Dynamic PEEP Study: A Non-Invasive Diagnostic Exam to Assess for Effective PEEP in Fragile Children With Severe BPD

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Abstract

Objective

Tracheobronchomalacia (TBM) is common in neonates with bronchopulmonary dysplasia (BPD) and is associated with higher morbidity. This study evaluates the value of a CT protocol to assess the degree of TBM and gauge the adequacy of prescribed PEEP.

Study Design

Four infants with severe BPD on invasive mechanical ventilation underwent a chest CT protocol, including limited reduced- dose expiratory scans with varying PEEP levels.

Results

Baseline PEEP was adjusted in all subjects after performing the Dynamic PEEP CT. In two infants, the PEEP was increased due to significant TBM, and in the other, two without signs of TBM PEEP was decreased. The clinical course improved in all patients after adjusting PEEP.

Conclusion

A "Dynamic PEEP" study is a highly reliable and non-invasive imaging modality for the evaluation of adequate ventilator settings in infants with severe BPD who are not optimal candidates for bronchoscopy.

Introduction

Significant changes in the field of neonatology have led to increased survival in extremely premature infants. However, this improved survival has been accompanied by an increase in bronchopulmonary dysplasia (BPD), which results in chronic lung dysfunction and remains the most common complication in this extremely preterm population[1].

Infants who are exposed to positive-pressure ventilation for prolonged periods are subjected to persistent airway distension and hyperoxia and have an increased risk for recurrent infection. Each of these entities may lead to airway damage and subsequent tracheobronchomalacia [1–6, 10]. Tracheobronchomalacia is commonly identified in neonates with BPD, with a reported incidence of 10–86% in those that undergo bronchoscopy[3–6]. In infants with severe BPD, Hassinger et al. found a 48% and 40.7 % incidence of tracheomalacia and bronchomalacia respectively[7]. Moderate or severe tracheobronchomalacia in a ventilated patient may present as respiratory distress, difficulty weaning from mechanical ventilation, failure of extubation or tracheal decannulation, recurrent infections, wheezing, cough, or death[1,4]. The diagnosis of tracheobronchomalacia is associated with increased morbidity, including more frequent pneumonia, aggravation of gastro-esophageal reflux, chronic ventilator dependence, and longer duration of hospital stay[4–6].

A key concept in ventilator management of infants with tracheobronchomalacia is to establish the appropriate amount of positive end-expiratory pressure (PEEP). Inadequate PEEP has the potential to cause complications throughout the respiratory tract, including significant airway collapse and/or obstruction, as well as atelectasis and the accompanying atelectrauma. Ventilated infants with tracheobronchomalacia will often experience worsening respiratory distress as PEEP is weaned due to airway collapse[4–6].

The level of PEEP required to maintain airway patency is often greater than that needed to maintain adequate functional residual capacity (FRC), which may lead to significant alveolar over-distension. Lung hyperinflation with alveolar over-distension imposes extra load on the respiratory muscles, making it difficult to produce spontaneous breaths, which may lead to worsening of patient-ventilator dyssynchrony. Hyperinflation can also increase intrathoracic pressure that impedes venous return to the heart, decreasing preload of both cardiac ventricles[6]. High pulmonary vascular resistance from elevated intrathoracic pressure may also lead to reduced compliance of the left ventricle and increased right ventricular afterload[8]. These effects may predispose the infant to decreased cardiac output and potentially unnecessary or inappropriate treatment with vasoactive medications.

The diagnosis of tracheobronchomalacia and dynamic airway collapse is generally made by rigid or bedside flexible bronchoscopy. This procedure often requires sedation and has risks in infants with severe BPD, in particular those with high ventilator settings, FiO2 and other comorbidities such as pulmonary hypertension. We present our experience with four infants with severe type II BPD[1,8] who underwent non-invasive "Dynamic PEEP" CT studies to assess their degree of tracheobronchomalacia and gauge the adequacy of prescribed PEEP.

Patients And Methods

We used chest CT to evaluate for tracheomalacia in four infants with severe BPD who were ventilator-dependent via tracheostomy. Patients were admitted to the Neonatal Intensive Care Unit (NICU) at Children's National Hospital, a Level IV referral center in Washington DC Flexible bronchoscopy was deferred in all patients due to risk associated with small tracheal tube size, high FiO2 requirement, and moderate to severe pulmonary hypertension. A chest CT protocol with a minimum of three preselected PEEP levels ("Dynamic PEEP" study) was performed for each patient between the time period of February 2018 and June 2018. All studies were performed without sedation. The Children's National IRB approved the study, which complied with the Health Insurance Portability and Accountability Act.

