Accuracy of Transthoracic Lung Ultrasound for Diagnosing Anesthesia-induced Atelectasis in Children

Cecilia M. Acosta, M.D., Gustavo A. Maidana, M.D., Daniel Jacovitti, M.D.,
Agustín Belaunzarán, M.D., Silvana Cereceda, M.D., Elizabeth Rae, M.D., Ananda Molina, M.D.,
Sergio Gonorazky, M.D., Stephan H. Bohm, M.D., Gerardo Tusman, M.D.

ABSTRACT

Background: The aim of this study was to test the accuracy of lung sonography (LUS) to diagnose anesthesia-induced atelectasis in children undergoing magnetic resonance imaging (MRI).

Methods: Fifteen children with American Society of Anesthesiology's physical status classification I and aged 1 to 7 yr old were studied. Sevoflurane anesthesia was performed with the patients breathing spontaneously during the study period. After taking the reference lung MRI images, LUS was carried out using a linear probe of 6 to 12 MHz. Atelectasis was documented in MRI and LUS segmenting the chest into 12 similar anatomical regions. Images were analyzed by four blinded radiologists, two for LUS and two for MRI. The level of agreement for the diagnosis of atelectasis among observers was tested using the κ reliability index.

Results: Fourteen patients developed atelectasis mainly in the most dependent parts of the lungs. LUS showed 88% of sensitivity (95% CI, 74 to 96%), 89% of specificity (95% CI, 83 to 94%), and 88% of accuracy (95% CI, 83 to 92%) for the diagnosis of atelectasis taking MRI as reference. The agreement between the two radiologists for diagnosing atelectasis by MRI was very good (κ, 0.87; 95% CI, 0.72 to 1; $P < 0.0001$) as was the agreement between the two radiologists for detecting atelectasis by LUS (κ, 0.90; 95% CI, 0.75 to 1; $P < 0.0001$). MRI and LUS also showed good agreement when data from the four radiologists were pooled and examined together (κ, 0.75; 95% CI, 0.69 to 0.81; $P < 0.0001$).

Conclusion: LUS is an accurate, safe, and simple bedside method for diagnosing anesthesia-induced atelectasis in children. (ANESTHESIOLOGY 2014; 120:1370-9)

ATELECTASIS is a side effect of general anesthesia which can be found in all types of interventions and patients of all ages.[1–4] The reported incidence of anesthesia-induced atelectasis in children varies, ranging from 12 to 42% in sedated and nonintubated patients[5,6] and from 68 to 100% in children with general anesthesia with tracheal intubation or laryngeal mask.[3–8]

Such lung collapse causes arterial blood oxygenation to decline during and after anesthesia.[9–11] Although anesthesia-induced atelectasis resolves spontaneously in children with American Society of Anesthesiology's (ASA) physical status classification I to II after minor surgical procedures, this entity may persist in the postoperative period in high-risk children undergoing complex surgeries.[12] In the latter population, atelectasis potentially increases the risk for ventilator-induced lung injury[13,14] and could be associated with postoperative pulmonary complications.[12–17]

Despite its high prevalence during anesthesia, bedside diagnosis of atelectasis remains challenging. Anesthesia-induced atelectasis is commonly small and thus mostly invisible on standard chest radiograph, whereas it can easily be diagnosed by tomographic imaging techniques such as computed tomography or magnetic resonance imaging (MRI). However, these latter are clinically

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What We Already Know about This Topic

- Atelectasis is seen in the majority of children and adults undergoing general anesthesia

What This Article Tells Us That Is New

- Using magnetic resonance imaging as the standard, bedside ultrasound had a positive predictive value of 71%, a negative predicted value of 96%, a sensitivity of 88%, and specificity of 89% for the diagnosis of anesthesia-induced atelectasis

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impractical, expensive, time-consuming, and with harmful exposition to x-ray.[3–8]

Sonography is a simple, noninvasive, and radiation-free methodology which has gained increasing usage in daily practice. Lung sonography (LUS) plays an important role in diagnosing pulmonary diseases in children, including obstructive and compressive atelectasis of different origins.[18–22] To our knowledge, the role of LUS for detecting anesthesia-induced atelectasis in children has not been determined before.[20–22] Yet, the clinical implications of a simple reliable bedside diagnosis of atelectasis are important. Just as in adults, LUS could identify children needing a recruitment maneuver to reexpand their lungs and help optimize ventilator treatment during anesthesia.[23,24] In addition, LUS

could identify critically ill children with high risk for developing pulmonary complications due to residual atelectasis after surgery.[12,15–17]

The aim of this pilot observational study was to define the accuracy, sensitivity, and specificity of LUS for diagnosing anesthesia-induced atelectasis in children. For this purpose, we investigated anesthetized children scheduled for cranial MRI studies taking additional chest MRI images as reference for the concomitant LUS studies. Thereafter, independent staff radiologists compared pairs of chest MRI and LUS images.

