

Effects of Recruitment Maneuver on Atelectasis in Anesthetized Children

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Background: General anesthesia is known to promote atelectasis formation. High inspiratory pressures are required to re-expand healthy but collapsed alveoli. However, in the absence of positive end-expiratory pressure (PEEP), reexpanded alveoli collapse again. Using magnetic resonance imaging, the impact of an alveolar recruitment strategy on the amount and distribution of atelectasis was tested.

Methods: The authors prospectively randomized 24 children who met American Society of Anesthesiologists physical status I or II criteria, were aged 6 months–6 yr, and were undergoing cranial magnetic resonance imaging into three groups. After anesthesia induction, in the alveolar recruitment strategy (ARS) group, an alveolar recruitment maneuver was performed by manually ventilating the lungs with a peak airway pressure of 40 cm H₂O and a PEEP of 15 cm H₂O for 10 breaths. PEEP was then reduced to and kept at 5 cm H₂O. The continuous positive airway pressure (CPAP) group received 5 cm H₂O of continuous positive airway pressure without recruitment. The zero end-expiratory pressure (ZEEP) group received neither PEEP nor the recruitment maneuver. All patients breathed spontaneously during the procedure. After cranial magnetic resonance imaging, thoracic magnetic resonance imaging was performed.

Results: The atelectatic volume (median, first and third standard quartiles) detected in the ZEEP group was 1.25 (0.75–4.56) cm³ in the right lung and 4.25 (3.2–13.9) cm³ in the left lung. The CPAP group had 9.5 (3.1–23.7) cm³ of collapsed lung tissue in the right lung and 8.8 (5.3–28.5) cm³ in the left lung. Only one patient in the ARS group presented an atelectasis of less than 2 cm³. An uneven distribution of the atelectasis was observed within each lung and between the right and left lungs, with a clear predominance of the left basal paradiaphragmatic regions.

Conclusion: Frequency of atelectasis was much less following the alveolar recruitment strategy, compared with children who did not have the maneuver performed. The mere application of 5 cm H₂O of CPAP without a prior recruitment did not show the same treatment effect and showed no difference compared to the control group without PEEP.

ATELECTASIS and poorly ventilated lung areas appear during general anesthesia in adults as well as in children.^{1–4} It is of concern that collapsed lung tissue not only reduces lung compliance but also causes venous admixture and arterial oxygenation impairment.^{1,3,5,6}

With the use of more advanced technology, the diagnostic sensitivity and specificity for alveolar collapse

increased. Computed tomography (CT) has been used to study the distribution and the quantification of poorly ventilated or nonventilated lung tissue. Using the six inert gas elimination technique, Hedenstierna *et al.*^{5,7} demonstrated that lung collapse is an important cause of gas impairment during general anesthesia. For the study of collapsed lung tissue, magnetic resonance imaging (MRI) is an alternative to the CT scanner: It combines the high image resolution and three-dimensionality⁸ of the latter but does not subject patients to radiation.

In recent years, the advantages and disadvantages of alveolar recruitment maneuvers for the diseased lung have been a matter of much discussion.^{9–12} The use of opening maneuvers in healthy anesthetized patients has proved to be effective in recruiting collapsed pulmonary areas.^{1,13,14} Although the magnitude and the mechanism of alveolar collapse of healthy and sick lungs differ considerably, the clinical significance of a decrease in functional residual capacity is similar: a compromise in arterial oxygenation and pulmonary compliance.^{3,5,6,10}

In healthy lungs, collapsed areas are re-aerated, and a normal functional residual capacity is restored if airway pressures are raised beyond the alveolar opening pressure. Bendixen *et al.*¹ and later Rothen *et al.*¹³ have claimed that this pressure is approximately 40 cm H₂O.

Lachmann¹⁵ recommended opening collapsed lungs by applying sufficient levels of peak inspiratory pressure and maintaining alveoli open by using sufficient levels of positive end-expiratory pressure (PEEP). Based on this treatment concept, we designed an alveolar recruitment strategy (ARS) to treat healthy but partially collapsed lungs during general anesthesia. The positive effect of this strategy on arterial oxygenation and on lung compliance has recently been demonstrated.¹⁴

General anesthesia for children undergoing MRI studies is common clinical practice and provides a good model for investigating atelectasis formation. Using MRI, we studied the effect of an alveolar recruitment strategy on the amount and the distribution of atelectasis in children with healthy lungs who were undergoing general anesthesia. The treatment effects of a recruitment maneuver were compared with those of 0 and 5 cm H₂O of end-expiratory pressure.

Materials and Methods

Patients

The study was conducted at the Hospital Privado de Comunidad in Mar del Plata, Argentina, and was approved by the local ethics committee. Patients younger

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than 7 yr of age who met American Society of Anesthesiologists physical status I or II criteria and were scheduled for MRI under general anesthesia were eligible for this study. In addition, patients had to be free of diseases of the thorax or the upper abdomen. Prior to enrollment into our investigation, a written consent was obtained from the children's next of kin. After fulfilling all of the above inclusion criteria, the patients were randomly assigned to three treatment groups by opening sealed envelopes.

