

Distribution of Ventilation Measured by Electrical Impedance Tomography in Critically Ill Children

Hussam S Inany, Jordan S Rettig, Craig D Smallwood, John H Arnold, and Brian K Walsh

BACKGROUND: Electrical impedance tomography (EIT) is a noninvasive, portable lung imaging technique that provides functional distribution of ventilation. We aimed to describe the relationship between the distribution of ventilation by mode of ventilation and level of oxygenation impairment in children who are critically ill. We also aimed to describe the safety of EIT application. **METHODS:** A prospective observational study of EIT images obtained from subjects in the pediatric ICU. Images were categorized by whether the subjects were on intermittent mandatory ventilation (IMV), continuous spontaneous ventilation, or no positive-pressure ventilation. Images were categorized by the level of oxygenation impairment when using S_{pO_2}/F_{IO_2} . Distribution of ventilation is described by the center of ventilation. **RESULTS:** Sixty-four images were obtained from 25 subjects. Forty-two images obtained during IMV with a mean \pm SD center of ventilation of $55 \pm 6\%$, 14 images during continuous spontaneous ventilation with a mean \pm SD center of ventilation of $48.1 \pm 11\%$, and 8 images during no positive-pressure ventilation with a mean \pm SD center of ventilation of $47.5 \pm 10\%$. Seventeen images obtained from subjects with moderate oxygenation impairment with a mean \pm SD center of ventilation of $59.3 \pm 1.9\%$, 12 with mild oxygenation impairment with a mean \pm SD center of ventilation of $52.6 \pm 2.3\%$, and 4 without oxygenation impairment with a mean \pm SD center of ventilation of $48.3 \pm 4\%$. There was more ventral distribution of ventilation with IMV versus continuous spontaneous ventilation ($P = .009$), with IMV versus no positive-pressure ventilation ($P = .01$) cohorts, and with moderate oxygenation impairment versus cohorts without oxygenation impairment ($P = .009$). There were no adverse events related to the placement and use of EIT in our study. **CONCLUSIONS:** Children who had worse oxygen impairment or who received controlled modes of ventilation had more ventral distribution of ventilation than those without oxygen impairment or the subjects who were spontaneously breathing. The ability of EIT to detect changes in the distribution of ventilation in real time may allow for distribution-targeted mechanical ventilation strategies to be deployed proactively; however, future studies are needed to determine the effectiveness of such a strategy. *Key words:* electrical impedance tomography; EIT; EIT safety; imaging; mechanical ventilation; bedside imaging; monitoring; noninvasive monitoring; positive pressure ventilation. [Respir Care 2020;65(5):590–595. © 2020 Daedalus Enterprises]

Introduction

Respiratory distress or failure is a major cause of admission to the pediatric ICU, with many of these patients

requiring mechanical ventilation.¹ Mechanical ventilation, whether invasive or noninvasive, is a therapy often used to maintain or improve gas exchange of patients with

Dr Inany is affiliated with the Division of Critical Care, Department of Pediatrics, UCSF Benioff Children's Hospital, University of California — San Francisco, San Francisco, California, and with the Division of Respiratory Diseases, Boston Children's Hospital, Harvard Medical School, Boston, Massachusetts. Drs Rettig, Smallwood (deceased), and Arnold are affiliated with the Division of Critical Care Medicine,

Department of Anesthesiology, Perioperative and Pain Medicine, Boston Children's Hospital, Harvard Medical School, Boston, Massachusetts. Dr Walsh is affiliated with the Department of Health Professions, Liberty University, School of Health Sciences, Lynchburg, Virginia.

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respiratory distress or failure. Mechanical ventilation improves gas exchange by improving the distribution in ventilation. Yet, improper use of mechanical ventilation can create a multitude of injuries; two of which (atelectasis and overdistention) can be detected by electrical impedance tomography (EIT).

EIT is a noninvasive, radiation-free, portable lung imaging technique, which provides real-time monitoring of the regional distribution of ventilation. This technology uses a series of electrodes. Subphysiologic currents are passed between the electrodes, and impedance is measured between and among the series, and a 2-dimensional cross-sectional image is created.² EIT was shown to be helpful in identifying changes in the distribution of ventilation and in detecting overdistention in those subjects on mechanical ventilation with different PEEP levels.³ However, the majority of EIT studies are performed in the adult population.