Materials and Methods

After approval by the Institutional Review Board (Mar del Plata, Buenos Aires, Argentina), we prospectively studied a consecutive series of children with general anesthesia for MRI studies. The inclusion criteria were age between 1 and 7 yr old, ASA physical status I to II, corresponding written informed consent of the parents, and the need of programmed MRI of the head. The exclusion criteria were cardiac, pulmonary, and/or pleural diseases, upper airways infections, and diseases of the chest wall. This study was performed in the MRI environment of the Hospital Privado de Comunidad, Mar del Plata, Argentina.

Anesthesia and Monitoring

In 15 fasted children, general inhalatory anesthesia was induced in the presence of their parents without previous premedication. Anesthesia was induced by inhalation of sevoflurane in pure oxygen using a Mapleson D system with a flow of 200 ml kg^{-1} min^{-1} and an i.v. dose of 1 µg/kg fentanyl. A laryngeal mask of proper size was placed and its position checked by observing the motion of each hemithorax, the shape of the capnogram, and by chest auscultation. Spontaneous ventilation was kept during the entire study period without continuous positive airway pressure. After placing the patient onto the MRI table, anesthesia was maintained with sevoflurane 0.8 to 1 minimum alveolar concentration in a mix of 50% oxygen and 50% air at a flow rate of 400 ml kg^{-1} min^{-1} through a 7-m-long Bain system. Noninvasive blood pressure, airway pressures, and capnography were monitored using a S5 Datex monitor (GE, Helsinki, Finland). Pulse oxymetry was measured by a Nonin 7500 (Nonin Medical Inc., Plymouth, MA) approved for the MRI environment.

MRI Images

The MRI study was performed with a Siemens Magnetom Symphony MRI scanner 1.5 Tesla (Maestro Class, Erlangen, Germany). After the brain imaging, which lasted approximately 20 to 30 min, patients were repositioned such that they were lying supine in the body coil with their arms parallel to either side of the body. Thereafter, a frontal scout view of the thorax was obtained to confirm an optimal chest position within the coil. Chest scans consisted of (1) T2 coronal half-Fourier acquisition single-shot turbo spin echo images taken with a repetition time of 830 ms and an echo time of 96 ms and (2) T2 axial half-Fourier acquisition single-shot turbo spin echo imaging with a repetition time of 827 ms and an echo time of 116 ms. Coronal and axial slice thicknesses were 6 mm with a distance of 1.5 mm between them. To avoid artifacts from breathing movements, MRI imaging was synchronized with the end of inspiration using the device's respiratory triggering function. Each MRI sequence took approximately 2 min and depending on a child's respiratory rate prolonged the duration of anesthesia by approximately 5 to 10 min.

Magnetic resonance imaging image analysis was performed off-line by two independent blinded radiologists (A.B. and A.M) expert on MRI. Recorded Digital Imaging and Communication in Medicine images were handled using the eFilm 3.1.0 software (Merge Healthcare, Milwaukee, WI). As suggested in our previous MRI study,[8] we divided each axial cut into six equal sectors which radiated at identical angles from the center of the thorax to the periphery (fig. 1A) using a specific eFilm tool. First, the radiologists drew a vertical line through the middle of the thoracic vertebral body which divided the axial cut into two segments corresponding to the right and left lungs. Then, two oblique lines were placed through the midpoint of the vertical line at angles of 60° and 120°, respectively. This way each half was further divided into an anterior, a lateral, and a posterior segment. By drawing a horizontal line crossing the inferior border of the carina (fig. 1B), the coronal view was divided into a cranial and a caudal segment. Thus, each MRI examination was subdivided into 12 equal regions consisting of 6 regions for the caudal and 6 for the cranial lung.

On T2 images, normally aerated lung tissue appears as *hypointense* (black) because the nonmagnetic oxygen atoms do not create a signal, whereas atelectatic lung tissue shows up as *hyperintense* (white).[8] Anesthesia-induced atelectasis primarily appears in gravity-dependent subpleural areas and usually follows a classical radial subsegmental or segmental distribution. Using both the coronal and the axial cuts, the radiologists recorded on a chart the presence or absence of atelectasis in each one of the 12 lung subsegments. As each cranial and caudal lung segment comprised at least five to six axial scans, the radiologists recorded a positive diagnosis of atelectasis within a subsegment whenever signs of atelectasis could be found on at least one of the axial scans.