Anesthesia and Monitoring

No premedication was given. Anesthesia was induced by the inhalation of halothane in pure oxygen using an open Mapleson D system with a flow of $200 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. Prior to intubation, a dose of 0.01 mg/kg atropine and 1 $\mu\text{g}/\text{kg}$ fentanyl was administered. No muscle relaxation was given to any of the subjects. Once a deep level of anesthesia was reached, patients were ventilated to apnea and intubated with a cuffed endotracheal tube (Willy Rusch AG, Kempen, Germany), the size of which was determined by direct inspection of the trachea distal to the vocal cords. The cuff was then inflated to prevent air leakage during the study period. Immediately after intubation, tube position was checked by chest auscultation and by independently observing the motion of each hemithorax. The fraction of inspired oxygen (F_{IO_2}) was kept at 100% during the entire study period.

Patients were supported until spontaneous ventilation resumed, maintaining this last condition during the entire study period. Anesthesia was maintained by a halothane concentration of 1% at the vaporizer dial mixed into an oxygen flow of $400 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. Before placing the children onto the investigation table in the MRI room, they were switched to a Bain system. These anesthetic conditions were now maintained until the end of the study period.

The MRI apparatus, using its cardiac triggering function, monitored the patients' heart rate. The Nonin 8600 pulse oximeter (Nonin Medical Inc., Plymouth, Minneapolis) is approved for magnetic resonance environments. Automated noninvasive blood pressure was monitored with Cardiocap monitor (Datex Instruments Corp., Helsinki, Finland), with a cuff of proper size. Respiration and heart sounds were transmitted to the anesthetist *via* an esophageal stethoscope connected to a 4-mm tube of 7 m length. In addition, the patients' respiratory movements were monitored by observing the bag of the breathing system.

A Mallinckrodt variable orifice PEEP valve (Mallinckrodt Laboratories Ltd., Athlone, Ireland) was used to pressurize the system. It was placed between the expiratory limb and the anesthetic bag of the Bain system.

The airway pressure was monitored by a calibrated pressure transducer of a Cardiocap monitor with a cath-

eter put into the exhalation circuit just proximal to the valve at the gas outlet.

Before the start of the clinical investigation, we tested the proper function of the Bain system and the PEEP valve according to the methods described by Bagger¹⁶ and Banner *et al.*¹⁷ The results of these pilot studies were similar to those reported in the literature and are therefore not reported in this article.

Study Protocol

Before inducing general anesthesia, patients were randomly assigned to one of three groups. After induction, patients were intubated, were allowed to breathe spontaneously, and were then placed into the MRI device. Once their position was correct, they were immediately ventilated according to the following treatment protocols:

Zero end-expiratory pressure (ZEEP) group: 0 cm H₂O end-expiratory pressure.

Continuous positive airway pressure (CPAP) group: CPAP, 5 cm H₂O end-expiratory pressure.

ARS group: To avoid body movements and to fully control manual ventilation, we deepened the anesthetic level by temporarily increasing the halothane concentration from 1 to 1.5% at the vaporizer dial 2 min prior to and during the ARS maneuver. Immediately thereafter, we returned to the basal halothane concentration.

Once ventilation was controlled manually, we performed the recruitment maneuver in a similar fashion to our previous report.¹⁴ CPAP was increased progressively in steps of 5 cm H₂O every four breaths up to the target CPAP level of 15 cm H₂O. Once the target CPAP level was reached, ventilation was manually assisted until complete control of respiration was gained. Thereafter, airway pressure was manually increased up to 37–40 cm H₂O of peak inspiratory pressure (PIP). We maintained a respiratory rate of approximately 30 breaths/min without end-inspiratory pause or breath holding. These elevated pressures were continued for 10 consecutive breaths before CPAP was reduced to 5 cm H₂O and maintained at this level while patients resumed spontaneous ventilation throughout the rest of the study period.

Tidal volumes were not monitored during the maneuver. The total time for performing the recruitment maneuver was around 2 min. Manual ventilation was performed at 10 breaths/min respiratory rate until spontaneous breathing was resumed (approximately 3 min after the end of ARS).

All patients were lying in the supine position with their arms secured parallel to either side of the body. Imaging of the brain was performed using a magnetic head coil. MRI time was approximately 15–20 min. After finishing the cranial investigation, the head was liberated from its suspension without disconnecting the patient from the

Table 1. Baseline Characteristics of Patients by Treatment Group

	ZEEP (n = 10)	CPAP (n = 8)	ARS (n = 8)
Age (months)	24.5 (13.3–42.8)	21 (10–42)	41.5 (17.8–69)
Weight (kg)	13.5 (10.8–16.5)	12 (8.6–15.5)	16 (11.2–25.8)
Examination time (min)	55.5 (50–60)	53 (45.8–63.8)	57.5 (50–65)
ASA, n (I/II)	5/3	4/4	2/6
Sex (female/male)	5/3	3/5	5/3

Data are presented as median (50%), first (25%), and third (75%) quartile; percentiles for weight according to age.

