Ventilation distribution in mechanically ventilated children in response to positioning: An exploratory study

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Background. Traditionally, it was understood that children universally show greater ventilation of the non-dependent lung. Recent studies have questioned the understanding of ventilation distribution patterns in the paediatric population. There are no studies examining the effect of body position in mechanically ventilated infants/children.

Objectives. To determine the effect of body position on regional ventilation distribution in mechanically ventilated children.

Methods. Thoracic electrical impedance tomography (EIT) measurements were taken in left- and right-side lying, supine and prone positions in mechanically ventilated infants/children. Functional EIT images were produced, and regional relative tidal impedance (ΔZ) in the left, right, ventral and dorsal lung regions was calculated. The proportion of ventilation occurring in large lung regions and regional filling were also calculated.

Results. Seventeen children ($n=8$; 47% male) aged 6 months - 6 years are presented. Many of the children ($n=8$; 47%) consistently showed greater ventilation in the right lung in both side-lying positions, and in the dorsal lung region ($n=6$; 35%) in both the supine and prone positions. Regional filling was similar between lung regions in the different body positions.

Conclusion. Ventilation distribution in mechanically ventilated infants/children with mild lung disease is variable and similar to that of healthy spontaneously breathing infants/children.

Keywords. Paediatric critical care, mechanical ventilation, body positioning, ventilation distribution, electrical impedance tomography, infants/children.

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Contribution of the study

Ventilation distribution in mechanically ventilated children with mild disease is not dissimilar to that in healthy infants and children. Positioning to optimise ventilation should be tailored to each child's responses. This study provides exploratory data describing ventilation distribution in mechanically ventilated infants and children. These data can be used to inform further research study design.

In mechanically ventilated infants/children, positioning is an important component of medical and physiotherapeutic management. Positioning can improve oxygenation through improved ventilation-perfusion matching, aid in the mobilisation and clearance of secretions, and prevent the development of decubitus ulcers.[1-3]

It is well established that ventilation may not be homogeneously distributed during mechanical ventilation (MV). Factors such as the underlying condition(s), use of paralysis or sedation, and ventilatory settings have the potential to alter ventilation distribution.[4] Studies in adults and older children have consistently shown that where no spontaneous breathing is permitted, ventilation is greatest in the non-dependent lung region, whereas where spontaneous breathing or effort is permitted, ventilation is greatest in the dependent lung region.[5-8] The effect of supported modes of ventilation on ventilation distribution is relatively unknown in children. The understanding of ventilation distribution in the paediatric population has until recently been based on studies performed in the 1980s using 81m-krypton ventilation scanning in heterogeneous populations.[9-12] More recent studies have explored ventilation distribution in mechanically ventilated children. These studies describe ventilation distribution relative to the centre of ventilation, and this lies ventrally or dorsally.[13,14]

Electrical impedance tomography (EIT) is a promising non-invasive imaging technique that allows for real-time, bedside monitoring of lung function and global and regional ventilation distribution.[15,16] Studies using EIT in neonates have found that ventilation distribution in the supine and prone positions is similar irrespective of body position and the degree of MV assistance received.[17,18]

For appropriate positioning to be used in clinical practice, an understanding of how ventilation distribution is affected by position in mechanically ventilated infants/children aged >6 months is important. This study aimed to describe the distribution of ventilation, measured using EIT, in response to different body positions in infants/children with mild lung disease.

Methods

A prospective descriptive study was conducted in the paediatric intensive

care unit at Red Cross War Memorial Children's Hospital, Cape Town, South Africa. Ethical approval was obtained from the Human Research Ethics Committee of the University of Cape Town (ref. no. 179/2013) Informed consent was obtained from the parents or legal guardians of the children, and assent was obtained from the child where appropriate.

