Changes in Functional Residual Capacity and Lung Mechanics during Surgical Repair of Congenital Heart Diseases

Effects of Preoperative Pulmonary Hemodynamics
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Background: To characterize the impact of lung volume changes in the lung function impairment after the surgical repair of congenital heart diseases, combined measurements of functional residual capacity, lung clearance index, and respiratory mechanics were performed in children with hypoperfused lungs (tetralogy of Fallot [TOF]) or with pulmonary hyperperfusion (ventricular septal defect [VSD]).

Methods: Lung volume and clearance were assessed by using a sulfur hexafluoride washout technique, and the mechanical properties of the respiratory system were assessed using a low-frequency oscillation technique. Lung volume and oscillatory measurements were made preoperatively, before and after cardiopulmonary bypass and aortic clamping (AC), and after chest closure.

Results: Impairments in airway (36 ± 2%) and tissue mechanics (22 ± 3%) were observed in the children with TOF after bypass; AC and chest closure were associated with marked decreases in functional residual capacity (−24 ± 3% and −13 ± 2% for TOF and VSD after AC, respectively) and increases in lung clearance index (−60 ± 6% and −24 ± 3% for TOF and VSD after AC, respectively). Smaller impairments in lung mechanics were observed after bypass and AC in children with VSD.

Conclusions: These findings suggest that the lung volume loss and lung mechanical deteriorations are probably caused by a diminished tethering effect of the lung periphery through a reduced filling of the pulmonary capillaries. This effect seems to be more pronounced in children with hypoperfused lungs (TOF) than in those with pulmonary hyperperfusion (VSD). The beneficial postoperative changes in children with VSD are consequences of the reversal of the pulmonary vascular engagement after surgical repair.

MONITORING of the lung function parameters is essential in the perioperative period in children with congenital heart diseases (CHDs). A description of the altered airway and lung tissue mechanics during surgical repair of CHD facilitates the characterization of cardiopulmonary interactions and hence might contribute to optimization of the perioperative management. Anesthesia and cardiopulmonary bypass (CPB) enhance the ventilation perfusion mismatch by decreasing the functional residual capacity (FRC), inducing an inflammatory response and promoting interstitial water extravasation.

In addition, the overall change in respiratory function depends on the preoperative pulmonary hemodynamic condition of the patient. The lungs of children with a congenital cardiac malformation involving a high flow and/or pressure in the pulmonary circulation (ventricular septal defect [VSD]) are stiffened, resulting in deteriorated lung function, which improves significantly after surgical repair. Children with hypoperfused lungs might also be compromised because of the loss of the stabilizing effects of normal pulmonary hemodynamics on the alveolar architecture.

It has been suggested that the consequence of altered pulmonary hemodynamics and the deleterious effects of anesthesia and CPB could exert their effects via a loss in lung volume and a decrease in pulmonary compliance. These two important lung function parameters have yet to be measured simultaneously in the presence of different pulmonary hemodynamic conditions. In our study, we assessed the changes in lung volume and lung mechanics in children undergoing the surgical repair of CHD involving hypoperfused or hyperperfused lungs by performing measurements at different stages of the cardiac surgery and CPB. This approach permits a more accurate characterization of the contribution of pulmonary capillary filling to the observed changes in FRC and lung mechanics.

Materials and Methods
After approval by our institutional ethics committee at the University Hospitals of Geneva, Switzerland, and the provision of parental written informed consent, 24 children undergoing cardiac surgery of CHD with CPB were enrolled in the study. Twelve children had CHD with pulmonary hyperperfusion (tetralogy of Fallot [TOF]), and 12 had CHD involving pulmonary hyperperfusion (VSD).
Anesthesia