ARS = alveolar recruitment strategy group; CPAP = continuous positive end-expiratory pressure group; ZEEP = zero end-expiratory pressure group.

breathing circuit. Once again, the position of the endotracheal tube was checked.

The study was performed with a Siemens Magnetom Impact (Siemens, Erlangen, Germany) with a body coil of 1 Tesla. A frontal scout view of the entire thorax was obtained to optimally position the patient's chest within the magnetic coil. Each scanning sequence used T1 imaging at a repetition time of 630 ms and an echo time of 15 ms, and T2 imaging at a repetition time of 3,200 ms and an echo time of 90 ms. Slice thickness was 8 mm with a distance of 0.8 mm between them (gap). Each thoracic imaging sequence (T1 and T2) took approximately 11 min. Data on the duration of the anesthesia (not including the time for induction) are given in table 1.

To avoid artifacts or interference from breathing movements, the MRI device is equipped with a respiratory triggering function using electrodes placed on the patient. Proton H⁺ signals were obtained at a radio frequency of 20–240 ms. Imaging was synchronized with the end of each inspiration to obtain the images during a brief time window of absent respiratory movements and to better evaluate the amount of collapsed lung at the moment of maximum pulmonary inflation. This means that the MRI device acquired proton H⁺ signals only at this moment of the respiratory cycle, during each T1 and T2 thoracic sequence (approximately 11 min). Acquired T1 and T2 data from each end-inspiration time window were mathematically converted into images.

Diagnosis of Atelectasis

Since oxygen atoms are nonmagnetic, the normally hypoventilated and overdistended lung zones are not visible and appear as hypointense (black). The collapsed

areas differ in their signal intensity, looking either iso-intense in the T1 or hyperintense in the T2 images.^{18–22} In addition, there are other radiologic signs²³ that are helpful to define atelectasis: (1) atelectatic zones are homogeneous, *i.e.*, the same intensity is seen within the entire collapsed area; and (2) air bronchogram is frequently present in this kind of atelectasis.

Volume of Atelectasis

The MRI device used in this study lacks the software required for calculating volumes at the same time that images are obtained. For this reason, volume measurements were performed manually off-line by two radiologists (A. T. and E. G.). Transversal, anteroposterior, and craniocaudal diameters were determined in centimeters, according to the scale depicted on each of the images. Atelectatic volumes were then calculated using the following formula:

$$\begin{aligned} \text{Volume (cm}^3\text{)} &= \text{anteroposterior diameter (cm)} \\ &\times \text{transversal diameter (cm)} \\ &\times \text{craniocaudal diameter (cm)} \end{aligned}$$

First, we obtained the craniocaudal axis from the greater atelectasis image in the coronal cut (fig. 1A). Second, the atelectatic area was calculated by multiplying the anteroposterior by the transversal diameter from the axial cut (fig. 1B). We chose the axial cut that represents the mean atelectatic area (broken line, fig. 1A) to avoid overestimation of atelectatic volume. Finally, we obtained the atelectatic volume by multiplying area by height from the craniocaudal axis. All available

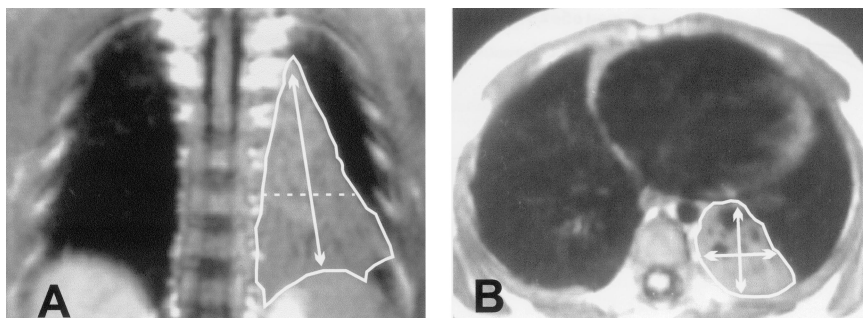


Fig. 1. Atelectasis volume measurement. (A) Coronal cut showing the greater amount of atelectasis in the craniocaudal axis. (B) Axial cut showing the intermediate atelectasis area (for more details, see text).

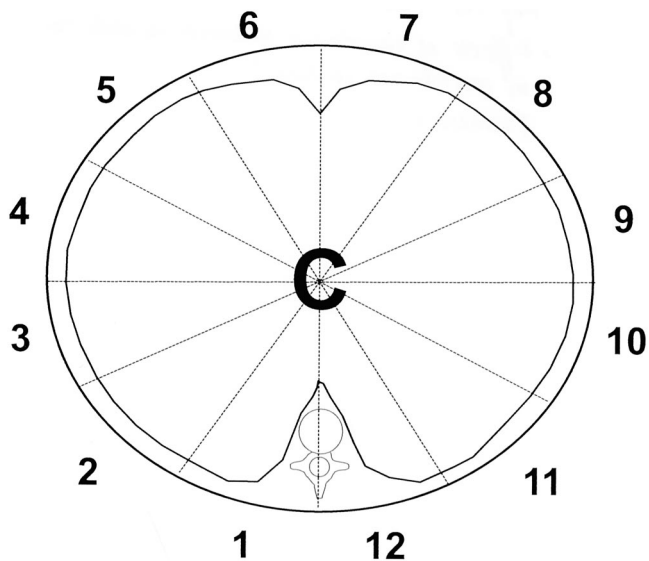


Fig. 2. Division of axial image into 12 segments all radiating from the center of the thorax. Sectors 1–6 = right lung; sectors 7–12 = left lung; C = thoracic center.

images were used for these calculations. An example of atelectasis volume measurement is shown in figure 1.