Infants/children aged between 6 months and 9 years receiving invasive MV were eligible for inclusion. Infants/children with haemodynamic instability, an underlying cardiac defect or a disease affecting respiratory mechanics, those who had had thoracic or abdominal surgery in the preceding 3 months or a general anaesthetic (surgery) in the preceding 6 weeks, and those with fragile or broken skin or dressings over the thoracic region (which would hinder the correct application of the electrodes), raised intracranial pressure or the potential for raised intracranial pressure (e.g. traumatic head injury, meningitis) were excluded from the study.

Regional ventilation was measured using EIT. EIT has been well validated and described in detail elsewhere.[4,19-27]

At the time of the study, no data on regional ventilation using EIT were available for this population, so the sample size was calculated using data obtained from healthy children.[28] It was calculated that a sample of 21 children would be required to detect a mean difference in relative impedance change (ΔZ) of 4.2, in large lung regions, and a standard deviation of 6 (alpha 0.05; power 90%).

Procedure

Regional ventilation was determined using the Goettingen Goe-MF II EIT system (Viasys/Carefusion, Germany). Sixteen neonatal-sized electrodes (Blue Sensor BR-50-K; Ambu, Denmark) were placed circumferentially at the 4th intercostal space (or nipple line). One reference electrode was placed on the abdomen. Measurements were taken in left- and right-side lying as well as supine and prone (children lying flat on their abdomen) positions. These positions were standardised between participants and have been described previously.[28] Each position was maintained for ~10 minutes prior to measurements, and measurements were taken for ~1 minute in each position, or until a series of five reproducible breaths was obtained. The order of positions was one of convenience to minimise the handling of these critically ill children.

The rate of data acquisition was 13 cycles/second.[29] Data were processed off-line using Auspex Software version 1.6 (Viasys Healthcare, Netherlands). The data were processed via a back-projection algorithm and the mean ΔZ values were depicted in a 32 × 32 pixel matrix, where each pixel was representative of the relative impedance change within the chest.[30] Five consecutive breaths of similar amplitude and without inspiratory or expiratory pauses were selected. Functional EIT (fEIT) images were then generated from the five breaths, and the data were used for further analysis (Fig. 1).[31] Regions of interest included left, right, dorsal and ventral regions (Fig. 1). Global ventilation was described as: (i) the total ΔZ in both left and right lung regions; and (ii) the global inhomogeneity (GI) index of all image pixel values. Regional ventilation was described by: (i) the pattern followed; (ii) ΔZ; and (iii) regional filling and emptying. The ventilatory pattern followed was determined by which lung consistently had a greater proportion of ventilation (>50%) in either side-lying position or the supine and prone positions. The overall ventilation pattern followed, i.e. which region received a consistently greater proportion of ventilation regardless of the position, was described as dependent (greatest in lowermost lung regions) or non-dependent (greatest in uppermost lung regions) left, right, ventral and dorsal patterns, respectively. ΔZ was calculated from the fEIT images as described above. The GI index describes the homogeneity of the distribution of the tidal volume within the lung and has been described in detail by Zhao et al.[31]

Regional filling was calculated using the filling index (FI), which describes the regional filling rate relative to the global filling rate.[8,32]

Baseline data collected included vital signs (heart rate, respiratory rate, oxygen saturation), ventilator settings and chest radiographic appearance (Table 1). Chest radiographs were assessed by one independent investigator and were classified as normal, unilateral changes or bilateral changes, based on the presence of infiltrates.

Statistical analysis

Data were tested for normality with the Shapiro-Wilk test. Differences in ΔZ between EIT measurements of selected regions of interest in different body positions and different radiographic presentations were determined using repeated measures analysis of variance (ANOVA), after ensuring that residuals were normally distributed. Post-hoc t-tests or Mann-Whitney U-tests were performed according to distribution to determine where any significant differences may have occurred. A bonferroni correction was applied for multiple comparisons. Analysis was performed using Statistica 12 (StatSoft, USA). To determine whether age (grouped by those younger and older than 12 months) or disease state (based on radiographic presentation) determined the pattern of ventilation (grouped by non-dependent, dependent or different), a multinomial logistic regression model was applied to the data using SPSS 23 (IBM, USA).