Differences in the respiratory system exist between the pediatric and adult populations. Children generate ventilation primarily through diaphragmatic excursion, which puts them at an increased risk of inadequate ventilation and atelectasis when the diaphragm is not used (due to oversupport or oversedation) or is fatigued or has unfavorable loading conditions (eg, with increased abdominal pressure). Children also tend to have a more compliant chest wall and thus a lower functional residual capacity. For these reasons, we thought that it was important to better describe the use of EIT in the pediatric population.

Spontaneous breathing has been associated with improved gas exchange and favorable changes in the distribution of ventilation.^{4,5} A normal tidal volume (V_T) strategy (6 mL/kg) has been proven to be beneficial when managing patients with ARDS.⁶ The concept of baby lung described by Gattinoni and Penesti,⁷ who hypothesized that most of the V_T will be delivered to the healthy part of the lungs in patients with ARDS could be as small as a lung of a child and might cause lung injury by overdistention, regardless of the V_T . The open lung approach has more recently highlighted the need for PEEP titration to maintain alveolar recruitment in tandem with a normal V_T approach.⁸ Although these concepts have been shown to be helpful, other studies showed that complications related to mechanical ventilation continues to occur despite using these lung-protective ventilation methods.⁹ A physiologic, evidence-based, and individualized approach is necessary but

QUICK LOOK

Current knowledge

Electrical impedance tomography is a noninvasive portable lung imaging technique shown to produce functional images of distribution of ventilation at the bedside. Ventral distribution of ventilation has been associated with level of injury, oxygen impairment, or controlled mechanical ventilation in animal studies and adult populations. However, lung injury and resolution may be different in pediatrics.

What this paper contributes to our knowledge

This study demonstrated that conditions associated with improvement (spontaneous breathing and higher S_{pO_2}/F_{IO_2}) had a more even distribution of ventilation that we were able to detect and monitor by using electrical impedance tomography. Future research should be targeted at intervening when distribution of ventilation is abnormal and before lung injury or impairment.

the collective experience shows that there is no one size fits all approach for mechanical ventilation. Being able to readily distinguish responder versus non-responder phenotype is emerging as an important aspect to developing an effective ventilation strategy.

The use of EIT to quantify the regional distribution of ventilation within a cross-section sampling of the lung may be a valuable tool in identifying responders versus non-responders before impaired gas-exchange deficits and thus able to individualize the mechanical ventilation strategy. Our group has described the use of EIT in quantifying the distribution of ventilation during recruitment maneuvers and in an animal model of ARDS.^{10,11} In this study, we aimed to describe the differences in the distribution of ventilation by the mode of ventilation and to determine the relationship of oxygen impairment to the regional distribution of ventilation in a general pediatric ICU population. We secondarily aimed to describe adverse events associated with the application of bedside EIT imaging.

Methods

Our study was a prospective observational study of subjects who required respiratory support. With the approval of the institutional review board at Boston Children's Hospital, subjects were enrolled after obtaining informed consent from patients, parents or guardians. Daily images were gathered while the subjects were on mechanical ventilation regardless of the mode of ventilation, and a postextubation image was obtained when possible, re-

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Correspondence: Hussam S Inany MD, 708 Long Bridge St, Apt 512, San Francisco, CA 94158. E-mail: hussam.inany@gmail.com.

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gardless of support level before discharge. EIT images were obtained by using the Pulmovista 500 (Dräger Medical, Telford, Pennsylvania) by following the manufacturer's recommendation. Images were obtained by placing the electrodes belt around the chest at the anatomic area of the fourth intercostal space. Each recording was 2 min in duration. A 1-min steady-state sample was selected and analyzed by using the software provided by the manufacturer of the Pulmovista 500 (EITdiag, Dräger Medical).

Images were categorized by the mode of ventilation that the subject was receiving at the time of imaging. The mode of ventilation was categorized in the following way: intermittent mandatory ventilation (IMV) category was determined when the mode of ventilation was set to synchronized IMV and the total frequency did not exceed the mandatory frequency; continuous support ventilation was determined when the mode of ventilation was set to pressure support ventilation or CPAP; the no positive-pressure ventilation group included subjects who received oxygen delivery via nasal cannula, high-flow nasal cannula (not > 0.6 L/kg), or breathing room air. Vital signs and ventilator settings were collected at the time of image collection in a data collection sheet.

