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Original Contribution

Evaluation of atelectasis using electrical impedance tomography during procedural deep sedation for MRI in small children: A prospective observational trial

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ABSTRACT

Study objective: To investigate the variation of poorly ventilated lung units (i.e., silent spaces) in children undergoing procedural sedation in a day-hospital setting, until discharge home from the Post-Anesthesia Care Unit (PACU).
Design: Prospective, single-center, observational cohort trial.
Setting: This study was conducted at the radiology department and in PACU at Bern University Hospital (Switzerland), a tertiary care hospital.
Patients: We included 25 children (1–6 years, ASA I-III) scheduled for cerebral magnetic resonance imaging scan, spontaneously breathing under deep sedation. Children planned for tracheal intubation, supraglottic airway insertion, or with contraindication for propofol were excluded.
Intervention: After intravenous or inhaled induction, deep sedation was performed with 10 mg/kg/h Propofol. All children received nasal oxygen 0.3 ml/kg/min.
Measurements: The proportion of silent spaces and the global inhomogeneity index were determined at each of five procedural points, using electrical impedance tomography: before induction (T1); before (T2) and after (T3) magnetic resonance imaging; at the end of sedation before transport to the PACU (T4); and before hospital discharge (T5).
Main results: The median [interquartile range (IQR)] proportion of silent spaces at the five analysis points were: T1, 5% [2%–14%]; T2, 10% [7%–14%]; T3, 12% [5%–23%]; T4, 12% [7%–24%]; and T5, 3% [2%–11%]. These defined significant changes in silent spaces over the course of sedation ($p = 0.009$), but no differences in silent spaces from before induction to before discharge from the PACU (T1 vs. T5; $p = 0.29$). Median [IQR] global inhomogeneity indices were 0.57 [0.55–0.58], 0.56 [0.53–0.59], 0.56 [0.54–0.59], 0.57 [0.54–0.60] and 0.56 [0.54–0.57], respectively ($p = 0.93$). None of the children reported anesthesia-related complications.
Conclusion: Deep sedation results in significantly increased poorly ventilated lung units during sedation. However, this does not significantly affect ventilation homogeneity, which was fully resolved at discharge from the PACU.
Trial registration: clinicaltrials.gov, identifier NCT04507581