Results

Seventeen (n=8 male) infants/children with a median age of 1.1 (range 0.5 - 5.5) years were included (Supplementary Table 1, available online at http://coding.samedical.org/file/2342). All the children received pressure-controlled synchronised intermittent mandatory ventilation. None received muscle paralysis during the study. Sixteen children (94%) received some form of sedation at the lowest dose to keep the child comfortable; this resulted in full ventilatory support in only 2 cases (12%), and the remaining children were able to trigger breaths on the ventilator. The children in this study did not have severe lung disease at the time of measurement, which was usually done towards the end of their course of MV. Thirteen children (76%) had bilateral radiographic changes, 2 had unilateral changes (on the right), and 2 had no changes. All 17 children had measurements in the side-lying positions, all 17 had at least one measurement in the supine position, and only 11 had at least one measurement in both the supine and prone positions. Inability to measure in the prone position in some children was due to newly inserted tracheostomies (day 0 or 1), or the child refusing to turn into the prone position.

Overall ventilation pattern followed

Side-lying positions

Three (18%) of the 17 infants/children demonstrated consistently greater ventilation in the uppermost lung region (the non-dependent ventilation pattern) (Fig. 2A). A similar number of children (n=3; 18%) showed consistently greater ventilation of the dependent (lowermost) lung region. Eight children (47%) demonstrated consistently greater ventilation of the right lung in both side-lying positions, while the remaining 3 (18%) showed consistently greater ventilation of the left lung.

Supine and prone positions

Two of the 11 children (18%) demonstrated consistently greater ventilation in the non-dependent lung (Fig. 2B). One child (9%) consistently demonstrated the dependent ventilation pattern. Two
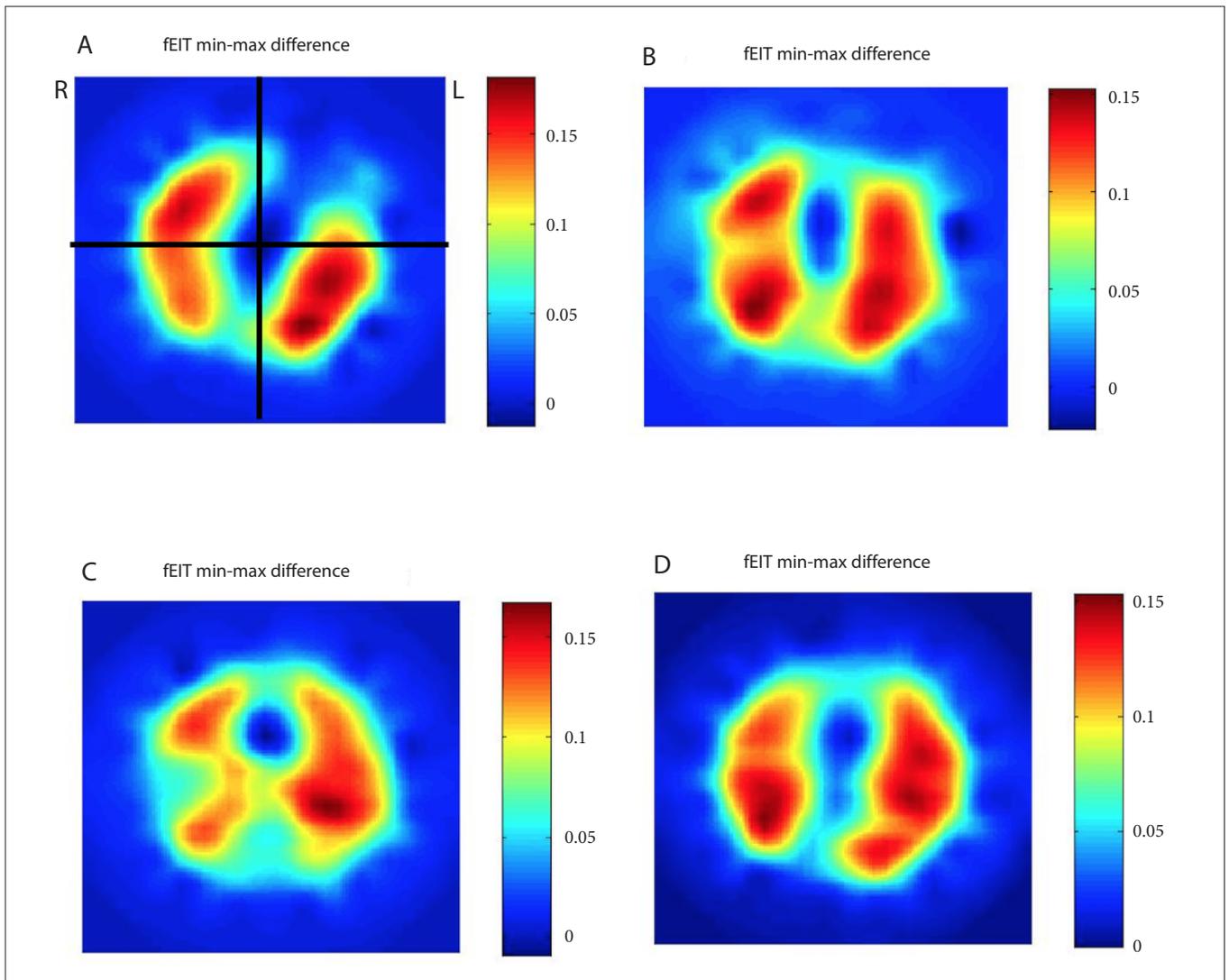
Fig. 1. fEIT images taken in the left-side lying (A) and right-side lying positions (B), in the supine position with the head turned to the right (C), and in the prone position with the head turned to the right (D). The regions of interest used in analysis are demarcated on (A), and the left (L) and right (R) sides of the child are indicated on (A). (fEIT = functional electrical impedance tomography.)