LUS Images

After the MRI study, patients were removed immediately from the MRI environment and LUS was performed with the portable echograph MicroMax (SonoSite, Bothell, WA) using a linear probe of 6 to 12 MHz. This probe allows high-resolution images with a selected depth of 4 cm. The chest was divided into 12 regions that matched with those evaluated by MRI (fig. 1C). Each hemithorax was divided into six sections using three longitudinal lines (parasternal, anterior, and posterior axillary) and two axial lines,
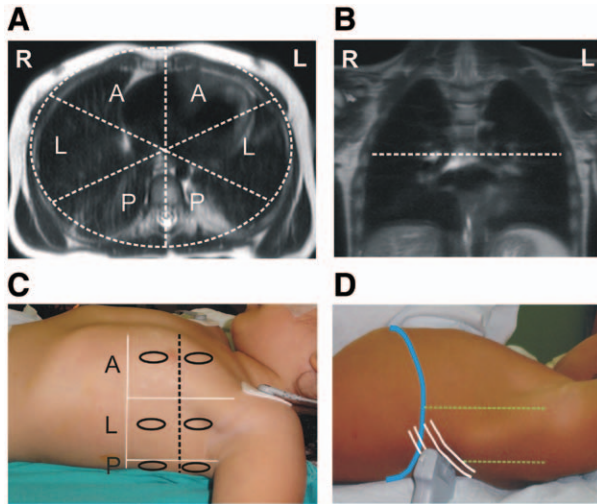
Fig. 1. Segmentation of magnetic resonance images (MRI) and lung sonographic images (LUS). (*A*) Axial MRI slices were first divided by a vertical midline and then divided into anterior (A), lateral (L), and posterior (P) segments. (*B*) Using a coronal MRI view, the lungs were divide into a cranial and a caudal region. (*C*) LUS examinations were performed in similar chest regions as the MRI analysis. The *dotted black axial line* divided the lungs into a cranial and a caudal region. Parasternal, anterior, and posterior axillary lines segmented the lungs into anterior (A), lateral (L), and posterior (P) segments. *Ellipses* depicted locations (midclavicular, lateral, and posterior axillary) where the probe LUS probe was placed during examinations with the classical LUS approach. (*D*) The posterior caudal regions were also assessed using an intercostal posterobasal view, which does not require the body position to be changed. The arms were displaced above the head and the probe was placed at the posterior axillary lines within the intercostal space right above the diaphragm.

one above the diaphragm and another one 1 cm above the nipples. As LUS provides regional information, we repeated the following examination sequence in each hemithorax and in all patients: (1) anterior, (2) lateral, and (3) posterior regions starting from the diaphragm (caudal lung) and moving toward the apex (cranial lung).[15,18] Each hemithorax was assessed using the two-dimensional classical view placing the probe perpendicular to the ribs looking for the *bat sign*, the pleura and lung tissue between the acoustic shadows of two adjacent ribs.[25] The LUS of a normal lung shows a *lung sliding* (caused by the respiratory movement of the visceral pleura relative to the fixed parietal pleura) and *A lines* (repetitive horizontal reverberation artifacts generated by air within the lungs separated by regular intervals, the distances of which being equal that between the skin and the pleural line).[25]

In addition to the above mentioned, we also applied an *intercostal posterobasal* (IPB) view for an improved assessment of posterior paradiaphragmatic atelectasis. The IPB view was explored placing the probe transversally within the intercostal space above the corresponding hemidiaphragm and immediately below the posterior axillary line (fig. 1D).

This way the posterior regions could always be assessed in supine position without having to change the patient's body positioning which may potentially have led to a redistribution of atelectasis.[1]

As LUS has never before been described for the assessment of anesthesia-induced atelectasis, we elected to diagnose this entity based on well-known LUS signs previously described for other forms of pulmonary consolidations[25–29] and based also on our own experience. We therefore postulated that anesthesia-induced atelectasis would be associated with the following LUS signs (fig. 2):

- Localized iso- or hypoechoic areas as compared with the highly reflective or anechoic normally aerated lung tissue.[25–29] This *consolidation* or tissue-like pattern is caused by a loss of lung aeration. It commonly arises from the pleural line and thus can be described as *juxtapleural consolidations* of various sizes (fig. 2, C–F).
- Static *air bronchograms* are observed as bright echogenic branching structures within these lung consolidations (fig. 2, C–D).[25,28,29]
- The *juxtapleural consolidations* commonly erases the typical normal A lines and a few focal *B lines* (vertical, laser-like lines that erase normal A lines) can be observed below them (fig. 2, C–F).[25,30]
- The lack of local respiratory movement or *lung sliding* and the presence of the *pulse sign* (a small motion within the lungs caused by the transmission of heart beats through the atelectatic area) are sometimes observed in large atelectatic areas.[25–27]

Therefore, anesthesia-induced atelectasis was diagnosed *a posteriori* as juxtapleural consolidations of various sizes. Such atelectasis can be associated with other LUS signs such as air bronchograms, absence of A lines, presence of line B, absence of lung sliding, and presence of the pulse sign.

Two independent blinded radiologists (S.C. and A.R.) unaware of the MRI findings analyzed the LUS image sequences for each lung region. The presence or absence of atelectasis in each lung region was registered on a chart. As both the posterior classical LUS view and our novel IPB view analyze the same posterior lung regions, the radiologists recorded a positive diagnosis if atelectasis was found in at least one of these views.