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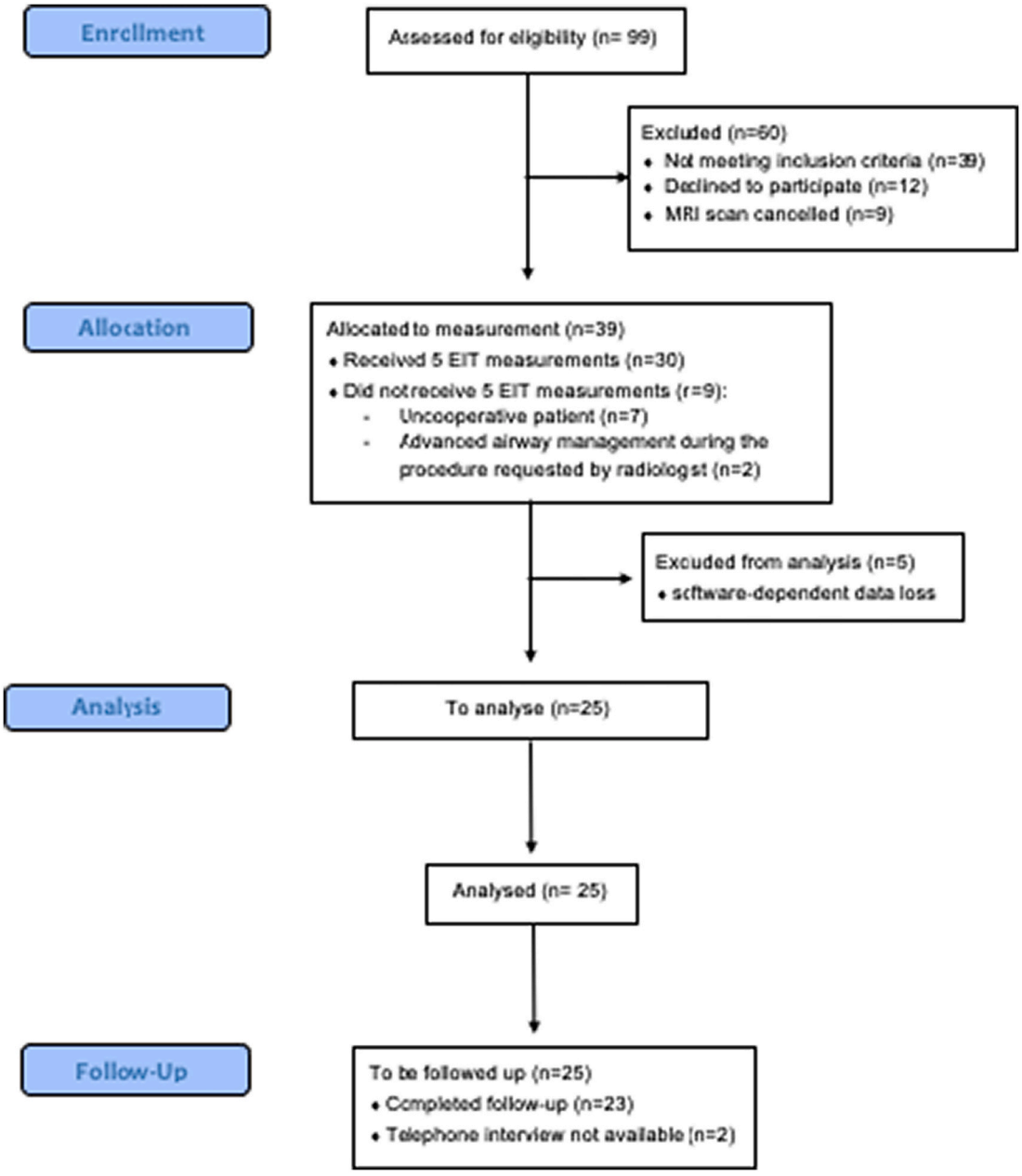

Fig. 1. Consort flow diagram.

1. Background

Due to the absence of ionizing radiation, magnetic resonance imaging (MRI) is frequently used for diagnostics in children. The noise level and long examination times define the requirement for intravenous procedural sedation or general anesthesia to guarantee the quality of the MRI images. During deep sedation, cardiovascular function is usually maintained, although spontaneous ventilation might not be adequate. The ability to independently maintain ventilatory function might be impaired, and the children might require assistance to maintain a patent airway.

Children undergoing anesthesia or procedural sedation can show low lung elastic recoil, with a closing volume that can exceed the functional residual capacity (FRC), which will expose them to airway collapse [1] and development of atelectasis. Moreover, the high fractions of inspired oxygen (FiO_2) used at induction of and emergence from anesthesia decrease lung volume in the immediate post-operative period, particularly for FiO_2 over 0.8 [2], and this might precipitate atelectasis. Furthermore, FRC decreases physiologically in the supine position, which is the usual positioning for an MRI scan.

Gunnarsson et al. demonstrated atelectasis in 81% of children undergoing general anesthesia for pulmonary computed tomography scans [3]. An MRI study also reported that sedation with propofol infusion and maintenance of spontaneous respiration showed lower extent of atelectasis than general anesthesia accompanied by positive pressure ventilation [4]. Despite the detection of atelectasis, there was no evidence of clinical changes or changes in the CO_2 and oxygen saturation (SpO_2) measurements.

In young children (aged 1–3 years), the risk for atelectasis is higher than in adults and atelectasis develops easier than in adults [3] and can persist for more than 24 h [5,6]. Due to decreased lung compliance and increased pulmonary vascular resistance, the development of atelectasis might be associated with hypoxemia and acute lung injury. These adverse effects of atelectasis persist into the postoperative period, and

Table 1
Demographics, comorbidities and cerebral MRI indications of the twenty-five analyzed patients.