children (18%) showed consistently greater ventilation in the ventral lung region, while the majority (*n*=6; 55%) showed greater ventilation of the dorsal lung region in both the supine and prone positions. Owing to the small number of infants/children examined in both the supine and prone positions, we were not able to determine whether age groups were associated with the overall ventilation pattern followed.

Regional ventilation distribution
Side-lying positions
Global ventilation was unaffected by left or right side-lying positions. Regional ventilation was unaffected by position change within and between the left and right lungs (Table 2). A significant interaction between the effect of lung region and position on ΔZ was found ($F_{(2,56)}$=3.47; *p*=0.04), with greater ventilation in the left lung region in the dependent position, while the ventilation in the right lung region remained relatively unchanged between positions. The GI index was similar in both side-lying positions (Table 2).

The majority of the infants/children had bilateral lung disease (*n*=13; 76%). No significant interaction was found between the effects of type of lung disease (unilateral, bilateral or none) and position (dependent or non-dependent) and the proportion of ventilation occurring in the left

lung region ($F_{(4,18)}$=1.24; *p*=0.33) and right lung region ($F_{(4,18)}$=1.24; *p*=0.33). The age of the child, grouped by those aged <12 months and those aged ≥12 months, was not associated with the overall ventilation pattern followed in side-lying positions.

Supine and prone positions
Global ventilation and regional ventilation were unaffected by the supine and prone positions (Table 2). Regional ventilation, both within and between the ventral and dorsal lung regions, was unaffected by position ($F_{(1,18)}$=0.58; *p*=0.81). No significant difference in the GI index was found between the supine (median 0.90) and prone positions (Table 2).

The interaction between the effects of disease pattern seen on the chest radiograph and position and the proportion of ventilation in either the ventral ($F_{(2,7)}$=0.01; *p*=0.99) or the dorsal ($F_{(2,7)}$=0.01; *p*=0.99) lung regions in the supine and prone positions was not significant.