All patients received 0.5 mg/kg midazolam for premedication 30 min before anesthesia induction. Anesthesia was induced either by the inhalation of sevoflurane (up to 5%) or with intravenous propofol (2–3 mg/kg). A cuffed endotracheal tube (Microcuff-Heidelberg, Weinheim, Germany) was inserted after the intravenous administration of atracurium (0.5 mg/kg) with additional boluses to ensure complete neuromuscular blockade throughout the whole of the study period. Analgesia was provided by intravenous administration of a bolus of 0.5 µg/kg sufentanil and 0.15 mg/kg ketamine followed by continuous infusion of sufentanil (0.5–1 µg·kg⁻¹·h⁻¹) and ketamine (0.1 µg·kg⁻¹·h⁻¹). Anesthesia was maintained in all patients with intravenous propofol (8–10 µg·kg⁻¹·h⁻¹).

Children were mechanically ventilated (Datex Ohmeda, Helsinki, Finland) with a fraction of inspired oxygen (FIO₂) of 0.5, a tidal volume of 10 ml/kg, and a respiratory rate adapted to an end-tidal carbon dioxide of 5 kPa. During the time of aortic clamping (after the FRC measurement), all patients received a constant positive airway pressure of 6 hPa, and the FIO₂ was reduced to 0.21. After aortic declamping, a lung recruitment maneuver to total lung capacity was performed by increasing the peak inspiratory airway pressure manually to 37–40 hPa for 10 consecutive breaths. Mechanical ventilation was restarted as it was before.

Assessment Times

Measurements with the low-frequency forced oscillatory technique and the assessments of FRC and ventilation distribution were performed (1) 5 min after intubation, (2) after the insertion of the chest retractor, (3) after the onset of CPB, (4) after aortic clamping during the administration of the cardioplegia solution, (5) after aortic declamping but still under CPB, (6) after weaning from CPB while the chest was still open and with the retractor in situ, (7) 5 min after chest closure, and (8–10) 30, 60, and 90 min after the completion of surgery. Two or three FRC and forced oscillatory measurements were performed under each study condition, and the results were averaged. All FRC assessments were performed during propofol at the same tidal volume with positive end-expiratory pressure maintained at 3 hPa. Similarly, all forced oscillatory recordings were collected at a mean pressure of 3 hPa to ensure a standardized volume history.

Measurement of FRC and Ventilation Homogeneity

An ultrasonic transit-time airflow meter (Exhalyzer D with intensive care unit insert; Eco Medics, Duernten, Switzerland), which simultaneously measures the flow and molar mass of the breathing gas in the mainstream, was placed between the ventilator circuit and the endotracheal tube. The measurement setup has been described previously. Briefly, a multibreath washout technique with sulfur hexafluoride as tracer gas was used to measure FRC and the lung clearance index (LCI), a common index of ventilation homogeneity. FRC and LCI calculations were performed with Spiroware software (version 1.5.2; ndd Medizintechnik AG, Zurich, Switzerland).

Measurement of Airway and Respiratory Tissue Mechanics

The forced oscillation technique used in the current study has been described previously. Briefly, the oscillatory signal applied to measure the input impedance of the respiratory system (with chest closed) or the lungs (with chest open) was introduced into the trachea during short apneic periods (8 s) interposed during mechanical ventilation at end-expiration. The loudspeaker generated a small-amplitude pseudorandom signal between 0.5 and 21 Hz. Tracheal pressure was sensed via a 2-mm-OD catheter, positioned 1–2 cm beyond the distal end of the endotracheal tube, by a miniature pressure transducer (model 33NA002D; ICSensors, Malpitas, CA). Central flow (V') was detected by a screen pneumotachograph attached to an identical type of differential pressure transducer. To separate the airway and tissue mechanics, a model containing a frequency-independent (newtonian) resistance representing the flow of airway resistance (Rₑ) and airway inertance in series with a constant-phase tissue compartment characterized by damping (G) and elastance (H) was fitted to the impedance spectra. Tissue hysteresivity (η) was calculated as G/H. Respiratory and lung mechanical parameters were normalized to the lung volume by multiplying them by the corresponding FRC, thereby obtaining the specific airway resistance (sRₑ) and specific tissue damping (sG) and elastance (sH).