Images were also categorized by the severity of oxygen impairment determined by the S_{pO_2}/F_{IO_2} at the time of data collection. The level of oxygen impairment when using S_{pO_2}/F_{IO_2} was categorized into mild, moderate, and severe by applying cutoffs derived from the equation used to determine the relationship between S_{pO_2}/F_{IO_2} and P_{aO_2}/F_{IO_2} by Rice et al¹² to categorize the severity of impairment with the following ranges: 235–315 for mild, 148–235 for moderate, and <148 for severe. The subjects with $S_{pO_2}/F_{IO_2} > 315$ were categorized as none to indicate the absence of significant oxygenation impairment.

Distribution of ventilation is described by the center of ventilation. The center of ventilation is an EIT index, which represents the average of the dorsal-ventral distribution of tidal variation. The center of ventilation is given in percentage of the anteroposterior chest diameter, with values $>50\%$ indicating that the center of ventilation is located in the ventral (anterior) half of the chest and values $<50\%$ indicating that the center of ventilation is located in the dorsal (posterior) half (Fig. 1).

The exclusion criteria were patients with unstable spinal injuries or diseases; body mass index > 50 kg/m²; active implants, such as pacemakers or diaphragm pacer; a history of or active cardiac arrhythmias; skin integrity issues in the area of the electrodes belt would be placed that prohibit the placement of electrodes in the proper plane; open chest; chest tube; and flail chest; and any patient the medical team believed as not appropriate to enroll in the study based on medical, social, or emotional concerns.

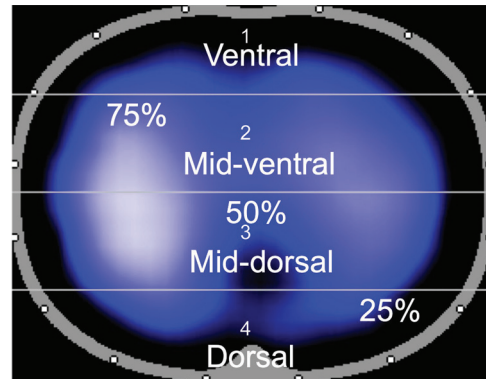


Fig. 1. Center of ventilation (CoV). Values $>50\%$ indicate CoVs located in the ventral (anterior) half of the chest and values $<50\%$ indicate CoVs were located in the dorsal (posterior) half.

Table 1. Subject Demographics and Characteristics

Demographics and Characteristics	Results
Subjects, <i>n</i>	25
Age, mean \pm SD y	8 \pm 5
Body mass index, mean \pm SD kg/m ²	19 \pm 4
Diagnosis, <i>n</i> (%)	
Respiratory	14 (58)
Surgical	8 (33)
Neurological	2 (9)

Data Collection and Statistics

All data were collected on a data collection form and/or entered directly into REDCap.¹³ The results were exported to SPSS for further analysis. A mixed-effects linear regression model was developed to assess this relationship between the center of ventilation and the mode of ventilation and level of oxygenation impairment, including a random effect for subjects to account for repeated measurements within the same subject. S_{pO_2}/F_{IO_2} for subjects with $S_{pO_2} \geq 98\%$ were excluded for the accuracy of categorization.

Results

Center of Ventilation by Mode of Ventilation

Sixty-four images were collected from 25 subjects and analyzed. Demographics are shown in Table 1. Fifteen images were recorded while the subjects were receiving IMV with a mean \pm SD center of ventilation of $55 \pm 6\%$, 12 images while the subjects were receiving continuous spontaneous ventilation with a mean \pm SD center of ventilation of 48.1 ± 11 , and 8 images while the subjects were receiving no positive-pressure ventilation with a mean \pm SD center of ventilation of 47.5 ± 10 (Fig. 2). There was a significant positive association between IMV and the center of ventilation