Characteristic	Detail	Data
Demographics		
Age (years) [mean (±SD)]		3.9 (1.6)
Height (cm) (mean [range])		105 [84.0;110]
Weight (kg) [mean (±SD)]		17.0 (5.39)
Gender [n (%)]	Female	12 (48.0)
	Male	13 (52.0)
Comorbidities		
American Society of Anesthesiologists	I	5 (20.0)
Physical status [n (%)]	II	18 (72.0)
	III	2 (8.0)
No comorbidities [n (%)]	Yes	17 (68.0)
Known or suspected myopathies [n (%)]	Yes	0 (0)
Congenital heart diseases [n (%)]	Yes	0 (0)
Chromosome abnormalities [n (%)]	Yes	0 (0)
Other congenital malformations [n (%)]	Macrocephaly	2 (8.0)
	Trigonocephaly	1 (4.0)
Phelan-McDermid-Syndrome [n (%)]	Yes	1 (4.0)
Syndromic disease [n (%)]	Yes	2 (8.0)
Neurofibromatosis type 1 [n (%)]	Yes	1 (4.0)
Cerebral conduct disorder [n (%)]	Yes	1 (4.0)
Hypopituitarism [n (%)]	Yes	3 (12.0)
Indications for cerebral MRI		
Suspicion for epilepsy [n (%)]	Yes	6 (24.0)
Non-tumoral space-occupying lesions [n (%)]	Yes	1 (4.0)
Tumoral space-occupying lesions [n (%)]	Yes	4 (16.0)
Developmental delay [n (%)]	Yes	8 (32.0)
State after penetrating head injury [n (%)]	Yes	1 (4.0)
Lymphatic malformation [n (%)]	Yes	1 (4.0)
Phenotypic abnormalities of the head [n (%)]	Yes	4 (16.0)

can impact upon patient perioperative morbidity, recovery and safety [7].

To counterbalance this phenomenon, the application of positive end-expiratory pressure (PEEP) is known to prevent atelectasis after the induction of anesthesia, even when using 100% oxygen [8,9]. Also, the use of briefly applied peak airway pressure of 30 cm to 40 cm H_2O has been shown to re-expand the lungs to an almost normal vital capacity [10]. In mechanically ventilated children who have received ultrasound-guided recruitment maneuvers and PEEP, high concentrations of inspired oxygen did not result in significant atelectasis [11]. However, during procedures that require intravenous deep sedation with spontaneous respiration, it is impossible to perform recruitment maneuvers, and during MRI it is impossible to apply PEEP through non-invasive ventilation or a high-flow nasal cannula, due to the strong magnetic field.

Electrical impedance tomography (EIT) has been introduced as a bedside radiation-free technique that provides dynamic breath-by-breath information on regional changes in lung aeration and ventilation heterogeneity [12]. Currently, there are no data on atelectasis during deep procedural sedation in spontaneously breathing children, and also on the progression of atelectasis until discharge. With the present study, we wanted to evaluate the effects on FRC and ventilation homogeneity of intravenous deep sedation under spontaneous breathing for children undergoing elective cerebral MRI using EIT.

The main study objective was to investigate atelectasis development and its regression, in terms of poorly ventilated lung units (i.e., silent spaces), in children under controlled circumstances during deep sedation, and until discharge, using EIT in a day-hospital setting. These results should support the evidence favoring deep procedural sedation during diagnostic imaging procedures avoiding hypoxemia or critical pulmonary events. This could further raise the safety standards of pediatric anesthesia.

2. Methods

Approval for this study was obtained from the Cantonal Ethics Committee of Bern (reference number KEK-BE 2020–01421, 29.07.2020), and it was registered at ClinicalTrials.gov (NCT04507581). Written informed consent was obtained from the parents or legal guardians of all of the patients before study enrolment.

This prospective, single-center, observational cohort trial was conducted at the Department of Anesthesiology and Pain Medicine at Bern University Hospital (Bern, Switzerland) from August 2020 to February 2021. The study followed the current version of the Declaration of Helsinki, and the Swiss Law for Human Research, and was developed according to the protocol defined and illustrated in Fig. 1.

The inclusion criteria were for children aged 1 year to 6 years with American Society of Anesthesiologists physical status I to III who were to undergo elective cerebral MRI that required deep sedation. The indications for MRI were either a neurological disease or the exclusion of intracerebral tumors like summarized in Table 1. Exclusion criteria were the need for intubation or a supraglottic airway device, contraindication for propofol administration, and congenital heart or lung disease and oxygen dependency.