Location of Atelectasis

To localize atelectatic lung areas, axial cuts through the aortic arch (upper), through the pulmonary hilum (middle), and at the level of the diaphragm dome were divided into 12 sectors of identical angles, each one of them defining the area between the broken lines radiating from the center of the thorax to the periphery (fig. 2). Sectors 1–6 comprised the right lung, and sectors 7–12 comprised the left lung.

Putting a transparent chart of the 12 lung sections over the thoracic center (fig. 2), the radiologist designated a value of 1 if atelectasis was present in a determined section (irrespective of its size) or 0 if atelectasis was not present. From these dichotomous data, a 12-digit code consisting of zeros and ones was generated to qualitatively describe the distribution of alveolar collapse. To obtain information on the craniocaudal distribution of anesthesia-induced atelectasis, all three of the aforementioned axial cuts were analyzed in the same way.

Image Analysis

All images were analyzed independently by two board-certified members of the department of Diagnostic Radiology at the Hospital Privado de Comunidad (A. T., E. G.). Each observer performed a second image analysis at least 10 days after the first one. Both observers were blinded as to the treatment the patients had received.

Statistical Analysis

All data were analyzed using the statistical program SPSS for Windows (SPSS Inc., Chicago, IL). A total of 26

Table 2. Atelectatic Volumes

	ZEEP	CPAP	ARS
Atelectasis volume (cm ³)			
Right	1.25 (0.75–4.56)*	9.5 (3.1–23.7)	0††
Left	4.25 (3.2–13.9)	8.8 (5.3–28.5)	0††

Data are presented as median, first (25%) quartile, and third (75%) quartile. Significant difference (Mann-Whitney U test) between *ZEEP and CPAP, between †CPAP and ARS, between ‡ZEEP and ARS. All $P < 0.05$.

ARS = alveolar recruitment strategy group; CPAP = continuous positive end-expiratory group; ZEEP = zero end-expiratory pressure group.

patients were included in the statistical analysis: 10 in the ZEEP and 8 in both the PEEP and ARS groups. Atelectatic volume is characterized by median (50%), first quartile (25%), and third quartile (75%). For differences between treatment groups, the nonparametric Kruskal-Wallis test and Mann-Whitney U test were used.

Variability in image analysis within and between observers was assessed by analyzing deviations from the 12-digit code describing the patterns of alveolar collapse by κ statistics (KIA). A KIA of 0.41–0.6 was considered a fair agreement, and a KIA of 0.61–0.8 was considered a strong agreement between observations. A KIA between 0.81 and 1.0 corresponded to almost identical observations. For each of the KIAs, a 95% confidence interval was determined.

Results

Baseline Characteristics

Twenty-six patients undergoing MRI of the cranium were randomly assigned to three treatment groups. Patient age ranged from 6 months to 6 yr. None of the patients showed any signs of cardiorespiratory, mediastinal, or abdominal disease. Table 1 gives the baseline characteristics.

Volume of Atelectasis

Compared with the other groups, treatment with an alveolar recruitment strategy resulted in a lower frequency of atelectasis observed on the MRI images. After the recruitment maneuver, minimal amounts of lung tissue remained collapsed in only one patient (lower than 2 cm³ in the left paradiaphragmatic lung).

All patients of the CPAP and ZEEP groups showed varying amounts of lung collapse. In the ZEEP group, the atelectatic volumes were significantly lower than in the CPAP group (table 2). Figure 3 shows representative MRI images of the upper, middle, and lower axial cuts and the corresponding coronal cut for the three treatment groups.

The two sets of volumes of atelectasis for each of the lungs obtained by observer 1 showed a strong correlation. Intraobserver correlation of the second observer was similar. Intraobserver correlation of both observers