All scans were performed on GE CT Discovery with 64 detectors. PEEP levels were chosen *a priori* based on clinical evaluation at the bedside prior to the study. The "Dynamic PEEP" protocol consisted of performing a diagnostic scan of the entire chest with a full inspiratory pause at the current ventilator settings. The inspiratory pause was performed on a Maquet Servo U ventilator for 3 seconds. Reduced-dose and field-of-view "limited" expiratory scans were then performed at a minimum of 3 different PEEP levels. Expiratory scans were achieved by performing an expiratory pause for 3 seconds, re-scanning was delayed for three minutes between changes in PEEP settings. The study consisted of a helical scan with thin-section coronal and axial reconstructions, from the tip of the endotracheal tube to the level just above the diaphragm. The field of view was narrowed to achieve radiation dose reduction. Decreasing field of view and reducing mAs settings for dynamic expiratory CT scans significantly decreased both volumetric CT dose index ($CTDI_{vol}$) and Dose Length Products (DLP) of "Dynamic PEEP" acquisitions.

CT studies were performed with the support of a NICU transport team and a pulmonologist (GP), who monitored the respiratory status during the exam. All CT images were interpreted by a pediatric radiologist (HH) and pulmonologist (GP) at Children's National Hospital.

Results

The demographics and ventilator settings of the four patients evaluated with a "Dynamic PEEP" CT are presented in Table 1. One patient (case #1) had a CT angiogram done immediately after the PEEP study to assess pulmonary vein stenosis.

Table 1
Patient characteristics and PEEP levels

Case No.	Gender	GA at birth (weeks)	Age at CT	PH treatment	FiO2/O2 Sat	PEEP prior to CT (cm H2O)	PEEP after CT (cm H2O)	FiO2/O2 Sat after PEEP change
1	Female	25 + 5/7	14 mo	Sildenafil	0.45/92	10	12	0.35/96
2	Male	23 + 5/7	10 mo	Sildenafil	0.5/94	8	7	0.4/94
3	Male	25 + 0/7	6 mo	Sildenafil/Bosentan	0.6/90	9	13	0.35/95
4	Male	25 + 0/7	8 mo	Sildenafil/Bosentan	0.4/94	11	9	0.35/94

Case 1:

CT findings included patchy bilateral upper and lower airspace opacities consistent with atelectasis and chronic lung disease. "Dynamic PEEP" CT of the thoracic airway was performed at PEEP levels of 8, 10, and 12 cm H_2O and demonstrated tracheal compression at PEEP of 8 and 10 cm H_2O. The trachea remained rounded with a more normal configuration at PEEP of 12 cm H_2O. Lung atelectasis worsened at PEEP of 8 and 10 cm H_20, with significant improvement at PEEP of 12 cm H_2O (Fig. 1). CT angiogram obtained during inspiration showed left upper pulmonary vein atresia with decompressing collaterals to a stenotic left lower pulmonary vein. Based on imaging findings from this study, ventilator settings were adjusted with an increase in PEEP from 10 cm H2O to 12 cm H2O.

Case 2: CT findings included coarse interstitial markings, segmental atelectasis in the right lower lobe, and several circumscribed areas of lucency representing air trapping. "Dynamic PEEP" CT of the thoracic airway was performed at PEEP levels of 5, 7, and 9 cm H_2O and demonstrated patency of the central airways with no evidence for tracheal collapse at any PEEP level (Fig. 1). PEEP had been set at 8 cm H2O prior to CT and, based on imaging findings, was effectively decreased to 7 cm H_2O in order to prevent lung hyper-expansion while maintaining adequate oxygenation.

Case 3:
CT findings included bilateral lung hyperinflation, multifocal areas of airspace disease with varying degrees of air bronchograms and volume loss, as well as a background of multiple bilateral streaky opacities indicative of atelectasis or scarring. "Dynamic PEEP" CT of the thoracic airway was performed at PEEP levels of 9, 11, and 13 cm H_2O. On the expiratory phase, the lowest PEEP with complete preservation of central airway caliber was 13 cm H_2O. There was a 50% reduction in the anterior-posterior airway caliber when PEEP was decreased from 13 cm H_2O to 11 cm H_2O (Fig. 2). PEEP was increased from 8 cm H2O to 13 cm H_2O based on the imaging findings in order to maintain central airway patency.