Statistical Analysis

Data were analyzed using the program Stats Direct (Altrincham, Cheshire, United Kingdom) software version 2.7.2 for Windows. Only pairs of LUS and the reference MRI images were included in the analysis. The level of agreement between the two observers for LUS and the two observers for MRI was analyzed using the total agreement observed and the κ reliability test.[31] The κ test was also used to assess the degree of agreement between the four observers using the Fleiss–Cuzick extension.[32] In this particular case, we treated all the raters symmetrically and supposed that none is definitive standard. Values for κ 0.20 or less indicate poor
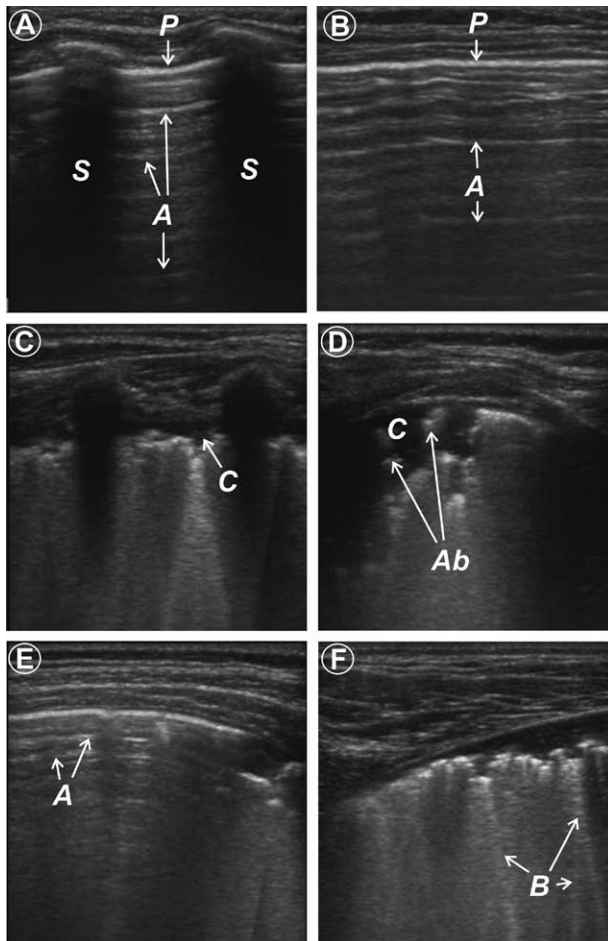
Fig. 2. Lung sonographic signs associated with anesthesia-induced atelectasis. (*A*) The classical lung sonographic approach showing the *bat sign* in normal lungs: the pleural line (*P*) appears as a *hyperechoic blunt, thick, and flat horizontal line* between the ribs. Typical A lines appear as repetitive *bright horizontal lines* below the pleural line and between the acoustic shadows (*S*) of both ribs. (*B*) Normal lung viewed by the intercostal posterobasal approach showing the pleural line (*P*) and A lines but without the acoustic shadows of the ribs. (*C* and *D*) Anesthesia induced-atelectasis is commonly observed as hypoechoic juxtapleural consolidations (*C*) in both, the classical and the intercostal posterobasal approach, respectively. Air bronchograms (Ab) can be observed within the consolidation in *D*. (*E* and *F*) The hyperechoic limit of the juxtapleural consolidation is wrinkled because it is the interface between the aerated and nonaerated lung parenchyma. A few B lines originating from an atelectasis erase the normal A lines. For more details see text.

agreement, between 0.20 to 0.40 fair agreement, between 0.40 to 0.60 moderate agreement, between 0.60 to 0.80 good agreement, and 0.80 or greater very good agreement between raters. For each κ, a 95% CI was determined and a *P* value less than 0.05 was considered statistically significant.

Diagnostic test 2×2 table was used for the assessment of sensitivity = [TP/(TP + FN)] × 100; specificity = [TN/(FP + TN)] × 100; positive predicted value = [TP/(TP + FP)] × 100; negative predicted value = [TN/(TN + FN)] × 100; and

diagnostic accuracy = [(TP + TN)/(TP + TN + FP + FN)] × 100; where *TP* is true positive, *TN* is true negative, *FP* is false positive, and *FN* is false negative.

Results

Since November 1, 2012 to March 1, 2013, 15 patients (6 women and 9 men), with ASA physical status I, aged 4.5 ± 2 yr, and weighing 20.5 ± 7 kg were successfully studied (fig. 3). The mean study time was 43 ± 11 min without any clinical complications occurring during and after anesthesia.

Magnetic resonance imaging and LUS images of 180 pairs from the different lung regions (12 regions per patient in a total of 15 patients) were included in the analysis. MRI images revealed atelectasis in 39 of 168 respective lung regions of 14 patients (93%). Most of them were crescent-like or subsegmental originating from the subpleural areas. LUS detected atelectasis in the same 14 patients. Figure 4 depicts the spatial distribution of atelectasis for all patients showing a good match between both methodologies. Anesthesia-induced atelectasis prevailed in the dependent predominantly caudal lung areas.

Figure 5 shows the LUS images of the only patient without atelectasis in comparison with one representative patient suffering from atelectasis in the posterior caudal right lung.

Juxtapleural consolidations of various sizes were diagnosed by both radiologists who ranked this sign the most common LUS sign of atelectasis in this study. Table 1 presents the prevalence of the additional LUS signs in those patients in whom anesthesia-induced atelectasis was found. The presence of B lines was the commonest additional LUS sign, whereas the lack of lung sliding and the pulse sign was found in less than half of the cases.

The statistical agreement between the two radiologists who diagnosed atelectasis by MRI and the two analyzing LUS was very good (MRI: κ, 0.87; 95% CI, 0.72 to 1; *P* < 0.0001 and LUS: κ, 0.90; 95% CI, 0.75 to 1; *P* < 0.0001, respectively). When data from the four radiologists were pooled and examined together, we found a good agreement between MRI and LUS (κ, 0.75; 95% CI, 0.69 to 0.81; *P* < 0.0001).

