Pediatr Cardiol (2014) 35:990–997
DOI 10.1007/s00246-014-0886-6

ORIGINAL ARTICLE

Monitoring of Regional Lung Ventilation Using Electrical Impedance Tomography After Cardiac Surgery in Infants and Children

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Received: 15 November 2013 / Accepted: 6 February 2014 / Published online: 26 February 2014

Abstract Electrical impedance tomography (EIT) is a noninvasive method to monitor regional lung ventilation in infants and children without using radiation. The objective of this prospective study was to determine the value of EIT as an additional monitoring tool to assess regional lung ventilation after pediatric cardiac surgery for congenital heart disease in infants and children. EIT monitoring was performed in a prospective study comprising 30 pediatric patients who were mechanically ventilated after cardiac surgery. Data were analyzed off-line with respect to regional lung ventilation in different clinical situations. EIT data were correlated with respirator settings and arterial carbon dioxide (CO_2) partial pressure in the blood. In 29 of 30 patients, regional ventilation of the lung could sufficiently and reliably be monitored by means of EIT. The effects of the transition from mechanical ventilation to spontaneous breathing after extubation on regional lung ventilation were studied. After extubation, a significant decrease of relative impedance changes was evident. In addition, a negative correlation of arterial CO_2 partial pressure and relative impedance changes could be shown. EIT was sufficient to discriminate differences of regional lung ventilation in children and adolescents after cardiac surgery. EIT reliably provided additional information on regional lung ventilation in children after cardiac surgery. Neither chest tubes nor pacemaker wires nor the intensive care unit environment interfered with the application of EIT. EIT therefore may be used as an additional real-time monitoring tool in pediatric cardiac intensive care because it is noninvasive.

Keywords Congenital heart disease · Electrical impedance tomography · Regional lung ventilation · Intensive care

Introduction

After corrective surgery for congenital heart disease, infants and children usually depend on respiratory support for a time period ranging from a few hours up to several days after surgery. The length of mechanical ventilation after surgery depends on patient age, type of heart disease and surgical procedure performed, comorbidity and the individual patient's postoperative course. Although being mechanically ventilated, the patient's respiratory function must be monitored closely. This is achieved by repeated arterial blood gas analysis, continuous transcutaneous pulse oximetry and repeated chest X-rays to assess proper aeration and ventilation of both lungs. In addition, chest X-ray gives information about the correct position of the endotracheal tube, chest tubes, central venous lines, and pacemaker wires. Disadvantages of conventional chest X-ray include its discontinuous character and its incapability to exactly depict areas of inhomogeneous lung aeration due to

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its two-dimensional character. Finally with repeated chest X-rays, patients are exposed to an increasing amount of ionizing radiation. Other imaging methods, such as computed tomography (CT) and magnetic resonance imaging (MRI), are not routinely used in monitoring the respiratory function of pediatric patients after cardiac surgery due to (1) exposure to a comparatively large amount of ionizing radiation (CT), (2) the incompatibility of MRI with temporary pacemaker wires and other technical equipment, (3) the discontinuous character of CT and MRI, and (4) the need to transport the mechanically ventilated and potentially hemodynamically unstable patient outside the intensive care unit. Therefore, no tool to continuously monitor regional lung ventilation in a pediatric population after cardiac surgery for congenital heart disease has been established yet in routine caret. Recently, electrical impedance tomography (EIT) has been identified as an imaging technique to visualize regional lung ventilation in animal studies as well as in healthy and critically ill human subjects [3, 11, 13, 17, 22, 26]. EIT is a radiation-free imaging technique that allows for continuous bedside monitoring of regional lung ventilation over a long period of time [8]. The ability of EIT to determine changes of regional lung ventilation has been validated for the adult as well as for the pediatric population [3, 4, 15, 19]. EIT has been studied in adults and children with a variety of pulmonary disease [2, 18, 28]. However, the use of EIT in pediatric patients after cardiac surgery has not yet been studied. Application of EIT in adult patients after cardiac surgery has given promising results [5, 7, 16].

In the present study, we used EIT to determine its applicability as a monitoring tool to control regional lung ventilation in mechanically ventilated pediatric patients after cardiac surgery. Because patients are not exposed to ionizing radiation when EIT is used, and because regional lung ventilation can be continuously monitored at the bedside over a long period of time, it is an attractive tool for the monitoring of mechanically ventilated infants and children.