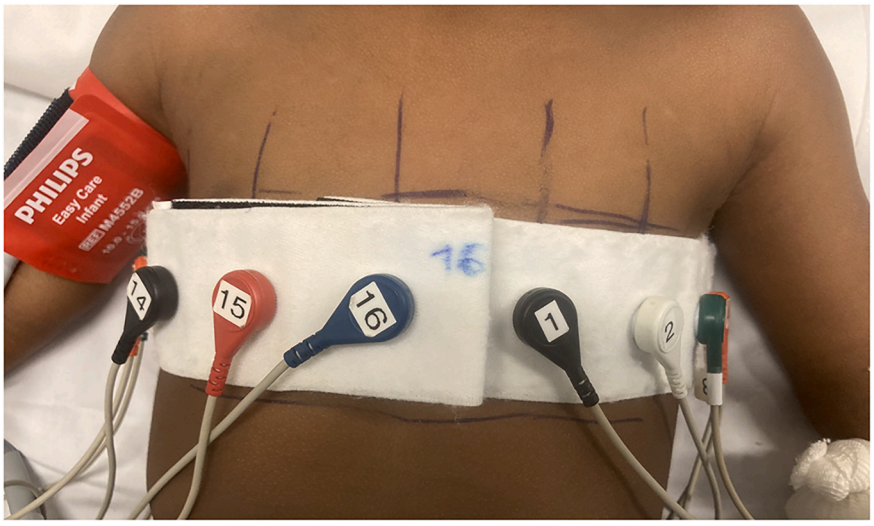

Fig. 2. Placement of loose-fitting belt with 16 evenly spaced electrodes around the chest of between the 4th and 6th intercostal space, in a thoracic median plane. To ensure that the belt was reapplied in the same position after the MRI the upper and lower edges of the belt as well as the position of 4 electrodes on the chest were marked with a marker (Permission to publish the photo was obtained from the parents).

All the children enrolled were premedicated according to the clinical judgement of the anesthesiologist responsible, with 0.5 mg/kg midazolam rectal or oral, or 2 μg/kg dexmedetomidine nasal, 20 min before the procedure. Standard monitoring included end-tidal CO_2, SpO_2, non-invasive blood pressure and an ECG, measured continuously via an anesthesia MRI monitor (Expression MR400, GE Healthcare, Chicago, United States of America). The last three of these were also monitored in the post-anesthesia care unit (PACU; IntelliVue MX500; Philips, Amsterdam, The Netherlands). Desaturation and related interventions were recorded as safety issues throughout the whole period.

After monitoring and intravenous line placement, bolus propofol 2 mg/kg to 3 mg/kg was administered followed by continuous infusion of propofol 10 mg/kg/h. All the children received nasal oxygen (0.3 l/kg/min) via a pediatric cannula (Microstream Smart CapnoLine; Philips Healthcare, Amsterdam, The Netherlands), which also allowed the measurement of end-tidal CO_2. The depth of the sedation was evaluated according to the Richmond Agitation–Sedation Scale [13]. During cerebral MRI all the children were in a supine position. Study exclusion included the need for face-mask ventilation, insertion of a laryngeal mask, or placement of a tracheal tube.

We evaluated the effects of deep procedural sedation with spontaneous breathing for elective cerebral MRI on atelectasis formation and ventilation homogeneity using EIT (PulmoVista 500; Dräger, Lübeck, Germany). EIT is a non-invasive, radiation-free technique to assess the spatial and temporal ventilation distribution based on the changes in electrical properties of the tissue during the respiratory cycle. The high diagnostic value of the EIT method was tested in several studies, resulting in sensitivity of 93% and specificity of 87% for detection of Extra-Vascular Lung Water [14], a sensitivity of 90.9% and a specificity of 98.6% for the PE diagnosis [15] and 96.0% sensitivity and 97.6% specificity for detection of individual breaths [16]. In dogs, the EIT is able to measure changes in gas volumes with an accuracy of 30 ml [17]. This technology poses no risk for awake or anaesthetized children. It has been validated for the measurement of regional lung volume distribution, in comparison to computed tomography [18], MRI [19] and positron emission tomography [20].