Lung sonography showed a sensitivity of 88% (95% CI, 74 to 94%) and a specificity of 89% (95% CI, 83 to 94%) for the diagnosis of anesthesia-induced atelectasis. The positive predicted value was 71% (95% CI, 56 to 83%) and the negative predicted value was 96% (95% CI, 91 to 99%). LUS revealed four false-positive results in the anterior and lateral regions of the cranial right lung. On the contrarily, LUS failed to diagnose atelectasis in 15 cases (false negatives) in the posterior regions of the cranial right and left lungs. The calculated accuracy of LUS for the diagnosis of atelectasis in all children studied was 88% (95% CI, 83 to 92%).

Discussion

The main finding of this pilot study was that LUS accurately identified anesthesia-induced atelectasis in children.
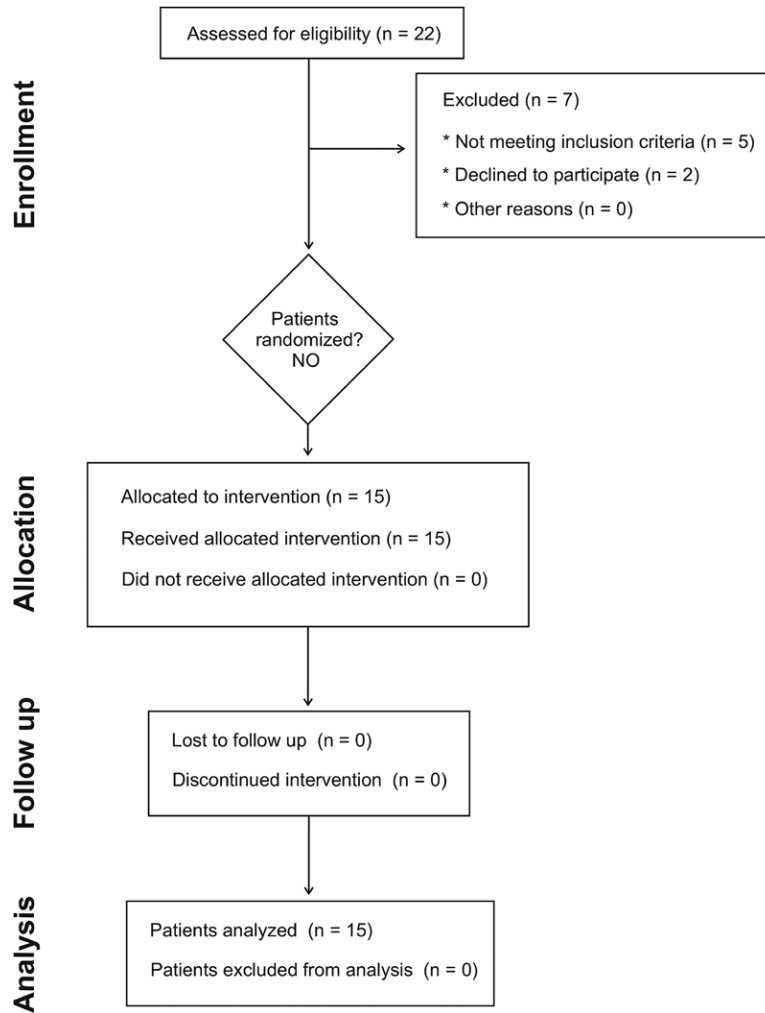
Fig. 3. The CONSORT flow diagram.

We demonstrated a good interobserver agreement between MRI and LUS for detecting atelectasis, which implies that LUS, despite its subjectivity and operator dependency, can be used as an easy-to-use, noninvasive, radiation-free bedside diagnostic tool helping anesthesiologists detect and treat atelectasis in the perioperative period.

Determination of the *accuracy* of a diagnostic test—in this case that of LUS for diagnosing anesthesia-induced atelectasis—is the most common way to assess and critically appraise the diagnostic value of any test. The accuracy is determined by the rates of true- and false-positive as well as true- and false-negative results. The sensitivity or true-positive rate is defined as the proportion of lung regions classified by LUS as having atelectasis among those with proven atelectasis on the MRI scans, whereas the specificity or true-negative rate is the proportion of lung regions classified by LUS as not having atelectasis among those in which the presence of atelectasis was already excluded by MRI. The 88% sensitivity and 89% specificity found in our study are similar to the ones reported for diagnosing consolidations of other causes by LUS.[27–30,33]

We found 4 false-positive and 15 false-negative incidences of atelectasis in 180 lung regions evaluated by LUS. These false-positive and false-negative findings were always located in cranial lung segments.

Some factors could explain these false diagnoses. A false-positive diagnosis of atelectasis for a tested region may be due to the fact that the square image generated by the linear probe can show atelectasis in an adjacent region, whereas the echo probe is moved over a region without atelectasis. Despite the limited depth of 4 cm of the linear probe, such image overlap is easily explained by the small thoracic dimensions of the young children examined in this study. Xirouchaki *et al.*[34] observed the same problem of overlapping images when diagnosing consolidations by LUS in critically ill adult patients.