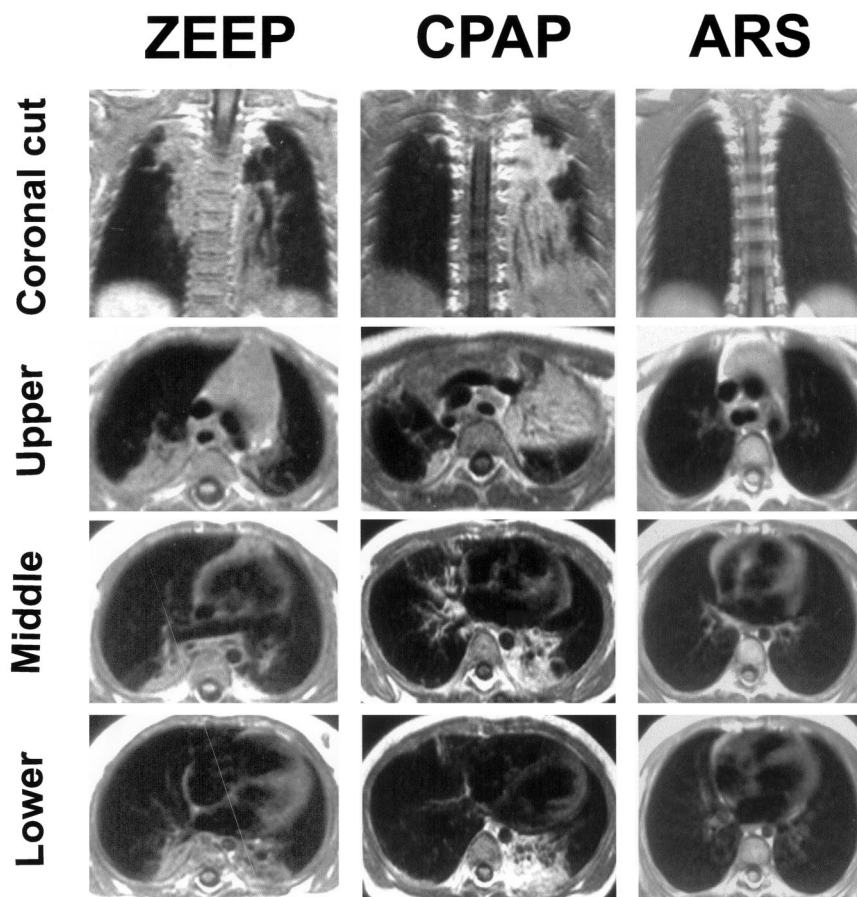


Fig. 3. Nuclear magnetic resonance images of representative patients for each of the three treatment groups. (Left) ZEEP = zero end-expiratory pressure; (middle) PEEP = positive end-expiratory pressure of 5 cm H₂O; (right) ARS = alveolar recruitment strategy with images taken at a PEEP of 5 cm H₂O. The top of each column shows a coronal view, followed by an upper, a middle, and a lower axial cut through the thorax (for details, see text). In children of the ZEEP group, atelectasis volume was 18 ml in the right lung and 16 ml in the left lung. In children of the CPAP group, atelectasis volume was 10 ml in the right lung and 33 ml in the left lung. The ARS group showed no atelectasis.

reached a significance level of $P < 0.001$. Interobserver correlation was intermediate ($P < 0.001$). Higher interobserver and intraobserver variabilities were found when the data were correlated separately for each treatment group. No significant differences in the volumes were found between the two sequential measurements of each of the two observers.

Distribution of Atelectasis

Figure 4 presents the accumulated distribution of atelectasis for all patients together and in all observations.

In all observations, the chance of atelectasis formation increases in the craniocaudal direction. The more homogeneous distribution of atelectasis over a wide range of sectors in the upper cuts is replaced by an increasing dominance of alveolar collapse in sectors 1, 2, 11, and 12 as we move toward the diaphragm.

Figure 5 presents frequency of atelectasis per segment as documented during one representative observation (observer 1, first analysis) separated according to treatment group.

The agreement between observations 1 and 2 of the second observer was almost complete with a κ coefficient KIA of 0.956 (95% confidence interval, 0.928–0.985). The same intraobserver analysis for observer 1 revealed a KIA of 0.797 (0.723–0.871). Agreement be-

tween the first observations of both observers was fair at a KIA of 0.581 (0.488–0.673) and also for their second observation, with a KIA of 0.596 (0.505–0.687). Taking both measurements of each observer into account, the calculated interobserver KIA of 0.588 (0.524–0.653) at an n of 1,872 describes a clear agreement between the two independent observers.

Discussion

Main Findings

All patients in the ZEEP group and CPAP group showed atelectasis on MRI, whereas after an alveolar recruitment maneuver, only one patient showed a small area of lung collapse ($< 2 \text{ cm}^3$). These results confirmed a ventilation concept already known in the adult population: Airway pressure needs to exceed a critical opening pressure to effectively reexpand healthy but collapsed lung tissue since the mere application of CPAP does not reverse lung collapse.^{13,14} Using a sufficient PEEP level after recruiting keeps the lung open,^{14,15} provided that the level of CPAP remains above the critical collapse pressure.