A loose-fitting belt with 16 evenly spaced electrodes was placed around the chest of each child between the 4th and 6th intercostal space, in a thoracic median plane (Fig. 2). During MRI the belt was removed. To ensure that the belt was reapplied in the same position after the MRI, the upper and lower edges of the belt as well as the position of the electrodes on the chest were marked with a marker.

Small electrical currents were administered through adjacent electrodes in a rotating mode. The resulting potential differences were measured, and the impedance distribution was sampled at 30 Hz. The EIT images were reconstructed based on the Graz consensus reconstruction algorithm for EIT (i.e., GREIT) using the torso mesh function which is based on CT scans [21]. The relative change in silent spaces (defined as areas with less than 10% impedance change) and measures of ventilation inhomogeneity, including the global inhomogeneity (GI) index, were calculated using customized code (Matlab R2021a; The MathWorks Inc., Nattick, MA, USA) [22–25]. We omitted the originally planned analysis of changes in end-expiratory lung impedance because of non-plausible results most likely due to the repositioning of the belt.

The EIT measurements were taken before induction of anesthesia (T1), 2 min after the end of induction, before the MRI procedures (T2), 2 min after completion of the MRI procedures (T3), 2 min after the end of anesthesia, before transport to the PACU (T4), and before discharge to home (T5; about 2 h after the procedure). Each measurement lasted 1 min. We performed telephone follow-up 7 days after the procedure, to enquire about pulmonary complications or need for re-hospitalization.

2.1. Statistical analysis

To date, there are only data for FRC and ventilation homogeneity impairment in anaesthetized children exposed to high levels of inspired oxygen [9]. This previous study set the sample size at 23 participants in each group. A similar study in adults set the sample size at 20 participants [26] per group. In the set-up of the present study, we had additional measurement points as unknown extra variables. For this reason, we increased the sample size to 25 participants.

There are no data on the extent of atelectasis in spontaneously breathing children under deep procedural sedation for MRI before and after the procedures (<3 h), and until discharge to home. Consequently, no data are available on the variance of any observed differences in atelectasis at the time of planning the present study that could be considered to alter the above-mentioned sample size of 25 participants.

2.2. Descriptive statistics

Continuous variables were examined using Shapiro–Wilk normality tests and are presented as means ±standard deviation for normally distributed variables, or otherwise, as medians with interquartile range (IQR). Categorical variables are presented as frequencies and percentages.

2.3. Primary and secondary outcomes

The primary outcome was change in silent spaces before discharge to home (T5; about 2 h after the procedure) compared to silent spaces before the procedure (T1). We used these silent spaces derived from EIT as the surrogate for atelectasis.

The secondary outcomes included the changes in silent spaces and GI index after induction of anesthesia and before the MRI procedure (T2), after the MRI procedure (T3), and before transport to the PACU (T4). Furthermore, these also included duration of deep sedation and the MRI procedure, and respiratory complications.

The primary outcome of silent spaces was determined as medians and IQRs at each analysis point. As these were constrained to lie in the 0% and 100%, a generalized linear mixed effect model was used (with a beta distribution for the outcome) to examine the repeated measures of the silent spaces using the R-package *glmmTMB* [27]. The analysis points (T1–T5) were chosen as fixed-effect factor covariates, and a random intercept for each patient accounted for the intra-patient correlations. The statistical significance of the analysis point covariate was tested by the drop in deviance compared to the null model.

For the secondary outcomes, *post-hoc* comparisons of the differences among the pairs of analysis points were adjusted for multiple comparisons using the Tukey method. The GI index was analyzed in the same fashion due to its bounded range. For zero values for silent spaces or the GI index, a marginal value of 0.001 was added to comply with the range of the beta distribution.

Missing data were imputed using predictive mean matching as the single imputation method using the R package *mice* [28]. All the analyses were based on the input dataset. Statistical significance was defined by $p < 0.05$, and all of the computations were performed with R version 4.0.5 [29] (The R Foundation for Statistical Computing, Vienna, Austria).

