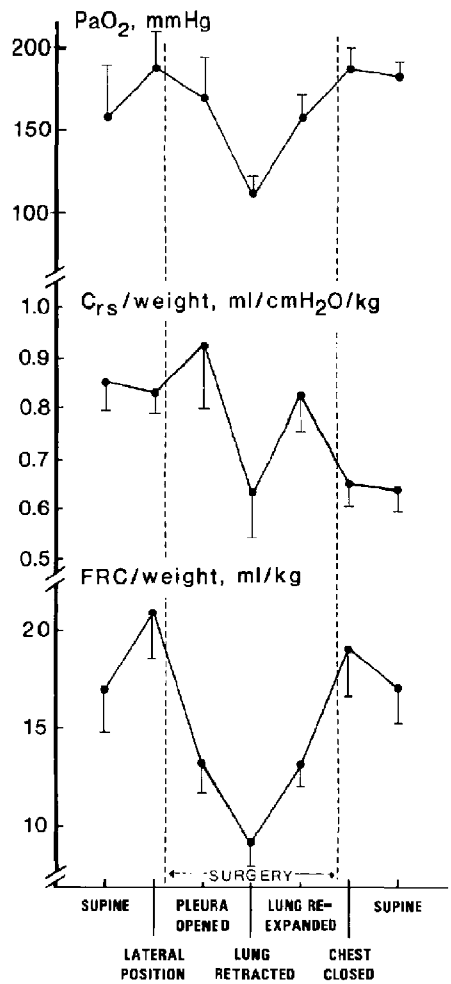

FIGURE 2 Arterial PO_2, C_{rs}/weight, and FRC/weight. Mean ± SEM. See text and Table II for results of statistical analysis.

TABLE II Probability values for comparisons between stages

	Comparison between stages:						
	1–2	2–3	3–4	4–5	5–6	6–7	1–7
PaO_2	0.37	0.18	0.0015	0.0061	0.011	0.68	0.81
C_{rs}	0.79	0.45	0.0065	0.0001	0.013	0.57	0.0069
FRC	0.0005	0.0003	0.0001	0.0003	0.0075	0.011	0.43

1 = before surgery, supine position; 2 = before surgery, lateral position; 3 = after opening the pleura, lung untouched; 4 = upper lung retracted; 5 = after re-expanding the lung; 6 = after closure of the thoracotomy, lateral position; 7 = after surgery, supine position.

after closure of the thoracotomy, and after turning the child to the supine position were about the same as the values obtained during the corresponding stages before surgery.

Compliance of the respiratory system (Figure 2)
In the supine position before surgery C_{rs} was closely correlated to FRC: C_{rs} ($ml \cdot cmH_2O^{-1}$) = 3.3 + 0.034 × FRC (ml), r = 0.99. The correlation to weight was: C_{rs} ($ml \cdot cmH_2O^{-1}$) = 0.80 + 0.83 × weight (kg), r = 0.91. The intercept was not significantly different from zero and C_{rs}/kg body weight during this stage was 0.87 ± 0.18 $ml \cdot cmH_2O^{-1} \cdot kg^{-1}$. No significant change occurred when the child was placed in the lateral position or when the pleura was opened, but retraction of the upper lung during the vascular repair caused a marked decrease in C_{rs} (p = 0.0065). In the supine position after surgery, C_{rs} was 0.64 ± 0.15 $ml \cdot cmH_2O^{-1} \cdot kg^{-1}$ which was somewhat less than in the same position before surgery (p = 0.0069).

Arterial oxygen tension (Figure 2)
In the supine position before surgery PaO_2 was 157 ± 83 mmHg. Neither turning the children to their side nor opening the pleura caused any significant change but retracting the lungs during dissection of the great vessels resulted in a decrease to 113 ± 30 mmHg (p = 0.0015). The lowest PaO_2 obtained in an individual child was 70.0 mmHg. After re-expanding the lung PaO_2 increased to 158 ± 38 mmHg (p = 0.0061). PaO_2 after surgery in the supine position was not significantly different from the value obtained in the same position before surgery.