Methods

Patients

Thirty patients (age 0–18 years, 10 female and 20 male), after primary corrective surgery for congenital heart disease or secondary surgical procedure, were included in the study after informed written consent was obtained from the parents and/or the patients, depending on patient age. Mean age was 5.6 ± 4.7 years (median 5.7); mean body weight was 21.7 ± 16 kg (median 19.8); and mean body length was 106.8 ± 34.1 cm (median 114). All patients were free of pulmonary disease before surgery. The local university Ethics Committee approved the study, and all measurements were performed according to the Declaration of Helsinki. Preoperative diagnoses of the patients and type of surgery (primary *vs.* secondary) are listed in Table 1. For statistical analysis, the study population was divided into three subgroups according to their age as follows: newborns and infants = 0 to 1 year of age ($n = 7$); children = 1 to 3 years of age ($n = 6$); and preschool through adolescent = 4 to 18 years ($n = 16$). The last subgroup was not further divided due to the limited number of study patients. In all patients, cardiac surgery was performed by way of a median sternotomy, and cardiopulmonary bypass was used. At the end of surgery, 2–4 chest tubes and temporary epicardial pacemaker wires were placed at the surgeon's discretion. After surgery all patients were kept tracheally intubated and mechanically ventilated and were transferred to the pediatric intensive care unit (PICU) where mechanical ventilation was continued until the patient was in stable cardiopulmonary condition and was sufficiently breathing on his or her own. Exclusion criteria were an open chest with Gore-Tex skin closure, severe congenital malformations other than cardiac and refusal of parental consent.

Table 1 Preoperative diagnoses and type of surgery

Diagnosis	Primary corrective surgery	Secondary surgery
Ventricular septal defect	$n = 5$	–
ASD	$n = 4$	–
Atrioventricular septal defect	$n = 5$	–
Tetralogy of Fallot	$n = 1$	$n = 4$
Double-outlet right ventricle	–	$n = 2$
Aortic stenosis, aortic regurgitation	$n = 4$	$n = 1$
Truncus arteriosus communis	–	$n = 1$
Transposition of the great arteries	–	$n = 1$
Pulmonary stenosis	–	$n = 1$
Mitral regurgitation	$n = 1$	–

Electrical Impedance Tomography (EIT)

EIT was used to analyze changes of regional lung ventilation in pediatric patients after cardiac surgery. Details of the EIT technique have been frequently described elsewhere [6, 8]. EIT is based on rotating emission of small electrical currents and measurement of the resulting potential differences using a set of electrodes attached circumferentially to the patient's thorax. EIT measurements were performed using the Göttingen Goe MF II-System (Viasys Healthcare, Höchberg, Germany) [12, 14]. Sixteen electrodes [(standard electrocardiogram electrodes) Blue Sensor BR-50-K; Medicotest, Olstykke, Denmark] were circumferentially attached around the patient's thorax at the inframammary line. EIT data were generated by applying electrical alternating currents of 5 $\mathrm{mA_{rms}}$ at 100 kHz in a sequentially rotating process. Measurements of the resulting surface potential differences between neighboring electrode pairs were performed. EIT images were reconstructed with a resolution of 32 × 32 pixels using the back-projection algorithm [1]. Thoracic impedance changes display lung ventilation [13]. The EIT images were recorded with a scan rate of 13 Hz (Science EIT Software, Version 1.02; University of Göttingen, Göttingen, Germany) and stored on a personal computer. Off-line analysis and generation of functional images was performed using Matlab software (Version 7.0; MathWorks, Ismaning, Germany).

Protocol

After admission of patients to the PICU after surgery, 16 electrodes were attached to the patient's thorax as described previously, and EIT measurements were performed regularly at hourly intervals. Additional measurements were performed after changing the respirator settings and immediately before and after extubation of the patients. After extubation, measurements were continued at 10-min intervals until patients were breathing spontaneously on a stable level (1–4 h after extubation). Respirator settings, tidal volume, and blood gas parameters were recorded along with the EIT data.

All EIT measurements were performed with the patients in a supine position. To study differences of regional lung ventilation with respect to the ventral and the dorsal parts of the lung, EIT data were collected from the ventral parts as well as from the dorsal parts of both lungs, and regional impedance changes were compared in both mechanically ventilated as well as spontaneously breathing patients.