3. Results

The characteristics of the 25 children included in the procedures (Fig. 1) are summarized in Table 1. Twenty-one children (86%) were induced intravenously, while 4 children (14%) needed inhaled induction due to difficult venous cannulation. After induction, all the children were sedated with 10 mg/kg/h propofol.

The Richmond Agitation–Sedation Scale score at the beginning of the MRI was −5 for 11 (44%) children, and − 4 for the other 14 (56%) children. The anesthesia duration was 103 ± 25 min (normally distributed; mean ± SD), while the duration of the radiological procedure was 50 [48–54] min (skewed distribution; median [IQR]). During the procedure, the children received nasal oxygen with a flow of 0.3 l/kg/min,

Table 2
Patient conditions during sedation, in the Post-Anesthesia Care Unit and at telephone follow-up assessment seven days after sedation. Note: two patients (8.0%) were lost for the 7-day follow-up.

Condition	Detail	Data [n (%)]
During sedation		
Any complications	No	25 (100)
Post-Anesthesia Care Unit		
Desaturation (SpO_2 < 92%)	No	25 (100)
Other post-anesthesia complications	No	24 (96.0)
Agitation (fractional propofol needed)	Yes	1 (4.00)
Follow-up telephone assessment after seven days		
Not contactable via telephone	Yes	2/25 (8.0)
Available for assessment	Yes	23/25 (92.0)
Any pulmonary complications since sedation	No	23/23 (100)
Re-hospitalization needed	No	23/23 (100)

which resulted in a mean flow rate of 5.0 ± 1.5 l/min. None of the children showed desaturation during the procedure, and in none of the procedures had to be terminated early due to complications (Table 2).

The median [IQR] proportion of silent spaces at the different analysis points were: T1, 5% [2%–14%]; T2, 10% [7%–14%]; T3, 12% [5%–23%]; T4, 12% [7%–24%]; and T5, 3% [2%–11%]. There was no significant difference in the silent space formation from before induction (T1) to before discharge to home (T5) ($p = 0.29$) (Fig. 3 and Table 3). The proportion of silent spaces varied significantly during the deep sedation ($p = 0.009$). Here, two measurements of silent spaces at analysis point T4 had to be excluded from the study because of artefacts.

The median [IQR] GI indices through the analysis were: T1, 0.57 [0.55–0.58]; T2, 0.56 [0.53–0.59]; T3, 0.56 [0.54–0.59]; T4, 0.57 [0.54–0.60]; and T5, 0.56 [0.54–0.57], with no significant variation over the analysis points ($p = 0.93$), and no significant differences between any two analysis points (Fig. 4 and Table 3). Age does not represent a risk factor for the development of atelectasis. We performed a sensitivity analysis and found that age was not a significant predictor in the beta GLMMs ($p = 0.76$ for the silent space outcome; $p = 0.71$ for the global inhomogeneity index).

In the PACU, none of the children showed respiratory complications or desaturation. Only one child showed postoperative agitation, which required two doses of propofol 1 mg/kg. Seven-day follow up was only possible in 23 patients: in two cases, the parents of the enrolled children could not be reached by phone. No anesthesia-related complications were reported, and none of the children had to be re-hospitalized (Table 2).

4. Discussion

This prospective observational trial showed that the proportion of silent spaces increased significantly during the deep procedural sedation for MRI. Atelectasis was fully resolved after the procedure, before the children were discharged home from the PACU, and without the need for any recruitment maneuvers. None of the children showed respiratory complications that prevented discharge or required re-hospitalization.

Respiratory complications are very frequent in pediatric anesthesia [30], and might be a source of critical adverse pulmonary events. The younger the child, the more at risk they are for suffering critical adverse pulmonary events due to their reduced FRC and increased oxygen requirements compared to adults. Atelectasis during anesthesia or deep sedation represents a risk factor for periprocedural respiratory complications and might worsen outcomes or delay discharge in an outpatient anesthetic setting, which would cause distress for families and health care providers.