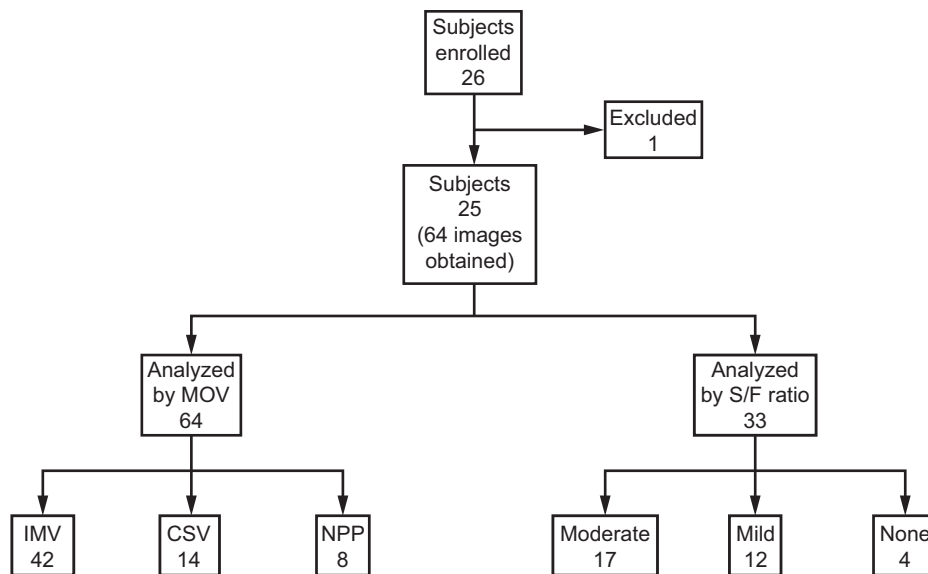


Fig. 2. Flow chart. MOV = Mode of ventilation; IMV = intermittent mandatory ventilation; CSV = continuous spontaneous ventilation; NPP = no positive-pressure support; S/F = S_{pO_2} to F_{IO_2} ; mild = mild oxygenation impairment; moderate = moderate oxygenation impairment; none = no oxygenation impairment.

when compared with no positive-pressure ventilation ($P = .009$) and with continuous spontaneous ventilation ($P = .01$) but no significant association between continuous spontaneous ventilation and center of ventilation when compared with no positive-pressure ventilation ($P = .28$).

Center of Ventilation by Level of Oxygenation Impairment

A total of 33 EIT images from 13 subjects with $S_{pO_2} \leq 97\%$ were analyzed (Fig. 3). We found a significant positive association between moderate oxygenation impairment (compared with no oxygenation impairment) and the center of ventilation ($P = .003$), but there was no significant association between mild oxygenation impairment (compared with no oxygenation impairment) and the center of ventilation ($P = .65$) or between moderate oxygenation impairment (compared with mild oxygen impairment) and the center of ventilation ($P = .79$). We did not enroll enough subjects who were severely hypoxemic to our study.

Adverse Events Related to the Application of the EIT Belt

During our study, we applied the electrode belt 64 times and obtained a total of 64 EIT images. The belt size ranged from extra, extra small pediatrics to extra, extra large adult according to the chart provided by Dräger Medical. However, we only used pediatric extra, extra small pediatrics to adult medium for our cohort. There were no skin breakdowns, burns, or other skin-related injuries. There

was no interference with or displacement of any medical devices, tubes, or lines. There were no significant changes in vital signs. There were no patient or family reports of discomfort with the safety check, calibration, or belt-placement procedure.

Discussion

In this study, our EIT measurements demonstrated that children who were receiving controlled mechanical ventilation tended to have a ventral distribution of ventilation. The same finding was also noted in the subjects with a higher level of oxygenation impairment indicated by lower S_{pO_2}/F_{IO_2} . These findings correlated with what we would expect physiologically from the consequences of dorsal atelectasis and were consistent with adult study findings, despite differences that may exist in the respiratory system of pediatric patients. It is well understood that the dependent regions are more prone to atelectasis and that the non-dependent regions are likewise more prone to overdistention in patients with lung disease that requires mechanical ventilation. It is also known that, as patients assume control of breathing and the respiratory muscles are engaged, there is an improvement in the distribution of ventilation to the dorsal regions of the lungs.