The relatively higher rate of false negative, thus undetected atelectasis, may be explained by the fact that small atelectasis can be hidden within the rib's acoustic shadows whenever the longitudinally oriented probe placed in the classical way crosses a rib. The problem is solved by using the IPB view where the linear probe is placed within the intercostal
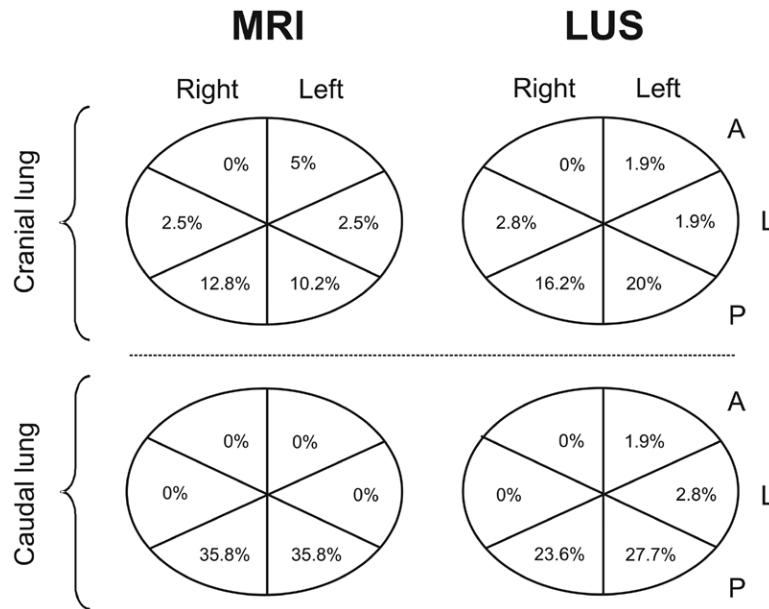
Fig. 4. Distribution of anesthesia-induced atelectasis in magnetic resonance images (MRI) and lung sonographic images (LUS). To facilitate comparisons between LUS and MRI, the lungs were divided into 12 segments, an anterior (A), lateral (L), and posterior (P) segment for both lungs which were further subdivided into cranial and caudal subsegments. The numbers within each one of the lung segments represent its respective percentage (mean value of two radiologists) of the total amount of atelectasis found.
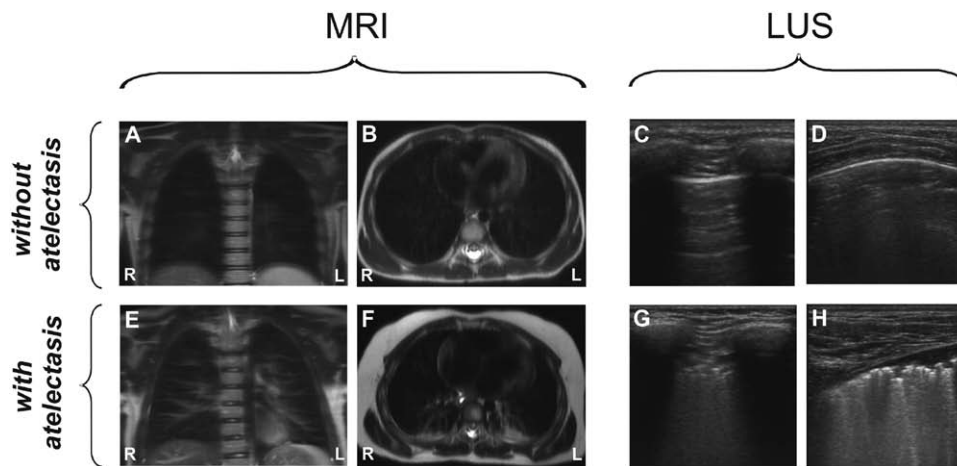
Fig. 5. Example of a lung sonography (LUS)–based diagnosis of atelectasis. (*A–D*) The *upper row of images* belongs to the only patient who did not develop atelectasis, whereas the *lower images* (*E–H*) belong to a representative patient with anesthesia-induced atelectasis. In both cases, the coronal and axial reference magnetic resonance images (MRI) images clearly confirm the presence or absence of atelectasis. The LUS images were taken in the posterior regions of the caudal right lung where atelectasis was most prevalent. Images generated by the classical LUS approach show the typical *bat sign* (*left LUS images*). The intercostal posterobasal view is not limited by the acoustic shadows of the ribs but openly exposes the normal lung (*upper image*) and consolidations (*lower image*) (*right LUS images*).

space, thus avoiding the rib's acoustic shadows. The effects of the two probe placements are depicted in one example in figure 6. We believe that the lack of false-negative diagnose in the inferior lung regions was due to the use of the IPB—an approach that was not applied in the superior lungs.