Statistical Analysis

Results are presented as mean ± SD (95 % confidence interval) if not indicated otherwise. After verifying data for Gaussian distribution and homogeneity of the variance, correlation was tested using Pearson and Spearman correlation coefficient, respectively. For comparison within each group, Student *t* test, analysis of variance, and Kruskal–Wallis test were used. p-values ≤ 0.05 were considered statistically significant. All statistical analysis were performed using SPSS version 15.0 (IBM, Somers, NY, USA).

Results

Quality of EIT Signals in a Pediatric Patient Population After Cardiac Surgery

In 29 of 30 patients, high-quality EIT signals could be recorded and subsequently be analyzed off-line. Neither wound dresses nor chest tubes nor the electrical equipment of the intensive care unit interfered with raw data quality. Because none of the patients required temporary or permanent pacing after surgery, interference of temporary pacemaker wires and pacemaker signals with raw data quality was ruled out by performing routine pacemaker threshold testing while acquiring EIT data. No changes of EIT signals due to pacemaker wires or pacemaker signals were observed. Routine postoperative care was not affected by EIT measurements. The electrodes attached to the thorax were tolerated well by the patients, and no additional sedative medication had to be administered to achieve high-quality EIT signals. In one patient, however, electrical noise from an undetermined origin interfered with the collection of EIT signals of sufficient quality.

Relative Impedance Changes After Extubation

To assess the efficacy of EIT to visualize changes of ventilation during the transition from mechanical ventilation to spontaneous breathing after extubation, relative impedance changes before and after cessation of mechanical ventilation were acquired. In all patients, a significant decrease of relative impedance changes after extubation was observed (21.6 ± 6.0 in mechanically ventilated patients versus 14.1 ± 2.9 after extubation, $p < 0.001$, $n = 29$, Fig. 1). Interestingly, the changes of relative impedance were less pronounced in the youngest patients (newborns and infants, 15.7 ± 2.7 *vs.* 13.0 ± 3.1, $n = 7$) compared with the 1- to 3-year-old children (26.0 ± 6.0 *vs.* 15.5 ± 1.9, $n = 6$) and the older group (4–18 years of age, 22.5 ± 5.2 *vs.* 14.1 ± 3.0, $n = 16$, Fig. 2). No sex-related differences were noticed (data not shown).

Differences of Impedance Changes in Ventral and Dorsal Regions of the Lung

In mechanically ventilated patients, there was a significant difference in regional lung ventilation with the ventral areas of both lungs being better ventilated than the dorsal parts ($p < 0.001$, $n = 29$). Similar results were obtained from patients breathing spontaneously after extubation ($p < 0.05$, $n = 29$, Fig. 3). No significant recruitment of the dorsal parts of the lungs could be observed in spontaneously breathing patients. However, differences in relative impedance changes between ventilated and spontaneously breathing patients were significantly greater in the ventral compared with the dorsal parts of the lung (ventral 4.4 ± 3.2, dorsal 2.7 ± 2.1, $p < 0.001$, $n = 29$), thus indicating a shift of relative impedance changes in favor of the dorsal areas of the lungs after extubation and thereby indicating recruitment of the dorsal parts of the lungs (Fig. 3). No age- or sex-related differences were observed (data not shown).