Of interest is that the CPAP group showed a higher atelectasis volume than the ZEEP group. Gattinoni *et al.*²⁴ and Puybasset *et al.*,²⁵ using CT in patients with

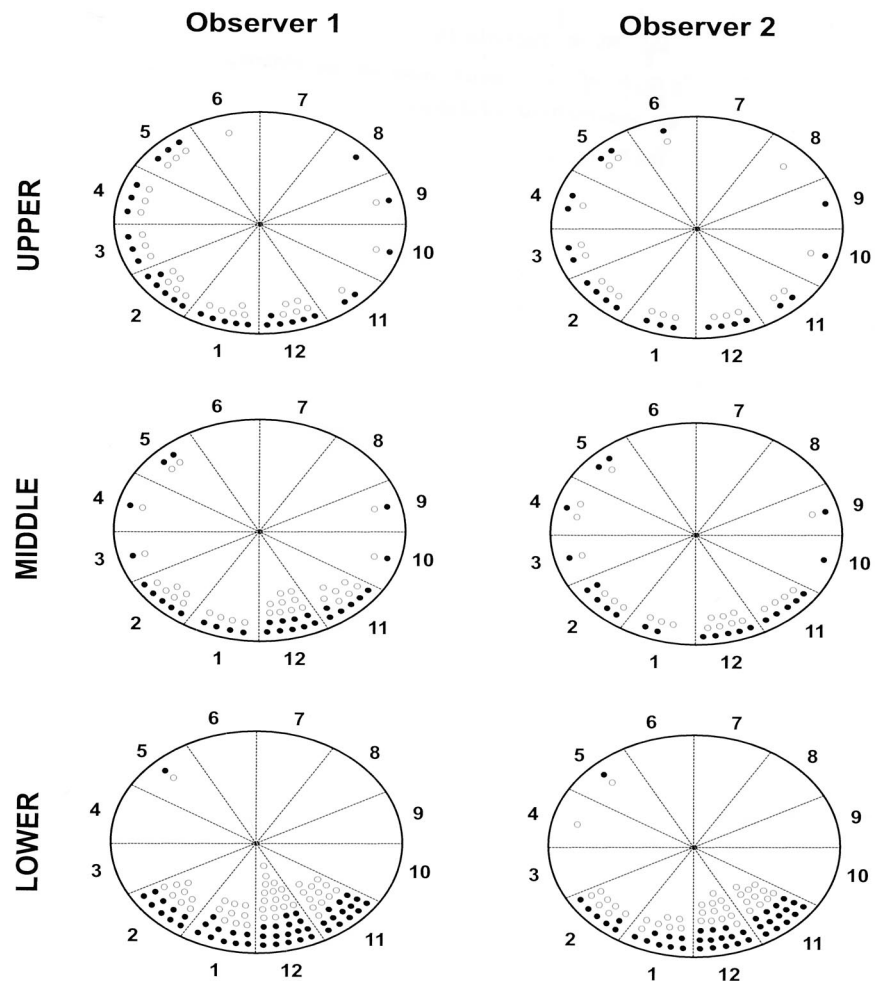


Fig. 4. Cumulative frequency of atelectasis for all 26 patients and all observations in each one of the 12 segments; a dot representing an atelectasis found during one of a total of two independent observations by the same observer separate for solid dot = first analysis, and open dot = second analysis.

acute respiratory distress syndrome, demonstrated that PEEP increased the amount of noninflated tissue in the most dependent zones of the lungs, suggesting that PEEP may be associated with alveolar collapse related to local compression atelectasis by overdistracted upper lobes. Our results are in agreement with these studies, although our patients were healthy children treated with only 5 cm H₂O of CPAP. Another possibility is the presence of more basal atelectasis in the CPAP group independent of randomization, but we are unable to prove this because we did not obtain baseline images.

In healthy anesthetized adults, the PIP needed to recruit alveoli is around 40 cm H₂O,^{1,13,14} and, ideally, this target PIP pressure should have been reached in all children. We have not measured airway opening and closing pressures in our patients; we assumed that in children, these pressures would be similar to the ones of adults. The high thoracic compliance in children younger than 7 yr of age could allow that 40 cm H₂O of peak pressure may easily achieve complete lung recruitment. On the other hand, a lower pulmonary compliance related to underdeveloped lung parenchyma, small airway diameter, and smaller alveoli^{26,27} would have

required an elevated PIP to reach a total recruitment. These theoretical considerations were well studied by Neureckas *et al.*²⁸ and Gaver *et al.*²⁹ They demonstrated that an airway of smaller radius required a greater opening pressure than a larger one. It remains to be explored whether lower levels of PIP are necessary for lung recruitment in healthy pediatric patients.

We previously described a well-standardized recruitment maneuver performed with a ventilator.¹⁴ Because our ventilator is not compatible with the magnetic environment, we performed this maneuver manually; therefore, the control of the applied inspiratory pressures was somewhat limited. This fact could explain why a small area of collapse persisted in one child of the ARS group.

The distribution of lung collapse showed characteristic patterns. In general, atelectasis predominated in the dependent parts of both lungs and usually reached all the way from the diaphragm up to the lung's apex. The presence of atelectasis, particularly located in sectors 1, 2, 11, and 12, could be associated with gravitational phenomena. There was a predominance of left lung atelectasis in the lower axial cuts (zones 11 and 12). A more homogeneous distribution of atelectasis was evi-