Regional filling
Side-lying
Regional filling was unaffected by position change (Table 2). No differences were found in regional filling between the left and right

Table 1. Sample characteristics (*N*=17)

	n (%)*
Age (years), median (range)	1.1 (0.5 - 5.5)
<12 months	6 (35)
≥12 months	11 (65)
1 - 3 years	10 (91)
4 - 6 years	1 (9)
Gender	
Male	8 (47)
Female	9 (53)
Ventilatory parameters	
Mode	
SIMV PC	17 (100)
Respiratory rate (breaths per minute)	
Pre-set, median (range)	25 (13.0 - 35.0)
Recorded, median (range)	33 (21.0 - 50.0)
Spontaneous, median (range)	10 (0 - 21)
MAP (cmH$_2$O), median (range)	11 (6 - 14)
PIP (cmH$_2$O), median (range)	17 (12 - 26)
PEEP (cmH$_2$O), median (range)	5 (5 - 7)
FiO$_2$, median (range)	0.30 (0.21 - 0.55)
Vital signs	
Heart rate (bpm), median (range)	114 (80 - 150)
Mean arterial blood pressure (mmHg) (*n*=15), median (range)	76.5 (63.0 - 103.0)
Oxygen saturation (%), median (range)	96 (91 - 100)
Chest radiographs	
Bilateral changes	13 (76)
Unilateral changes	2 (12)
No changes	2 (12)

SIMV PC = pressure-controlled synchronised intermittent mandatory ventilation; MAP = mean airway pressure; PIP = peak inspiratory pressure; PEEP = positive end-expiratory pressure; FiO$_2$ = fraction of inspired oxygen.
*Except where otherwise indicated.

lung regions when each lung was in the dependent and non-dependent positions (Table 2).

Supine and prone positions

Regional filling within the ventral and dorsal lung regions was unaffected by body position (Table 3). Supine and prone positions did not significantly affect regional filling between lung regions (Table 2).

Discussion

This study describes ventilation distribution with different body positions in mechanically ventilated infants/children with relatively mild lung disease in the absence of anaesthesia/deep sedation or muscle paralysis. Most children demonstrated consistently better ventilation of their right lung in side-lying positions, and of the dorsal lung in supine and prone positions. This finding is contrary to the previously established and generally applied concept that preferential ventilation occurs in the non-dependent lung regions,[9,11] but is similar to our previous work in healthy infants/children which found that ventilation distribution in spontaneously breathing infants/children was highly variable, with no clear or reproducible pattern.[28]

There are limited studies investigating the effects of MV and different body positions on the distribution of ventilation in infants/children beyond the neonatal period. Humphreys *et al.*[8] and others[5,33] investigated infants/children who were mechanically ventilated and anaesthetised, and found ventilation to be greater in the non-dependent lung in the supine position, which is in keeping with adult studies. These studies examined patients who were sedated, paralysed and fully ventilated, making direct comparison with our population difficult.

Our findings of greater ΔZ in the dependent lung regions in the side-lying positions are in keeping with a number of adult studies which report that during MV, where spontaneous breathing is allowed, ventilation is greatest in the dependent lung regions.[5,34-36] This finding did not differ significantly from that in spontaneously breathing infants/children.[28] While a more heterogeneous distribution of ventilation may be expected during MV with underlying respiratory disease, the application of positive end-expiratory pressure (PEEP) may help ameliorate this. The application of PEEP has been shown to minimise collapse of dependent lung regions and therefore improve compliance and facilitate better ventilation of the dependent lung regions.[19,37-39]