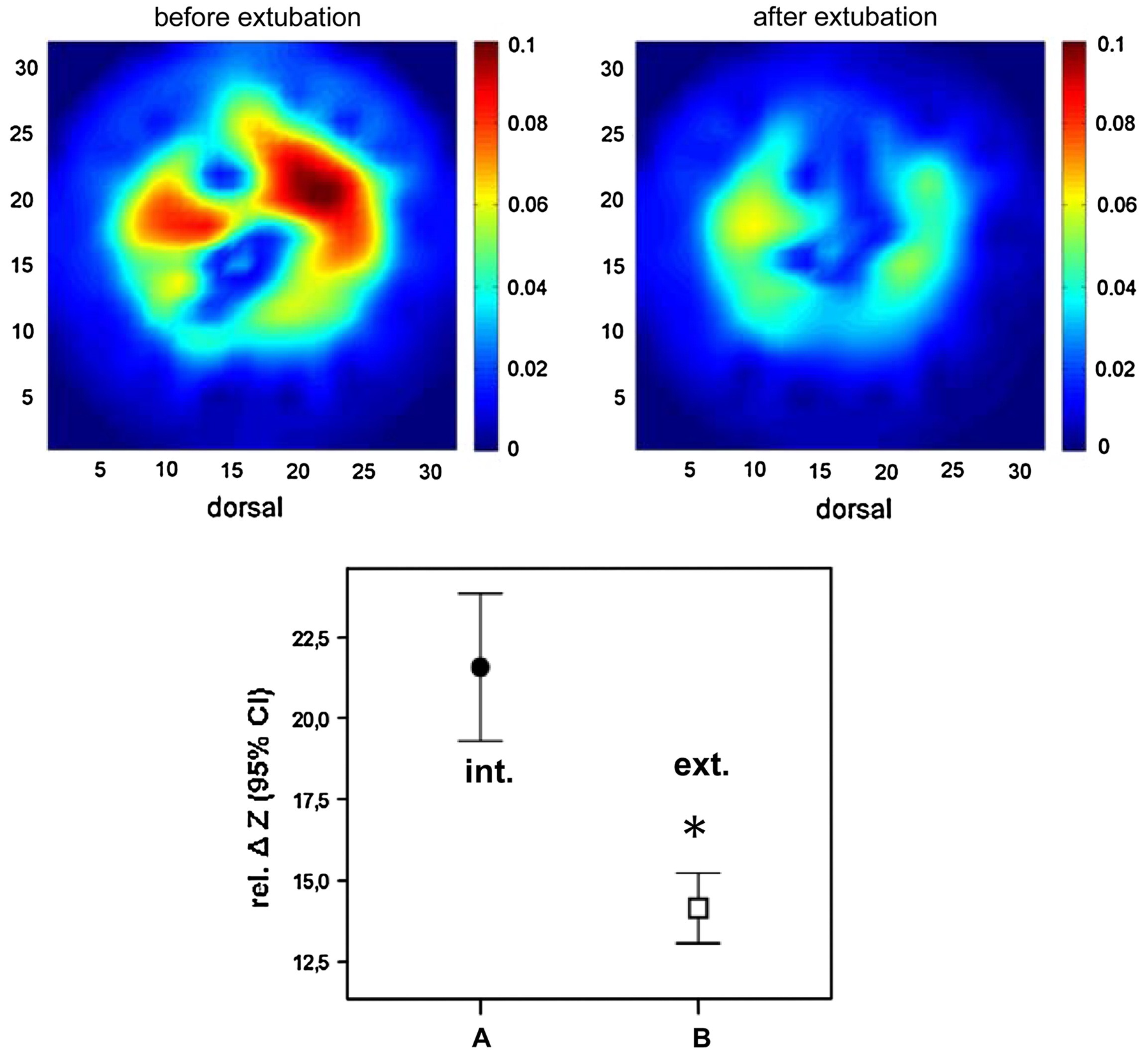

Fig. 1 (*Upper panel*) Functional EIT image before (*left*) and after (*right*) extubation recorded from a 3-year-old patient after atrial septal defect closure. *Red* color indicates areas of high impedance changes; *green* and *blue* colors indicate low impedance changes. Impedance changes after extubation are less than before. (*Lower panel*) A significant decrease of relative impedance changes after extubation is evident. **A** Before extubation (int. = tracheally intubated). **B** After extubation (ext. = extubated, mean ± SD, $p < 0.001$)

Age-Related Differences in Relative Impedance Changes After Extubation

The extent of relative impedance changes after extubation was dependent on the patient's age. Although in the youngest patient group (0–1 year of age) only minor changes of impedance with the transition from mechanical ventilation to spontaneous breathing were observed (15.7 ± 2.7 *vs.* 13.0 ± 3.1, $n = 7$), these changes were significantly greater in the patient group from age 1 to 3 years (26.0 ± 6.0 *vs.* 15.5 ± 1.9, $n = 6$) and from age 4 to 18 years (22.5 ± 5.2 *vs.* 14.1 ± 3.0, $n = 16$) ($p < 0.05$, Fig. 2). Interestingly, in the latter group of patients, relative impedance changes were less in children after secondary cardiac surgery compared with patients after primary cardiac surgery (18.8 ± 3.2 *vs.* 25.2 ± 4.6, $n = 9$, $p < 0.05$).