Discussion

FRC in the supine position after induction of anaesthesia was 17 ± 7 $ml \cdot kg^{-1}$, which corresponds to 60 ± 22 per cent of predicted awake values.[5] This agrees well with previous findings in children of similar age.[6] On the average, FRC increased by 22 per cent with the change to the lateral position. Findings in adults suggest that this change is due to expansion of the upper lung. Thus, in mechanically ventilated subjects, Rehder *et al.* found that the right lateral position caused a marked increase in the end-expiratory volume of the upper lung, while that of the lower lung was virtually unchanged, resulting in a 40 per cent overall increase in mean FRC.[1] Similar results were reported in spontaneously breathing adults.[1] We did not measure FRC of each lung, but find it reasonable to assume that the changes in FRC were similarly distributed in our patients. However, in anaesthetized spontaneously breathing children Helms *et al.*,[2] who used body plethysmography, did not find any significant change in the end-expiratory lung volume when turning the child to its side. They studied infants below one year of age, but this probably does not explain the disagreement between our findings and theirs, since the two infants in our study had an increase in FRC by 43 and 72 per cent, respectively. More probably, the discrepancy is explained by the different modes of ventilation or by the different methods of measuring lung volume.

As could be expected FRC decreased markedly when the pleura was opened and the lung retracted (Figure 2). A simultaneous decrease of PaO_2 occurred, but not to levels that may be considered dangerous. We believe that this was because both ventilation and perfusion were directed away from the compressed parts of the lung. Several mechanisms may be responsible for such a redistribution of blood flow, e.g., direct compression of the vessels, hypoxic pulmonary vasoconstriction[7] and narrowing of vessels in atelectatic areas.[8]

In spite of the marked changes in FRC and PaO_2 during the surgical procedure both returned to preoperative values at the end of the operation. The slight decrease in C_{rs} after the operation in relation to the preincision findings was not necessarily due to a change in pulmonary compliance. The decrease could as well have been caused by a change in thoracic compliance due to more superficial anaesthesia and less intense muscle paralysis.

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Résumé

La capacité résiduelle fonctionnelle (FRC), la compliance du système respiratoire mesurée à chaque respiration (C_{rs}) et la tension artérielle d'oxygène (PaO_2) ont été mesurées chez dix enfants âgés de deux mois à neuf ans lors d'une anesthésie générale pour correction de canal artériel persistant ou de coarctation de l'aorte. Les enfants étaient ventilés mécaniquement avec de l'halothane, protoxyde d'azote et oxygène. La FIO_2 était gardée constante pour chaque enfant. Après l'induction de l'anesthésie, la FRC était de 17 ± 7 $ml \cdot kg^{-1}$ (moyenne ± SD), correspondant à 60 ± 22 pour cent de la valeur prédite à l'état d'éveil. La FRC augmenta de 21 ± 8 $ml \cdot kg^{-1}$ (p = 0.0005) quand l'enfant était mis en position latérale droite et diminua à 13 ± 5 $ml \cdot kg^{-1}$ (p = 0.0003) quand la plèvre fut ouverte. Aucun changement significatif n'est survenu dans la C_{rs} ou la PaO_2 lors de ces manœuvres. La rétraction du lobe supérieur du poumon afin de visualiser les gros vaisseaux a occasionné une diminution significative de la FRC, C_{rs} et PaO_2. La PaO_2 la plus basse observée à ce stade était de 70.0 mmHg. Après la chirurgie la FRC et la PaO_2 sont revenues aux mêmes valeurs préop alors que la C_{rs} a diminué de 0.87 ± 0.18 en période préopérative à 0.64 ± 0.15 $ml \cdot cmH_2O^{-1} \cdot kg^{-1}$ (p = 0.0069). Cette étude démontre que la FRC augmente chez les enfants ventilés mécaniquement mis en position latérale et que la thoracotomie est associée à un changement marqué dans la FRC, C_{rs} et PaO_2.