A different pattern was observed in the supine and prone positions, with greater ventilation in the non-dependent lung regions. This finding is dissimilar to reports of no difference in ventilation between the dependent and non-dependent lung regions in the supine and prone positions in ventilated neonates.[18] Chest wall mechanics may be related to the pattern seen. The children in the present study were relatively young and may have had more compliant chest walls. This effect may be augmented by reduced muscle tension as a result of sedatives.[40] The increased chest wall compliance, together with the positive-pressure ventilation, may facilitate better ventilation to the non-dependent (ventral) lung region.[7,34] In the prone position, movement of the anterior chest wall is impeded by the bed, and a reduction in the abdominal hydrostatic pressure in the dorsal regions may facilitate improved diaphragm activity and lung compliance, resulting in
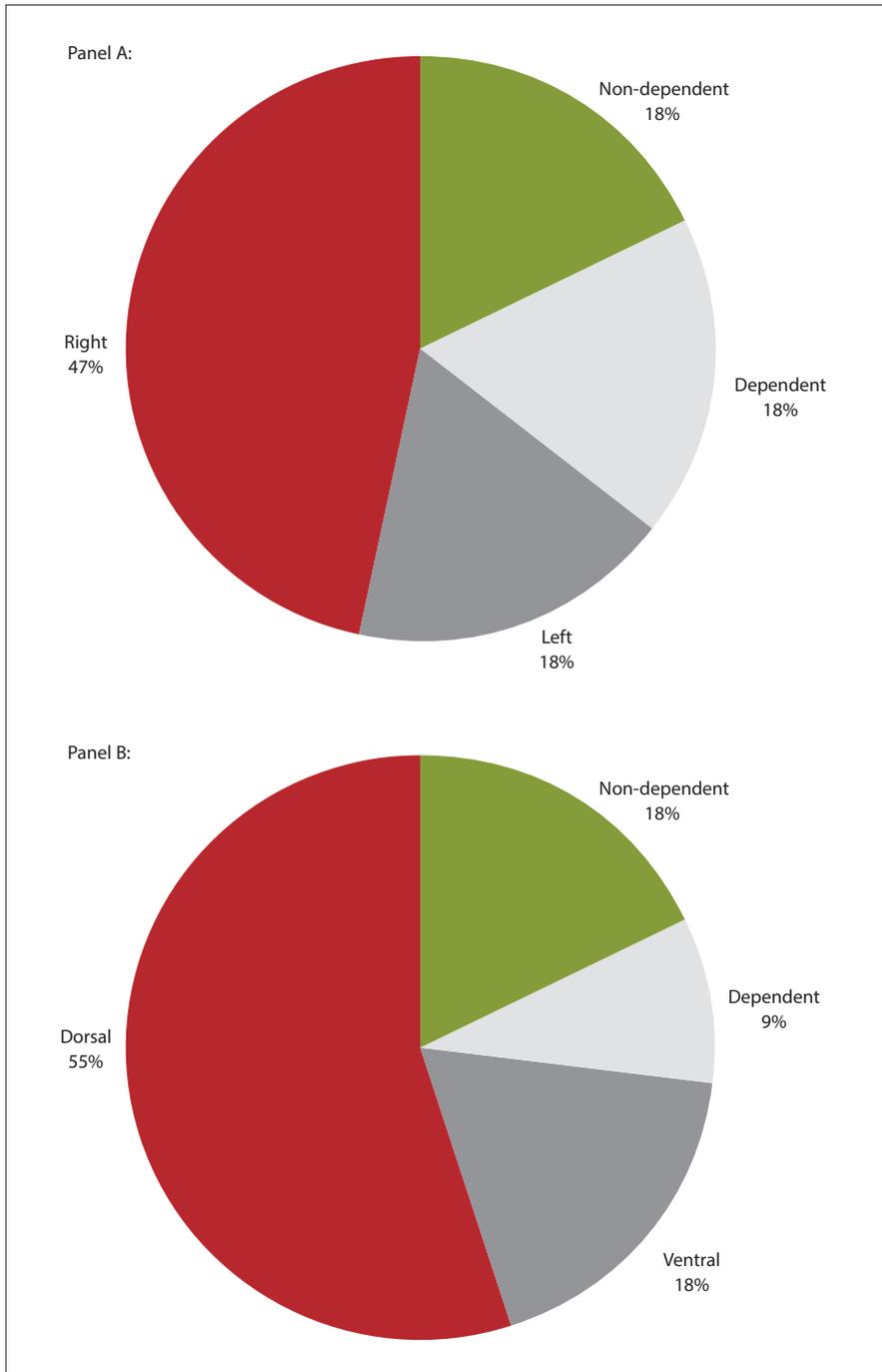
Fig. 2. Pattern of ventilation consistently followed in side-lying positions (A) and supine and prone positions (B).