Statistical Analysis

Because the procedural data proved to be normally distributed, as analyzed by the Shapiro–Wilks test, data are reported as mean ± SE. Two-way repeated-measures analysis of variance using a general linear model was used to test the significance within-subject fixed factors: the group assignment of the children and the time. These factors resulted in a 2 × 5 design in these statistical analyses. For pairwise comparisons, 95% confidence intervals for the differences were computed by taking into account the significant interactions between the factors. The Student–Newman–Keuls test was used for post hoc comparisons. The statistical tests were performed by using the SigmaStat statistical program package (Systat Software, Inc., Richmond, CA). P < 0.05 was considered significant.

Results

Table 1 shows the characteristics of the patients. Children with VSD tended to be younger than those with...
TOF, which was also reflected in the significantly greater weight of the latter. The duration of aortic cross clamping and the length of cardiopulmonary bypass were significantly shorter ($P < 0.01$ for both) in children with VSD (46 ± 2 and 71 ± 2 min, respectively) than in those with TOF (72 ± 2 and 98 ± 3 min, respectively).

Table 2 summarizes the results obtained in the two groups of children at the different stages of the surgery. In accord with the differences in body size, the lung volume indices were lower and the mechanical parameters were higher in children with VSD. There was a general tendency for FRC to decrease and LCI to increase as the surgery progressed. The significant changes in $R_{aw}$ in the two groups of children were gradual and opposite; the children with VSD exhibited increases and those with TOF decreases. The tissue mechanical parameters displayed gradual mild increases in both groups in both closed- and open-chest conditions.

The changes in FRC and LCI under the intact-chest conditions are summarized in figure 1. FRC and LCI demonstrated opposite changes postoperatively, with significant decreases in FRC and increases in LCI. The changes in FRC were more pronounced in the children with VSD, whereas children with TOF displayed greater increases in LCI after surgical correction of CHD.

The perioperative changes in the absolute and specific values of the overall respiratory system parameters are shown in figure 2. The trends in the perioperative changes in $R_{aw}$ in the two groups of children were opposite, with mild airway narrowing in the children with TOF and significant decreases in those with VSD. The tissue parameters exhibited similar patterns in both groups of children, with the changes generally being less than those for $R_{aw}$. The perioperative increases in the TOF group were reduced when the effects caused by the lung size differences were eliminated by calculating the specific forced oscillatory parameters through the use of the actual FRC. Normalization led to variable effects in the children with VSD: $SR_{aw}$ underwent greater decreases than $R_{aw}$, whereas the tendencies to change in $sG$ and $sH$ were just the opposite of those observed in G and H. No perioperative changes in $\eta$ were seen in the children with TOF, whereas this parameter decreased slightly in the VSD group.

The FRC and LCI parameters in the open-chest conditions at different stages of surgery are depicted in figure 3. Throughout the surgical procedure, the weight-corrected FRC was generally greater whereas LCI was lower in the children with VSD than in those with TOF. The onset of CPB and full circulatory arrest in pulmonary perfusion during aortic clamping led to significant decreases in FRC, with more pronounced changes in children with TOF. Reestabilishment of the pulmonary circulation resulted in increases in FRC, again with more marked effects in the lungs that were hypoperfused preoperatively. The alterations in LCI were similar to those in FRC.

Figure 4 demonstrates the changes in absolute and specific values of the pulmonary mechanical parameters. Significant increases observed in $R_{aw}$, G, and H in the

### Table 1. Demographic Data of Patients

<table>
<thead>
<tr>
<th>Age, mo</th>
<th>Hyperperfusion</th>
<th>Hypoperfusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (SD)</td>
<td>19.5 (7–65)</td>
<td>56 (8–122)</td>
</tr>
<tr>
<td>Sex, M:F</td>
<td>7:5</td>
<td>6:6</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>8 (4.5–17)</td>
<td>12.4 (4.8–27)</td>
</tr>
<tr>
<td>Height, cm</td>
<td>75.5 (60–109)</td>
<td>32 (63–142)</td>
</tr>
</tbody>
</table>

Data are given as mean (range).