Correlation of Relative Impedance Changes With P_{aCO_2}

To verify the expected negative correlation of arterial carbon dioxide (CO_2) partial pressure (P_aCO_2) and the relative impedance changes, in 23 out of 29 patients, P_aCO_2 from arterial blood gas analysis data were correlated with the changes of relative impedances. In the remaining patients, arterial blood gas analysis could not be obtained over the entire duration of EIT monitoring due to a failing arterial line or early removal of the arterial line. The P_aCO_2 values differed significantly between mechanically ventilated and spontaneously breathing patients with lower CO_2 partial

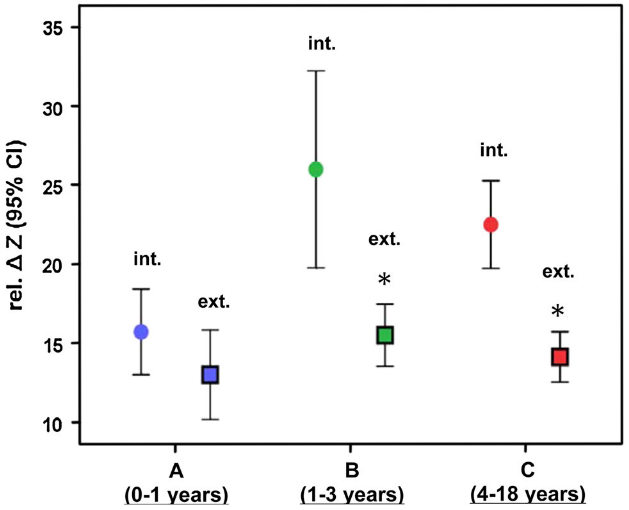

Fig. 2 Age-dependent decrease of relative impedance changes after extubation: The decrease of relative impedance changes is significantly less pronounced within the first year of life (mean ± SD, $p < 0.05$). *Circles* indicate impedance changes before extubation (int. = tracheally intubated), and *squares* represent impedance changes after extubation (ext. = extubated). **A** Age group 0–1 year. **B** Age group 1–3 years. **C** Age group 4–18 years

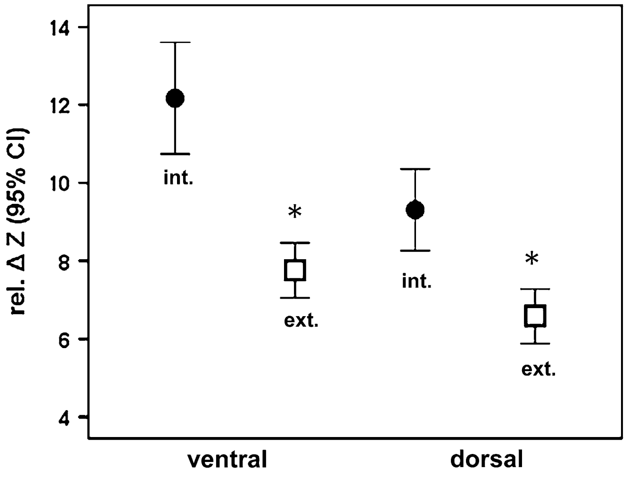

Fig. 3 No significant recruitment of the dorsal parts of the lung could be observed after extubation (squares, ext. = extubated) compared with mechanically ventilated patients (circles, int. = tracheally intubated). By trend, however, the relation of impedance changes shifted in favor of the dorsal parts after extubation, thus indicating some recruitment of the dorsal parts of the lungs. Both in the ventral parts and in the dorsal parts of the lung, relative impedance changes decreased significantly after extubation (mean ± SD, $p < 0.05$)

pressures in the ventilated patient group (39.3 ± 3.2 mm Hg *vs*. 42.7 ± 4.3 mm Hg, $n = 23$, $p < 0.05$). As expected, lower P_aCO_2 values in ventilated patients correlated with greater relative impedance changes and vice versa (correlation *coefficient* $r_s = -0.314$, Fig. 4). In spontaneously breathing patients, however, no correlation between impedance changes and P_aCO_2 was found (Fig. 4).