The *accuracy* of LUS for diagnosing anesthesia-induced atelectasis (the proportion of true-positive and true-negative rates) was 88% because LUS was fairly good at correctly identifying lung regions with and without atelectasis, whereas the rate of incorrect diagnosis was quite low. It is difficult to compare our results with other studies because, to our knowledge, LUS has never before been used to study anesthesia-induced atelectasis. However, our results match with the findings of several authors who described a high accuracy of LUS for detecting pulmonary consolidations of other causes comparing LUS with computed tomography as the definitive standard.[27,34] Comparing LUS with plane chest films, Zanobetti *et al.*[35] reported the agreement

Table 1. Prevalence of LUS Signs of Atelectasis in Children

LUS Signs	Observer 1 Total Observations = 55		Observer 2 Total Observations = 50	
	Number of Observations	Percentage of Total	Number of Observations	Percentage of Total
Juxtapleural consolidations	52	95 % (84–98)	49	98 % (89–99)
Absence of A lines	49	89 % (75–94)	44	88 % (73–94)
Presence of B lines	50	91 % (77–95)	45	90 % (78–96)
Air bronchograms	38	69 % (53–79)	35	70 % (55–82)
Absence of lung sliding	22	40 % (27–54)	22	44 % (29–58)
Presence of the pulse sign	22	40 % (27–54)	22	44 % (29–58)

The prevalence of LUS signs of atelectasis expressed as percentage of all observations and 95% CIs (in parenthesis).
LUS = lung sonography.
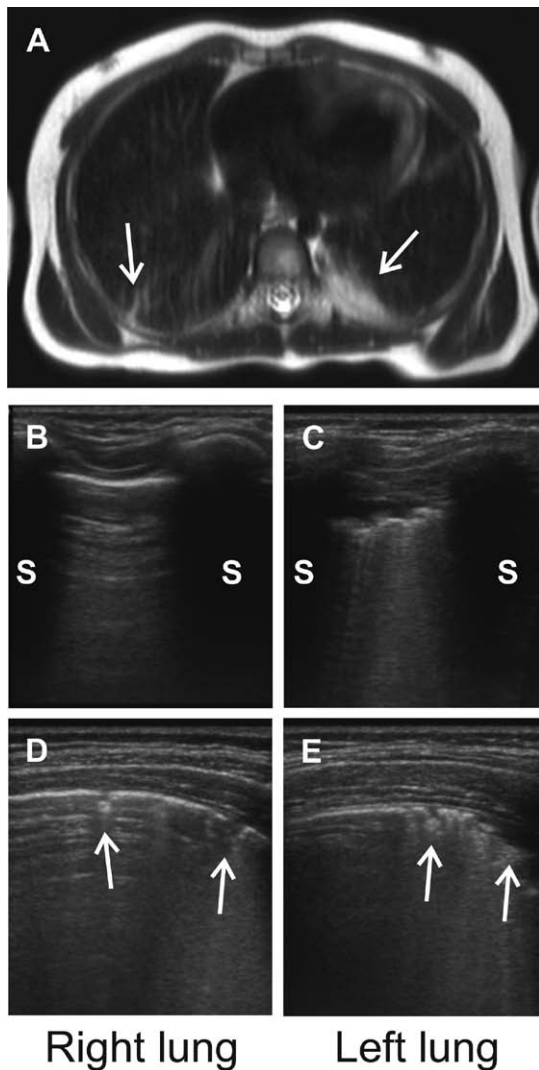
Fig. 6. Comparison of the classical LUS with the intercostal posterobasal approach in the posterior region in a case with small right and larger left dorsal atelectasis. In this patient, the big atelectatic area seen in the left lung on the magnetic resonance image scan (*A*) was easily detected by both the classical (*C*) and the intercostal posterobasal (*E*) approaches. A small atelectasis in the right lung (*arrows*) detected by the intercostal posterobasal view (*D*) was hidden below the ribs' shadows (S) when using the classical LUS view (*B*). LUS = lung sonography.

between both methods for diagnosing consolidations to be 70%. However, the authors emphasized that LUS was better than radiograph at distinguishing between consolidations of different origin such as atelectasis and pneumonia. However, Lichtenstein *et al.*[33] reported that the specificity of chest radiograph for diagnosing pulmonary consolidations was 95% and similar to the one of LUS (98%) but with a sensitivity of only 68%.

Most of the anesthesia-induced atelectasis we found were small compared with other types of consolidations such as pneumonia. The pathophysiology behind this entity of atelectasis differs from that of other consolidations and explains the qualitative and quantitative differences in the additional LUS signs between anesthesia-induced atelectasis and other consolidations. Thus, the most prevalent LUS sign we found was the presence of juxtapleural consolidations of different sizes. The LUS pattern of anesthesia-induced atelectasis seems to be quite different from the one observed in pneumonias because these consolidations are usually not only larger in size but often accompanied by pleural effusions and surrounding areas of compressive and/or obstructive atelectasis.[25,27]

For the same reasons, air bronchograms are much easier to recognize in larger consolidations than in the rather small anesthesia-induced atelectasis. The acoustic interface between the bronchial walls, the air within them and the collapsed alveoli produces strong linear reflections which characterize air bronchograms as short bright echogenic structures. The air bronchograms of pneumonias look different from those of anesthesia-induced atelectasis due to fluid-filled alveoli, interstitial edema, and mucus within the bronchial lumen.[28,29] The bronchograms in pneumonias are commonly larger, show a branching structure and are dynamic.[29]