greater ventilation in the non-dependent lung regions.[38,41,42]

The lack of age-related difference in this group may be related to the smaller number of children aged <12 months (*n*=6). Furthermore, if age-related differences account for the differences in respiratory mechanics resulting in the tendency of dependent lung regions to collapse,[11] the application of PEEP[19] and the more regular flow rates, tidal volumes and respiratory rates may help prevent airway closure in the dependent lung regions.

The radiographic presentation (unilateral, bilateral or normal) did not affect ventilation distribution, which is in keeping with the findings reported by Davies *et al*.[11] It must be noted, however, that these chest radiographs were not all taken on the day of study inclusion, and the condition may therefore have changed at the time of the study.

In side-lying positions, regional FIs were higher in the dependent lung regions, indicating slower initial but faster late filling in relation to global filling, in keeping with the principles put forward by Bryan *et al*.[43]

This finding may be the result of higher end-expiratory lung volume due to the application of PEEP.[38,44]

The dorsal lung regions had higher FIs in both the supine and prone positions, although this only reached statistical significance in the prone position. This finding is in keeping with the regional filling described in adults with acute respiratory distress syndrome (ARDS), where the ventral lung regions are relatively hyperinflated, whereas the dorsal lung regions are more recruitable in the supine position.[20] The higher FI in the dorsal lung region in prone may be attributed to the lower compliance in the prone position, and stabilisation of the anterior rib cage and better excursion of the dorsal diaphragm in that position. The more homogeneous filling in the prone position is in keeping with the findings of a study in children with paediatric ARDS.[45] It is possible that regional filling, and ventilation distribution, may differ depending on whether the breath was ventilator or patient driven. Although we were not able to differentiate between these in the analysis, the majority of children in our study were on assist modes and nearing the end of their course of MV, so the breaths analysed were more than likely to have been patient driven and ventilator supported. Furthermore, five reproducible breaths were selected for analysis in order to improve the uniformity of the breaths analysed. The effect of different flow rates and modes of ventilation, and whether the breaths are patient or ventilator driven, should be examined in future studies.

A major limitation of this study is that it is unclear which breaths were patient or ventilator driven, and this needs to be included in future studies to more accurately describe ventilation distribution in mechanically ventilated children. Whether there was hyperinflation on the chest radiograph was also not recorded. Hyperinflation may affect ventilation distribution, with a reduction in ventilation in the hyperinflated region. Although the sample size is comparable to similar studies in neonates[17,18,29,46] and was initially calculated to be adequately powered, final analysis indicated that it was underpowered (<80%). These results should therefore be confirmed in larger studies. Positioning was not absolutely standardised, although it was reproducible between participants, and this may have affected the results. The effect of time in the position and order of positions should be considered in future studies, since ventilation distribution may change over time and there may be

Table 2. Mean relative impedance change, filling indices and global inhomogeneity indices in the different body positions