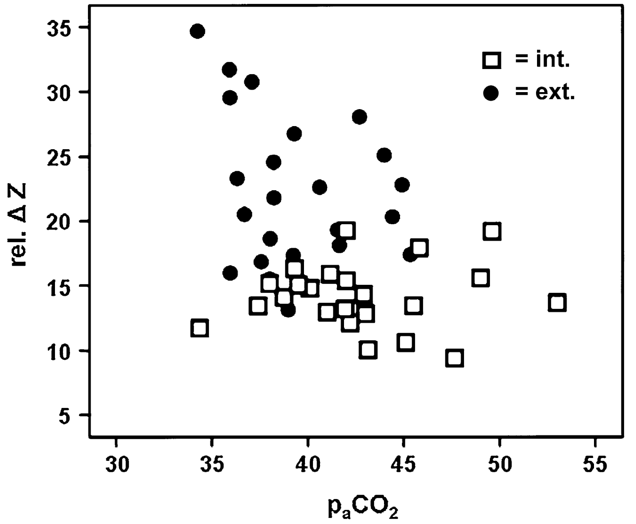

Fig. 4 For mechanically ventilated patients, a negative correlation of relative impedance changes and $PaCO_2$ could be showed (circles, int. = tracheally intubated), whereas there was no correlation in spontaneously breathing patients (squares, ext. = extubated)

Correlation of Relative Impedance Changes With Respirator Settings

To test for a possible correlation of relative impedance changes with respirator settings, relative impedance changes were correlated with both inspiratory pressure and breathing rate because both parameters were expected to primarily determine lung ventilation in mechanically ventilated patients. With respect to breathing rate, a significantly negative correlation could be shown (correlation coefficient −0.546, $p < 0.05$ $n = 29$), whereas the observed positive correlation for inspiratory pressure was statistically not significant (correlation coefficient 0.271, $p > 0.05$, $n = 29$).

Discussion

The present study was performed to test for the applicability of EIT to monitor respiratory function in children and adolescents after surgery for congenital heart disease. Previous work showed the use of EIT to monitor regional lung ventilation in healthy, spontaneously breathing newborns and children [10, 15, 23] as well as in critically ill and mechanically ventilated children [9, 27]. However, little is known about the application of EIT in pediatric patients after cardiac surgery. To maintain the patient under hemodynamically stable conditions, close monitoring of respiratory parameters and lung function is essential. Routine monitoring of respiratory function in mechanically ventilated pediatric patients mainly relies on arterial blood gas analysis, transcutaneous pulse oximetry, end-expiratory capnography, measurement of minute ventilation, and repeated chest X-rays. In the present study, however, a correlation of pulse oximetry data, end-expiratory CO_2 partial pressure values, and tidal volumes with the acquired EIT data were not performed because oxygen saturation depends not only on lung ventilation but also on inspiratory oxygen fraction (Fio_2). FiO_2 was individually titrated with respect to transcutaneous oxygen saturation and arterial O_2 partial pressure and was not kept on the same level in all patients. The CO_2 partial pressure measured capnographically at the end of expiration is influenced by dead space volume. Dead space volume in small children and infants largely varies with length and size of the endotracheal tube and was therefore not considered for evaluation because size and length of the endotracheal tube were chosen by the attending anesthesiologist with respect to the patient's age and body weight. Likewise, minute ventilation was not considered for evaluation because not only tidal volume but also breathing rate determines minute ventilation.

None of the monitoring tools mentioned previously, however, gives continuous information about regional ventilation of the lung. Therefore, we aimed to investigate whether EIT, which has been shown to allow for continuous monitoring of regional lung ventilation even in critically ill children, is suitable as an additional monitoring tool in pediatric patients after cardiac surgery. In adult patients after cardiac surgery, EIT has been successfully used to monitor regional lung ventilation [5, 7]. In contrast to adult patients, however, in young children after cardiac surgery, there is limited space for the application of EIT electrodes due to the smaller body size, wound dressings, and chest tubes. In addition, children may be less cooperative during the postoperative course, which can result in loss of proper skin contact of one or more of the EIT electrodes and therefore interfere with reliable acquisition of EIT data. It is important to address that none of the patients of our study received additional sedative medication or analgesics to accomplish ETI measurements.

We were able to demonstrate that high-quality EIT data could be obtained in 29 of 30 pediatric patients after cardiac surgery for congenital heart disease. The source of interference, which made the acquisition of reproducible EIT data impossible in 1 of 30 patients, remained unclear. However, because EIT measurements resulted in high-quality data in the same PICU setting in the other 29 patients, it seems unlikely that electrical noise from the PICU environment was the reason for this particular problem.