Two additional LUS signs frequently seen were the absence of A lines and the presence of B lines below the atelectatic area. As subpleural consolidations could sometimes be found only on small parts of the LUS display, it was common to see normal A lines on large portions of the LUS images next to a small focal atelectatic area (fig. 2E). The classical B lines originate from reverberations as the ultrasound beam is reflected at interlobular septa thickened by extravascular lung

water.[21,25,36–39] Thereby, the most common cause of B lines is pulmonary edema due to left heart failure, but other lung pathologies are also known to cause them as lung inflammation.[40,41] The B lines we observed in anesthesia-induced atelectasis born in subpleural consolidations. However, the few B lines we found differed from the many B lines observed in alveolar-interstitial pathologies.[21,25,36–39] We believe that the few B lines we saw are also related to the reverberation phenomenon caused by air and surfactant material trapped within the collapsed tissue.[41] To our knowledge, this is the first time B lines are observed in the absence of increased extravascular lung water or inflammation. Thus, B lines likely attest of poorly aerated lung zones whatever the causative mechanism, making LUS useful for assessing changes in lung aeration.

The other LUS signs associated with anesthesia-induced atelectasis are the pulse sign and the absence of lung sliding. Both signs have the same origin: the lack of local respiratory movements which has already been described for large subpleural consolidations.[26] However, anesthesia-induced atelectasis is not necessarily associated with these signs because atelectasis is focal and often too small to prevent respiratory movement in the pleural space behind it which could explain why we observed a low prevalence of these LUS signs in our patients.

Limitations

This study has some limitations. First, most of the children undergoing MRI studies are patients with ASA physical status I to II in whom intraoperative atelectasis rarely has clinical repercussions for the time period after anesthesia. This population does not represent critically ill children (ASA physical status III to IV) undergoing major and complex surgeries. In these sick patients, anesthesia-induced atelectasis can persist in the postoperative period thereby contributing to pulmonary complications and patient morbidity.[14–17] Because the objective of this study was the determination of the accuracy with which LUS detects anesthesia-induced atelectasis, we believe that it does not matter which ASA class of children was studied as long as they develop atelectasis. Thus, the objective of this study was reached because 93% of our patients with ASA physical status I to II showed signs of atelectasis during anesthesia.

Second, the number of subjects studied was small due to the inherent complexity of performing such protocols in children. However, the fact that we evaluated 180 paired LUS and in MRI lung segments should partially compensate this limitation.

Third, although the condition of independence of the observers was certainly accomplished, we assumed that each 1 of the 180 segments analyzed represented an independent observation. Such independency is debatable and therefore the κ values presented might have been different if a dependency among the segments were considered. Despite this potential limitation, we believe that the high degree of agreement between the results found by the independent observers as reflected by the κ values supports the approach taken in this study.

Fourth, spontaneous ventilation without positive airway pressure during anesthesia favors the development of atelectasis although the mere use of positive end-expiratory pressure cannot assure the absence of atelectasis.[6,8] According to newest evidence from a large population of anesthetized adults, ventilation without positive end-expiratory pressure should be discouraged.[42] However, considering that even low levels of positive end-expiratory pressure[7] are able to reduce the overall incidence of atelectasis, the lack of positive end-expiratory pressure in our study might have caused an overestimation of their presence.

Fifth, temporal factors could have affected our results because MRI and LUS were applied neither at the same time nor in random order but sequentially. It was demonstrated that anesthesia-induced atelectasis developed quickly during and after anesthesia induction and that their amount did not increase with anesthesia time.[1] On the contrary, Lutterbey et al.[6] showed a small increase in the prevalence of atelectasis in intubated children from 82 to 94% when lung MRI images were taken before or after a schedule MRI study. Such time-dependent increments in atelectasis formation could explain in part the false-positive results of LUS in our study. However, as opposed to Lutterbey's study, we performed the LUS examination within 10 min after the MRI images were taken. Therefore, we do not believe that during this short lapse of time, the amount of atelectasis increased enough to have affected our results. Furthermore, the imperfect anatomical matching of the corresponding LUS and MRI segments might have caused incongruent findings in the respective LUS and MRI images.

Our preliminary study was designed to validate LUS for diagnosis of anesthesia-induced atelectasis based on standard two-dimensional images. The role of advanced echo techniques such as pulsed Doppler,[43,44] three-dimensional images, or contrast echography on this particular entity should be tested in future studies.

Conclusion

Lung ultrasound is an accurate, safe, and simple bedside method for diagnosing atelectasis in anesthetized children.

Acknowledgments

Competing Interests

The authors declare no competing interests.

Correspondence

Address correspondence to Dr. Tusman: Department of Anesthesia, Hospital Privado de Comunidad, Mar del Plata, Buenos Aires, Argentina, Córdoba 4545, 7600 Mar del Plata,

Buenos Aires, Argentina. gtusman@hotmail.com. Information on purchasing reprints may be found at www.anesthesiology.org or on the masthead page at the beginning of this issue. ANESTHESIOLOGY's articles are made freely accessible to all readers, for personal use only, 6 months from the cover date of the issue.

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