First, although maintenance of spontaneous breathing is considered to be a protective factor, we demonstrated that atelectasis occurred in these children during the procedural sedation. Atelectasis is very common under general anesthesia in both children and adults, with reported incidence ranging from 68% to 100% [4,31,32], although data related to procedural sedation are lacking. During general anesthesia, several mechanisms contribute to the development of atelectasis, including reduced FRC, which promotes small airway closure [9] and contributes to the development of atelectasis. [7,33] The paralysis of the diaphragm results in an increase in transmural pressure, which decreases the stability of the lungs for the nitrogen washout during induction, therefore reducing the alveolar volume. [7,33] In anaesthetized spontaneously breathing children, the reduction in FRC can lead to lung collapse and small airway closure. Infants and younger children have smaller FRCs

Table 3
Proportion of silent spaces and global inhomogeneity indices at each analysis point. Data are summarized as Median and interquartile ranges.

Timepoint	Proportion of silent spaces (%)	Global inhomogeneity index
T1 (Before induction of anesthesia)	5 [2;14]	0.57 [0.55;0.58]
T2 (2 min after the end of induction, before start of the MRI)	10 [7;14]	0.56 [0.53;0.59]
T3 (2 min after completion of the MRI)	12 [5;23]	0.56 [0.54;0.59]
T4 (2 min after the end of anesthesia, before transport to the PACU)	12 [7;24]	0.57 [0.54;0.60]
T5 (Before discharge to home)	3 [2;11]	0.56 [0.54;0.57]

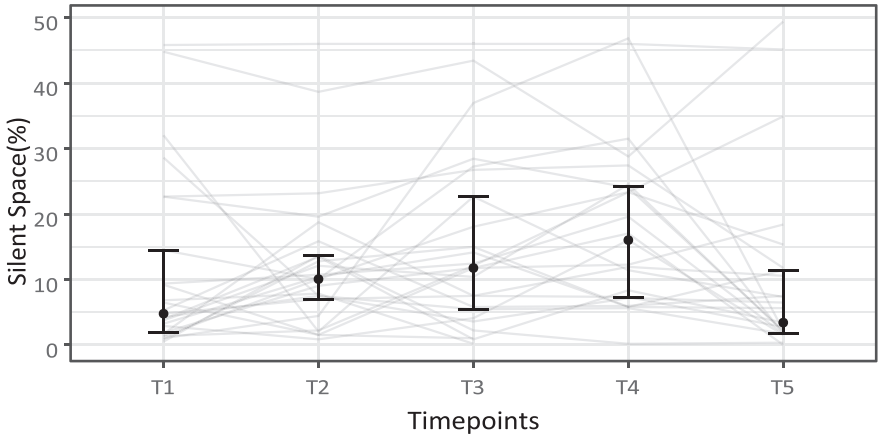

Fig. 3. Evolution of proportion of silent spaces across the different analysis points. Individual patients are shown as solid lines, and the median and interquartile range (IQR) of silent spaces at each analysis point are given.

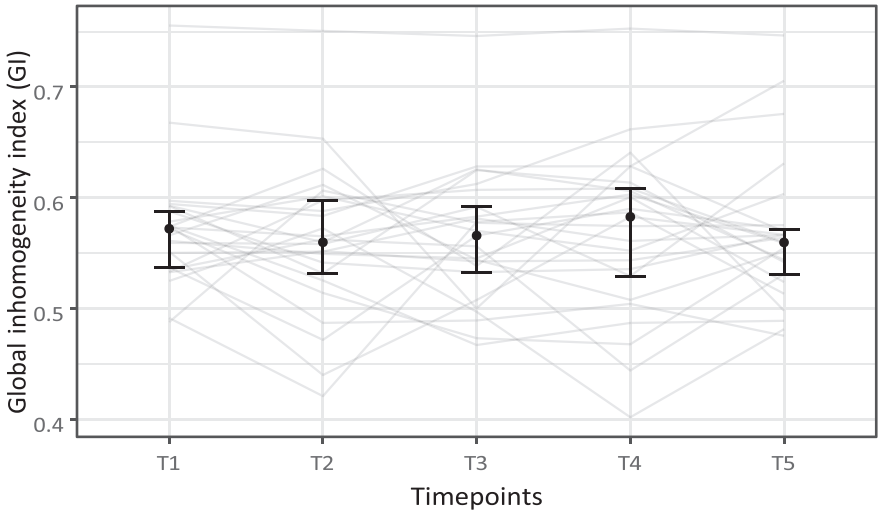

Fig. 4. Evolution of the global inhomogeneity (GI) index across the different analysis points. Individual patients are shown as solid lines and the median and interquartile range (IQR) of the GI index at each analysis point are given.