	Side-lying positions		
	Left side-lying (*n*=17)	**Right side-lying (*n*=17)**	**p-value between positions***
Left lung region, median (IQR)			
ΔZ	11.38 (8.60 - 16.21)	9.25 (5.95 - 13.58)	0.20
FI	0.84 (0.78 - 1.14)	0.83 (0.64 - 1.01)	0.29
Right lung region, median (IQR)			
ΔZ	11.51 (9.00 - 19.50)	11.57 (9.19 - 19.41)	0.95
FI	0.94 (0.64 - 1.01)	0.96 (0.91 - 1.12)	0.29
p-value between lung regions			
ΔZ	0.81	0.20	
FI	0.28	0.28	
Global ΔZ, median (IQR)	24.35 (15.18 - 37.89)	21.76 (15.49 - 31.94)	0.51
GI index, median (IQR)	0.89 (0.86 - 1.00)	0.93 (0.88 - 1.04)	0.65
	Supine and prone positions		
	Supine (*n*=15)	**Prone (*n*=11)**	
Ventral lung, median (IQR)			
ΔZ	16.44 (6.33 - 21.62)	9.79 (6.34 - 17.70)	0.50
FI	0.85 (0.76 - 1.10)	0.79 (0.64 - 0.89)	0.22
Dorsal lung, median (IQR)			
ΔZ	11.92 (10.53 - 19-47)	12.39 (10.19 - 18.85)	0.76
FI	0.93 (0.68 - 1.03)	0.99 (0.89 - 1.15)	0.22
p-value between lung regions			
ΔZ	0.93	0.45	
FI	0.22	0.22	
Global ΔZ, median (IQR)	27.90 (13.25 - 39.03)	21.81 (17.19 - 38.52)	0.76
GI index, median (IQR)	0.90 (0.85 - 1.04)	0.93 (0.82 - 0.94)	0.68

IQR = interquartile range; ΔZ = mean relative impedance change; FI = filling index; GI index = global inhomogeneity index.
*Mann-Whitney U-test was applied.

Table 3. Mean relative impedance change in the left, right, ventral and dorsal lung regions with different head positions in supine and prone positions

	Left lung	**Right lung**	**p-value***
SM (*n*=13)	13.38 (5.78 - 22.21)	16.25 (4.77 - 22.80)	0.98
SL (*n*=14)	13.21 (7.71 - 19.79)	15.48 (10.86 - 20.54)	0.57
SR (*n*=15)	16.60 (7.33 - 21.32)	16.60 (7.81 - 17.86)	0.93
PL (*n*=5)	15.45 (15.30 - 16.98)	15.80 (13.99 - 23.37)	1.00
PR (*n*=11)	9.76 (6.40 - 17.70)	12.39 (9.68 - 18.37)	0.19

SM = supine, head in midline; SL = supine, head to left; SR = supine, head to right; PL = prone, head to left; PR = prone, head to right.
*Mann-Whitney U-test was applied.

order effects.[47] Often with a position change, secretions are mobilised and endotracheal suctioning is required. For ethical reasons, endotracheal suctioning was permitted during the study. This may have influenced ventilation distribution; the loss of PEEP during open endotracheal suction as well as the application of negative pressure may result in decruitment of lung regions.[48,49] The classification of pattern based on the 50% cut-off may have resulted in the overestimation of some patterns. Whether there is a clinically meaningful difference in the proportion of ventilation between lung regions will need to be determined in future research in children.

This study provides previously lacking data that can be used to inform the development of future research investigating regional ventilation in mechanically ventilated infants/children and studies using EIT in this population. These findings could aid in improving the methodological rigour of future studies. Furthermore, the study has important implications for clinical practice in that the traditional generalisation of ventilation distribution in all children does not appear to be true. The lack of

a clear pattern of ventilation distribution in mechanically ventilated infants/children suggests a judicious approach when positioning infants/children for therapeutic purposes (such as re-expanding areas of collapse, improving ventilation-perfusion matching).

Conclusion

Ventilation distribution in mechanically ventilated infants/children, without anaesthesia or paralysis (but sedated), is variable, with most children consistently showing greater ventilation of their right or dorsal lung regions as measured by EIT. This study provides baseline data that can be used to inform future studies, and highlights areas for further research.

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