With the concept of individualization of care to meet specific patients' requirements, the application of an individualized adjusted PEEP has been shown to result in better respiratory system mechanics, driving pressure, and lung efficiency when managing patients with ARDS.⁸ EIT has the ability to detect changes in the distribution of

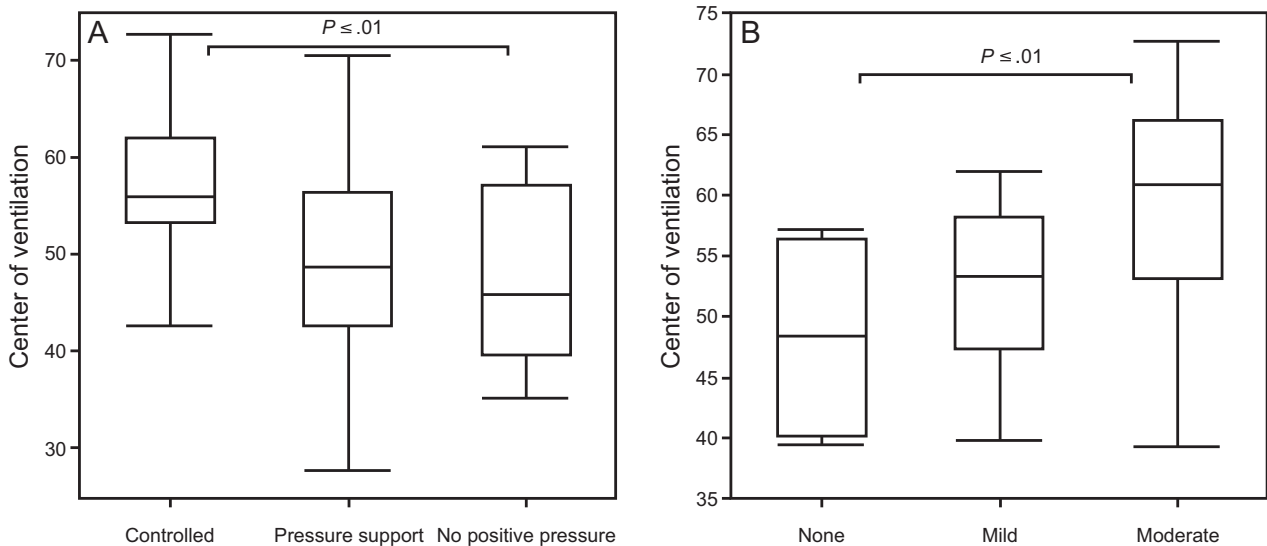


Fig. 3. Box plot, showing medians of centers of ventilation by mode of ventilation (A) and by level of oxygenation impairment (B).

ventilation, overdistention, and atelectasis in real time and plausibly before lung injury and gas-exchange deficiencies.

From a utility perspective, EIT is a radiation-free tool that can be applied at the bedside. We have not encountered any adverse events related to the application of the EIT belt and the process of recording images. It is important to remember that patients who require respiratory support are often severely ill and complex to move, and often have lines and tubes in place that can become dislodged during the process of patient transportation to obtain diagnostic images, not to mention the radiation exposure from a computed tomography of the chest or limited monitoring and access to the patient for a magnetic resonance image of the chest and, at best, they are only a snapshot in time because imaging would have to be repeated after an intervention. The use of EIT at the bedside without exposing the patient to any radiation or transitioning of beds can help to prevent such complications and allow easy re-imaging after changes in status or mechanical ventilation.

Limitations

There were some important limitations to our study. This was a small observational study that used a sample of convenience, so our data collection was not standardized by inspiratory pressure, V_T , PEEP, or mean airway pressure, although our approach to mechanical ventilation was standardized. We only had one subject who qualified as having severe oxygenation impairment and, therefore, was excluded. We could not guarantee that those in the IMV group were not using their respiratory muscles to synchronize with the mandatory rate and just not breathing above the set rate. In addition, our subjects did not wear the belts for prolonged periods and certainly not

> 24 hours at a time because this was against manufacturer recommendations.

Conclusions

Children who had worse oxygen impairment or who were receiving controlled modes of ventilation had a more ventral distribution of ventilation. Detecting changes in the distribution of ventilation, overdistention, or atelectasis is important when managing mechanical ventilation and adverse events associated with its use. The ability of EIT to detect changes in distribution of ventilation in real time and at the bedside may allow for distribution-targeted mechanical ventilation strategies to be deployed and explored proactively; however, future studies are needed to assess the ability of EIT to be used to direct interventions and to guide medical management in the pediatric ICU.

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