### Table 2. Functional Residual Capacity, Lung Clearance Index, and Forced Oscillatory Mechanical Parameters in Children with Pulmonary Hypoperfusion or Hyperperfusion at All Assessment Times

<table>
<thead>
<tr>
<th>Assessment</th>
<th>FRC, ml</th>
<th>LCI</th>
<th>$R_{aw}$ hPa · s/l</th>
<th>G, hPa/l</th>
<th>H, hPa/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypoperfusion (VSD)</td>
<td>218 (39)</td>
<td>7.9 (0.4)</td>
<td>13.4 (0.5)</td>
<td>38.9 (1.8)</td>
<td>148.0 (3.1)</td>
</tr>
<tr>
<td>Hyperperfusion (Fallot)</td>
<td>283 (45)</td>
<td>8.5 (0.3)</td>
<td>6.4 (0.2)</td>
<td>6.7 (0.5)</td>
<td>167.0 (2.5)</td>
</tr>
</tbody>
</table>

Data are given as mean (SE).

* $P < 0.05$ vs. the value obtained “open chest, retract” under open-chest conditions.

** $P < 0.05$ vs. the value obtained “after induction” under closed-chest conditions.

CPB = cardiopulmonary bypass; FRC = functional residual capacity; G = tissue damping; H = tissue elastance; LCI = lung clearance index; $R_{aw}$ = airway resistance; VSD = ventricular septal defect.
children with TOF during aortic clamping were absent in $s_{R_{aw}}$, $s_G$ and $s_H$ were stable throughout the open-chest measurements in this group. Comparable profiles were observed in the children with VSD, with the exception of $s_{R_{aw}}$, which exhibited gradual small decreases during the progression of surgery under open-chest conditions. No changes in $\eta$ were observed in this phase of the operation.

Discussion

The current study details the simultaneous changes in FRC and the lung or respiratory mechanics during different phases of surgical repair in children with CHD involving hyperperfused (tetrology of Fallot [TOF]) or hypoperfused (ventricular septal defect [VSD]) lungs after anesthesia induction (Preop), after chest closure (ChestClose), and 30, 60, or 90 min thereafter. * $P < 0.05$ versus Preop levels. # $P < 0.05$ between the groups.

Fig. 1. Functional residual capacity (FRC) and lung clearance index (LCI) and their changes relative to their preoperative levels phase in children with hypoperfused (tetralogy of Fallot [TOF]) or hyperperfused (ventricular septal defect [VSD]) lungs after anesthesia induction (Preop), after chest closure (ChestClose), and 30, 60, or 90 min thereafter. * $P < 0.05$ versus Preop levels. # $P < 0.05$ between the groups.

Methodologic Issues

Changes in FRC and LCI during the different phases of the cardiac surgery in children with various types of CHDs have been characterized in our previous study.4 There are a number of advances in the current study compared with this previous investigation, such as combining lung volume assessments with state-of-the-art lung mechanical measurements to obtain a more detailed characterization of the lung function changes. In addition, the different preoperative pulmonary hemodynamic conditions were separately assessed in the current study to reveal fundamentally different changing patterns in the mechanical parameters during the perioperative period in children with two distinguished types of CHDs.

Although comparison of the changes in the mechanical parameters with those obtained in a control group of age-matched children would be of interest, such a measurement condition cannot be present in a control group because all children undergoing CPB have cardiopulmonary diseases. Therefore, we can only rely on control data collected previously in healthy children undergoing general anesthesia. These measurements revealed that FRC after induction of anesthesia and neuromuscular blockade ranges between 22 and 24 ml/kg in children without cardiopulmonary diseases.23 Based on these previous data, a slightly reduced FRC in children with TOF (19 ml/kg) and a fairly normal FRC in the patients with VSD (22 ml/kg) can be anticipated.