compared to adults due to their less developed respiratory muscles [3], and this physiological predisposition [32] can lead to further oxygen desaturation. [5,34] Atelectasis is known to occur immediately after induction [35]. While 5 cmH_2O is not sufficient to prevent atelectasis, a recruitment maneuver associated with PEEP can reduce anesthesia-related atelectasis [35]. On the other hand, FiO_2 does not appear to promote the development of atelectasis in mechanically ventilated children provided that they receive recruitment maneuvers and PEEP. [11] That being said, atelectasis evaluated by lung ultrasonography still persists in 11.6% to 20.9% of children immediately preceding discharge from the PACU [36]. The present study shows that the atelectasis detected during sedation was resolved at discharge from the PACU. Despite the impossibility of performing recruitment maneuvers during the procedure (as the children were under spontaneous breathing), lung volumes returned to pre-induction values after deep sedation, and none of the children showed respiratory complications. This complete recovery might have reduced the risk of hypoxemia and subsequent complications.

Finally, we used the EIT-derived parameter of silent spaces to show that the atelectasis during the deep sedation were completely resolved at the time of PACU discharge. Silent spaces can be used to identify and quantify lung regions in which the air content changes minimally during tidal ventilation. [24] Ukere et al. suggested that silent spaces in dependent lungs can indicate atelectasis, whereas increases in silent spaces in non-dependent lungs can indicate overdistention. [37] One of the advantages of the EIT technique compared to the ultrasound used in recent studies [36,38] is that EIT can detect not only silent spaces, and indirectly atelectasis, but also pulmonary hyperinflation. Additionally, it overcomes some of the limitations of ultrasound examinations, like operator dependency. The potential of EIT to detect reductions in lung volumes shown in this study offers future possibilities not only to guide mechanical ventilation by customizing respiratory support and PEEP, but also to perform bedside monitoring of patient's lung volumes. This would allow individualized therapy in the PACU for children who need respiratory physiotherapy if they show persistent reductions in lung volumes.

Surprisingly, inhomogeneity of ventilation that was assessed here by the GI index did not vary throughout the measurement period, as was initially predicted. Silent spaces are used as a surrogate marker for atelectasis only, so some ventilation in these areas of the lung that are not captured by EIT might still occur. This would reduce the inhomogeneity measured by the GI index. Secondly, the GI index is a continuous variable that involves all of the pixels of the EIT image of the lungs, whereas silent spaces only involve the peripheral lung regions. This might make the GI index less sensitive to these specific changes. Parts of this finding could also be explained by hypoventilation during deep sedation itself.

Additional limitations of this study include the relatively small number of participants, the lack of randomization, the single-center design, and the absence of monitoring by EIT during the MRI because of the strong static magnetic field generated by the MRI scanner. Nevertheless, we have demonstrated for the first time that there are significant changes in lung atelectasis in this patient group.

5. Conclusion

In conclusion, the practice of procedural deep sedation with maintenance of spontaneous breathing with low-flow oxygen for radiological imaging like MRI results in significant variations in silent spaces (i.e., poorly ventilated lung units, which acts as a surrogate for atelectasis) during the sedation without affecting overall ventilation homogeneity. This effect is fully resolved before discharge to home from the PACU, about 2 h after anesthesia termination.

Author statement

Study design, conduct, analysis, and manuscript preparation: TRiv, TRie, RG, JBE, FP.

Patient recruitment, conduct of the study: TRiv, FP, AF, JBE.

Statistical analysis: MH.

Study design and finalizing the manuscript: TRiv, RG, LT, ND.

All authors agreed to the final manuscript version.

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Declaration of Competing Interest

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RG is Treasurer of the European Airway Management Society.

No other author has anything to declare with this study.

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