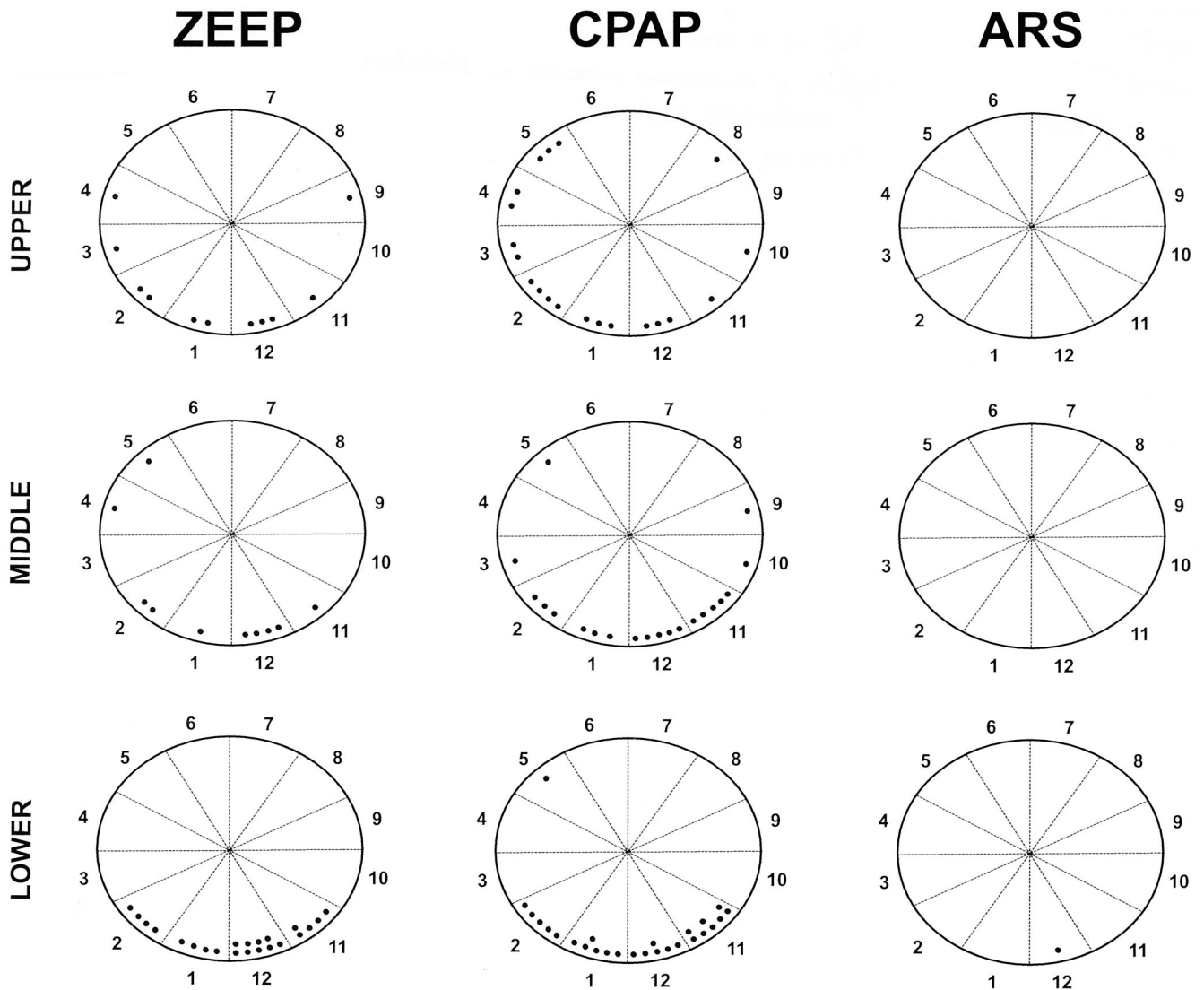


Fig. 5. Frequency of atelectasis per segment as documented during one representative observation (here observer 2, observation 1) separated according to treatment group.

dent in the cranial portions of the lungs, with small differences between the anterior and posterior zones, suggesting an association with nongravitational influences (fig. 4).

Also, there was more atelectatic tissue within the right upper and middle lobes (superior axial cut, corresponding to sectors 3, 4, 5, and 6). These findings are in good agreement with the observations made in children undergoing mechanical ventilation in intensive care units who present a high incidence of atelectasis in the right upper lung.³⁰⁻³² The underlying reason for this anatomical distribution is a matter of controversy: The most common factor is, by far, the intubation of the right mainstream bronchus, occluding the origin of the right upper lung bronchus. However, in our study, the correct position of the endotracheal tube was assessed by a coronal view (frontal scout) at the beginning of the study period, ruling out this mechanism in our patients.

The possibility of lung injury resulting from high airway pressures has to be balanced against the benefit of the recruitment maneuver performed in patients with small amounts of atelectatic lung. Recent clinical and experimental studies have clearly demonstrated that the application of high positive pressure and tidal volumes to lungs that are partially atelectatic and aerated at zero end-expiratory pressure may result in alveolar recruitment of collapsed lung regions and simultaneously in overdistension of noncollapsed lung areas.³³⁻³⁸

We have demonstrated the intraoperative benefits of the recruitment maneuver, which increased both arterial oxygenation and respiratory compliance.¹⁴ Persistence of lung collapse in the early postoperative period could be related to hypoxemia and to potential postoperative complications, like pneumonia, perioperative acute myocardial infarction,³⁹ central nervous system dysfunction,⁴⁰ and wound infection.⁴¹ To our knowledge, no

outcome data exist on the treatment of intraoperative atelectasis with recruitment maneuvers. Despite their proven positive and immediate impact on lung physiology, neither benefits nor harm of such procedures were systematically documented for the postoperative period. This essential question needs to be addressed in future studies.