No interference of EIT monitoring with chest tubes, wound dressings, or pacemaker wires or the electrical signals of temporary pacemakers was observed. No pacemaker malfunction (*e.g.*, oversensing) due to EIT signals was evident. Therefore, it seems unnecessary to exclude patients with cardiac pacemakers from monitoring pulmonary function by means of EIT as has been described in a study of adult patients after cardiac surgery [7].

Because the transition from mechanical ventilation to spontaneous breathing (*i.e.* extubation after surgery) was assumed to be a period of major changes in regional lung ventilation, we addressed the question of whether these changes could be detected by EIT. In all patients, the expected decrease in ventilation, expressed by a decrease in relative impedance changes, was observed. The decreased ventilation (*i.e.*, decreased relative impedance changes) after extubation is most probably due to the fact that patients are presenting with transient tachypnoea and decreased tidal volume initially after extubation. Recording EIT data for a longer period of time after extubation, one would expect an increase of relative impedance changes by time, especially after removing chest tubes and with decreasing pain-related discomfort. However, in the present study, EIT recordings were discontinued early after extubation because the permission of the local Ethics Committee allowed for EIT application for 30 min after extubation. Interestingly, the decrease of impedance changes was significantly less in patients <1 year of age compared with older patients. The observation that impedance changes reach their maximum in 1- to 3-year-old patients is in good accordance with previously published data on respiratory compliance in otherwise healthy infants, children, and adolescents [21, 25]. The slight decrease of impedance changes observed in the older patients (4 to 18 years of age) may additionally be attributed to the fact that 7 of 9 patients after a secondary surgical procedure were >4 years of age. Chest wall compliance seems to be decreased after previous cardiothoracic surgery [20].

We observed a negative correlation of CO_2 partial pressure with relative impedance changes. This phenomenon became evident during the weaning phase from the respirator. Weaning the patients from the respirator was accomplished by decreasing not only the set breathing rate but also peak inspiratory pressure and thereby tidal volume, which results in a decrease of impedance changes. In spontaneously breathing patients, tidal volume was not quantified, but it is presumably relatively unchanged in the initial phase after extubation. Minute volume seems to be guaranteed primarily by changing the breathing rate.

A major advantage of EIT is its continuous character. With an appropriate hardware and software, which is now commercially available (PulmoVista, Dräger, Germany), continuous monitoring of regional lung ventilation at the bedside, even in a pediatric population, seems possible. In small children and infants, however, a commercially available standard chest-belt, which includes the EIT electrodes and makes the whole EIT system more convenient for the patients and the ICU personnel, will probably not fit due to small body size, wound dressings, and chest tubes. In this selected patient population, in the light of a small thorax, an EIT system working with only eight electrodes would be favorable. Previous studies have shown the feasibility of EIT using an eight-electrode array [24]. Therefore, further studies are required to assess the use of EIT with a smaller electrode set in children and adolescents.

Conclusion and Limitations

Using EIT, a powerful tool to reliably and continuously monitor regional lung ventilation at the bedside, is available. EIT may serve as an additional method to monitor regional ventilation of the lung. However, it is not possible to visualize tracheal tubes, chest tubes, and central venous catheters by means of EIT. Therefore, conventional chest X-ray will still be essential in patients after cardiac surgery, but the use of EIT may decrease the frequent use of X-ray to assess lung ventilation.

Because EIT scans represent regional lung ventilation in a transverse slice of the thorax at the level of the circumferentially attached electrodes (slice thickness ±3 cm resulting in a reduction of EIT sensitivity by 50 %), information about regional ventilation of the apical and most basal parts of the lungs might be not available until the electrode set is moved to the region of interest, which of course will interfere with the unique character of the method. For instance, atelectasis of the upper right lobe may be missed interpreting EIT data from just one transverse layer of the thorax. Whether this applies even for small infants with a small thorax must be further evaluated. In older patients, additional sets of electrodes attached to the thorax above and below the first electrode set may cover areas of the lung, which would be missed otherwise.

For its routine use in the clinical setting of a PICU, the commercially available technical equipment must be tailored to the demands of a pediatric and cardiac surgery population. Data must be available in a real-time fashion, and automatically analyzed data must be easily available as well.

To further evaluate the use of EIT in pediatric patients after cardiac surgery, and due to the relatively small number of patients in a single center, multicenter trials are required in the future.

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