In the current study, the positive end-expiratory pressure of 3 hPa, the tidal volume of 10 ml/kg, and the $F_{I2}$
of 0.5 were kept constant during the measurements to maintain a standardized lung volume history. This regimen minimized the potential bias of the altered lung management on the values of FRC, LCI, and the lung or respiratory mechanics. Because standardization of the positive end-expiratory pressure resulted in different transpulmonary pressures under closed- and open-chest conditions and the mechanical parameters are contributed markedly by the chest wall, the measurements were divided into two regimens. Perioperative changes in the respiratory mechanics can be characterized from FRC measurements and impedance recordings under closed-chest conditions, whereas measurements under open-chest conditions reveal the effects of CPB and pulmonary circulatory arrest/reperfusion on lung function. The lung volumes, LCI, and forced oscillatory airway and tissue parameters obtained in the current study are in accord with values reported previously in children with CHD.4,8,20

Cardiopulmonary bypass and aorta clamping led to alveolar hypocapnia, which can cause lung mechanics to deteriorate.24 Although the contribution of this phenomenon to the lung volume and lung mechanical changes cannot be excluded, its effect is presumably identical in both groups of children, because the intraalveolar carbon dioxide level was not likely to be different at any
assessments time. The duration of CPB was unlikely to influence our main findings either, because the worsening in lung function observed after CPB is thought to be related to the use of extracorporeal circulation rather than the duration of CPB.8,25

**Perioperative Changes in the Respiratory System**

**Lung Volume and LCI Changes.** The measurements of FRC and LCI revealed a significantly lower resting lung volume in the preoperative phase in the children with TOF. This difference was probably caused by low pulmonary vascular pressures and subsequent loss of the tethering effect exerted by the pressurized capillaries.13,14 These differences disappeared postoperatively, indicating that reestablishment of the pulmonary hemodynamics in the children with TOF helped in the regaining of physiologic static lung volumes.

The preoperative hypoperfusion leading to a reduced tethering of the lung periphery may also explain the tendency to a greater LCI in the children with TOF. Furthermore, it might also have contributed to the finding that even the mild losses of FRC observed after chest closure (approximately 15%) resulted in marked increases (approximately 35%) in the lung ventilation heterogeneity index, LCI.

**Changes in Respiratory System Mechanics.** The postoperative changes in the respiratory mechanical parameters that were not corrected to FRC agree with those reported previously.8 The simultaneous lung volume measurements applied in the current study revealed the underlying mechanisms responsible for these changes. Postoperative reestablishment of the physiologic pulmonary blood flow and/or pressure in the children with TOF increased the Raw, G, and H. However, these increases were essentially eliminated when the changes were expressed in mechanical parameters (sRaw, sG, and sH) normalized to the lung volume. This finding indicates that the loss of lung volume was the primary cause of airway narrowing and respiratory tissue mechanical deteriorations rather than an active contraction of the airway smooth muscle or an altered intrinsic tissue viscoelasticity. In contrast, in the children with congested lungs, the decreases in both Raw and sRaw indicated an improved airway function after the surgical repair of CHD, despite the decrease in FRC. Interestingly, the normalized respiratory tissue parameters also exhibited slight postoperative improvements in these children. The most likely explanation for this immediate improvement in the airway and specific respiratory tissue mechanics is a reversal of the mechanical effects of the overloaded pulmonary vessels compromising the airspaces. The postoperative increase in airway caliber is reflected in the decreased sRaw; the decreases in sG and sH might partly reflect improvements in ventilation heterogeneities,26 which may also be reflected in the postoperative increases in LCI.