Another theoretical problem of high-pressure ventilatory strategies is hemodynamic compromise. High intrathoracic pressure can interfere with hemodynamics. Noninvasively measured arterial pressures, pulse oxymetry, and audible cardiac tones showed no significant changes during periods of high airway pressures.

Methodological Considerations and Study

Limitations

Molecular structures differ between tissues like blood, fat, bone, and muscle. Each molecular configuration has a characteristic relaxation time while exposed to a magnetic field, allowing its recognition by changes in its densities. Fisher⁴² and Gamsu *et al.*⁴³ have demonstrated that MRI can easily differentiate between these normal anatomic structures.

Since air and oxygen atoms are not magnetic, normal, hypoventilated, and overdistended lung areas are not visible with MRI; therefore, it is impossible to make a differential diagnosis between different ventilated lung zones. However, these quantitative investigations are possible using CT analysis of lung density. Since Hedenstierna *et al.*^{3,5,7} have addressed the issue of different lung densities in various CT studies, we did not concentrate on this aspect of alveolar collapse in this present investigation.

On the other hand, MRI is useful to evaluate all types of parenchymal consolidations because more H⁺ protons are present in these zones. Regarding parenchymal consolidations, MRI is known to be superior to CT in making a differential diagnosis. *In vitro* and *in vivo* studies have demonstrated the ability of MRI to differentiate between lung pathologies, including atelectasis. For example, Herold *et al.*²¹ demonstrated the role of MRI in diagnosing atelectasis and were even able to distinguish between obstructive and nonobstructive atelectasis, a differentiation not likely to be obtained by traditional CT imaging. Tobler *et al.*,¹⁹ comparing CT *versus* MRI in the diagnosis of atelectasis, found no difference between the two methods. MRI also allowed differential diagnosis of atelectasis in pathology samples. Shioya *et al.*²² demonstrated that MRI could recognize different kinds of tissues, including normal collapsed lung; their results showed that T2-weighted sequences were most valuable in discriminating tumor tissue from collapsed lungs.

Due to their lack of cooperation, all children needed general anesthesia before undergoing cranial MRI investigations. For the same reason, we lack control lung images prior to the anesthetic induction, which repre-

sents a major limitation of the present study. Previous studies using CT images demonstrate that approximately 90% of patients undergoing general anesthesia develop atelectasis.³ The presence of atelectasis in 100% of our patients in the ZEEP and CPAP groups confirms that the same observation is valid for children. There is no reason to think that seven of eight children in the ARS group did not develop atelectasis after anesthetic induction.

Diagnosis and localization of atelectasis were performed visually by the radiologist; therefore, subjectivity is an important limitation of the present study. Digital calculation of the atelectatic volumes was not available. Thus, measurements had to be performed manually after the study was completed. This gives rise to differences within and between the observers. Nevertheless, these differences did not reach statistical significance. The calculation of atelectatic volume is approximate since the shape of the atelectatic zones was not geometrically well defined. Regarding atelectasis localization, there is a limited precision with which the transparent template could be placed onto the images. The slightest deviation from the true center or a slight rotation shifted the lines separating the 12 sectors to another location on the image. Thus, during the four observations, the same lung zone on the MRI scan may be divided slightly differently by the radial line of the template. Therefore, adjacent sectors could show atelectasis in one analysis but none in the next one. Despite these limitations, agreement between observers was good, while that between the two observations of each observer was high, reaching almost entire identity in observer 2.

F_{IO₂} was kept at 100% during the entire study period, according to standard recommendations for general anesthesia in the MRI environments.^{44,45} It is known that high oxygen concentrations cause “absorption” atelectasis. Rothen *et al.*⁴⁶ demonstrated that the use of 100% F_{IO₂} for ventilating lungs after a recruitment maneuver caused a redevelopment of atelectasis within 5 min after the recruitment, while ventilating lungs with 40% oxygen mixed with nitrogen delayed the redevelopment of alveolar collapse. Atelectatic lung zones—approximately 40% of the initial size—reappeared after 40 min. However, PEEP levels above the collapse pressure keep the lung open regardless of the F_{IO₂} used.⁴⁷ In the ARS group, images were obtained approximately 40 min following the recruitment strategy at 100% F_{IO₂}. Despite the high oxygen concentration also in this group, there was no evidence of reoccurrence of alveolar collapse.

Conclusions

1. MRI is an effective method for studying atelectasis three-dimensionally during general anesthesia.
2. Frequency of atelectasis was much less following the alveolar recruitment strategy compared with children who did not have the maneuver performed.

3. Similar to the adult population, in children, the distribution of atelectasis prevailed in more caudal and dependent lung zones. In the cranial parts of pediatric lungs, atelectasis predominated in the upper right lung zones.

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