**Perioperative Changes in the Open Chest**

**Changes in Lung Volume and LCI.** In accord with our previous results,4 the opening of the chest and the positioning of a retractor increased the lung volumes in both groups of children (table 1), although the differences observed between the groups preoperatively remained throughout the open-chest measurements. These differences between the groups vanished after chest closure (fig. 1), suggesting that surgical repair of the CHD with hypoperfused or hyperperfused lungs...
resulted in an acute correction of the pulmonary hemodynamics with subsequent beneficial changes in FRC.

Running the CPB on full regimen and clamping the aorta caused significant decreases in FRC and increases in LCI in both groups of children, with the changes approximately twofold greater in the children with TOF. This finding indicates the increased susceptibility of hypoperfused lungs to the development of lung closure and ventilation heterogeneity. Previous results obtained in isolated perfused rat lungs demonstrated the importance of filled and pressurized capillaries in maintaining the normal architecture of the lung periphery by providing mechanical support to the alveoli. This mechanism is weakened during compromised and interrupted pulmonary perfusion (i.e., during CPB and aortic clamping), which leads to a decrease in FRC and marked increases in LCI. The involvement of this mechanism is confirmed by the greater changes in the children with TOF (fig. 3), where this tethering effect was chronically diminished due to the presence of pulmonary hypoperfusion. It is noteworthy that after reestablishment of the pulmonary circulation in the children with TOF after weaning from CPB, ventilation homogeneity increased in parallel with the increase in FRC, further confirming the beneficial effect of the pulmonary blood flow on the alveolar wall stability, leading to alveolar recruitment.

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Pulmonary Mechanical Effects of Lung Perfusion. Lung hypoperfusion or the complete absence of pulmonary perfusion compromises the lung mechanical properties. The current results in a clinical setting are

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Fig. 4. Changes in absolute values of airway resistance (dRaw), tissue damping (dG), elastance (dH), and hysteresivity (dH) and in their normalized values for lung volume (dSRaw, dSG, and dSH) in children with hypoperfused (tetralogy of Fallot [TOF]) or hyperperfused (ventricular septal defect [VSD]) lungs. Assessments were made after chest opening and retraction (OpCh) and after onset of cardiopulmonary bypass (CPB on), aortic clamping (Clamp), declamping (Declamp), and weaning from bypass (Wean CPB). * P < 0.05 versus OpCh levels. # P < 0.05 between the groups.
in accord with previous experimental observations demonstrating that the pulmonary mechanics are highly dependent on the pulmonary circulation. A decrease or interruption of the pulmonary circulation causes a decrease in lung volume and increases in the viscous resistance and elastance of the parenchyma, whereas reestablishment of the pulmonary perfusion leads to a recovery of the lung volume and mechanics (fig. 4, left panels). It is noteworthy, however, that these changes were not detected once the mechanical parameters were normalized to the lung volume (fig. 4, right panels). This finding suggests that the weakened tethering effect exerted by the empty pulmonary capillaries led primarily to a loss of lung volume, and the adverse changes observed in the airways and lung tissue mechanics were mainly consequences of the reduced FRC.

Conclusions

The combined measurements of lung volume and respiratory mechanical parameters in children with different types of CHDs demonstrated the primary importance of the absolute lung volume in interpreting the perioperative changes in the respiratory mechanics. The postoperative decrease of lung volume is responsible for the lung function impairment in children with hypoperfused lungs. In contrast, postoperative improvements in airway and respiratory tissue mechanics in children with VSD reflect the beneficial changes in airway and tissue mechanics caused by the reduction in lung congestion. The results of measurements made under different hemodynamic conditions confirmed the important role of the tethering effect exerted by the pressurized pulmonary capillaries in maintaining the normal lung architecture, particularly in the hypoperfused lungs of children with TOF. Because the loss of lung volume was the primary cause of the enhanced ventilation heterogeneities and impaired lung mechanical parameters, clinicians should aim at maintenance of the normal lung volume in patients with hypoperfused lungs.

The authors thank the children and their families who participated in this study.

References


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