Case 4:
CT findings included posterior wall and main-stem bronchi narrowing during expiration, atelectasis superimposed on ground-glass opacity throughout the right lobe, and multiple foci of nodular consolidation. The right lower lobe was hyper-inflated with a leftward mediastinal shift. The left lung was relatively small compared to the right, with dense areas of atelectasis, nodular consolidation, and ground-glass opacities. "Dynamic PEEP" CT of the thoracic airway was performed at PEEP levels of 7, 9, and 11 cm H_2O and demonstrated no significant changes in lung aeration or in diameter of the mid-thoracic trachea, right main-stem, or left main-stem bronchus at any PEEP level (Fig. 2). Based on these findings, the PEEP was effectively decreased from 11 cm H_2O to 9 cm H_2O to achieve adequate oxygenation and avoid hyperinflation.

Clinical course

The respiratory course improved in all patients after adjusting PEEP levels. The frequency of desaturations, bradycardic events (spells), and the number of rescue breaths provided via a bag valve mask improved in the patients where PEEP was increased. Work of breathing (retractions) and gas exchanged (PCO2 and O2 saturation) also improved. In patients where PEEP was decreased, hyperinflation in chest x rays improved, and compliance improved by assessment of pressure-volume loops. Peak inspiratory pressures remained stable, with average PIPs between 30 to 40 cmH2O. There were no respiratory or cardiovascular complications after adjusting the PEEP level. All patients were successfully discharged home on invasive mechanical ventilator support.

Discussion

We found that a "Dynamic PEEP" CT protocol can provide essential information to assist in the ventilator management of patients with severe BPD and suspected tracheobronchomalacia. In particular, it provides a way to optimize PEEP, promote patient safety by minimizing the need for bronchoscopy and procedural sedation, and allows for assessment of the pulmonary, cardiac, and vascular anatomy.

This approach may be particularly suitable for patients unable to undergo flexible bronchoscopy due to clinical instability or small tracheal tube size. In all four cases, we demonstrated that information from a "Dynamic PEEP" study was able to identify optimal distending pressures in patients with TBM. Importantly, each study led to ventilator changes, two in which PEEP was increased, and two where it was decreased.

In skilled hands, flexible bronchoscopy is an excellent tool that can be used to identify tracheobronchomalacia and assess optimal PEEP[7, 11,13]. While performing bronchoscopy, one can set varying levels of PEEP on the ventilator in order to determine the minimal appropriate distending pressure to overcome airway collapse and reduce the chance of barotrauma. Despite this, bronchoscopy in the neonatal population is limited by multiple factors. In infants, the relative size of the bronchoscope to the airway and the difficulty maintaining respiratory stability during the procedure, particularly in those diagnosed with BPD and pulmonary hypertension, may limit the quality of information obtained. Moreover, bronchoscopy often requires sedation and does not provide information regarding lung parenchymal disease and its response to varying PEEP levels[10 –11].

The "Dynamic PEEP" CT approach to diagnose TBM eliminates the subjectivity of a visual evaluation during bronchoscopy related to the operator experience and mitigates the effect sedatives have on airway dynamics. Prior studies have shown the utility of CT scans to evaluate airway malacia and PEEP levels in patients with a history of tracheoesophageal fistula and bronchopulmonary dysplasia [12,14–15]. A significant limitation of CT, in general, is the concern over the higher doses of radiation relative to other imaging modalities, particularly in the pediatric population. We were able to minimize the radiation dose by decreasing the field of view and amperage of the CT tube while maintaining a high level of diagnostic confidence in measuring airway lumen changes in response to various PEEP levels (Table 2). Previous studies showed no changes in diagnostic accurary of CT scans after reducing the radiation dose. Lee et al [16], showed comparable diagnostic confidence in patients evaluated for tracheobronchomalacia when CT images were acquired with a reduced dose technique of 50% from standard dose technique in pediatric patients.

Table 2
Diagnostic dose is the dose of routine diagnostic quality CT performed with the "limited PEEP" scan. Total PEEP scan dose includes CTDIvol and sum of DLP of all the "limited" PEEP CT scans performed during the study.

	Patient 1		**Patient 2**		**Patient 3**		**Patient 4**	
Dose	Diagnostic	Total PEEP	Diagnostic	Total PEEP	Diagnostic	Total PEEP	Diagnostic	Total PEEP
CTDI vol (mGy)	3.37	0.58	2.89	1.16	2.79	0.34	2.89	0.58
DLP (mGy-cm)	35.37	41.73	44.53	78.48	54.91	23.7	54.83	18.27

Another critical aspect of a CT scan is that it can provide information regarding the lung parenchyma and other airway abnormalities. A higher PEEP level demonstrated improvement in atelectatic areas and showed pulmonary vein stenosis with collaterals in our first case. Identifying airway and pulmonary vascular problems is crucial since it can help to predict the clinical course and long-term management. For example, pulmonary vein stenosis is a relatively common complication of extreme prematurity and was identified in 4.7% of infants with severe BPD.[11] Infants with pulmonary vein stenosis in association with BPD have worse outcomes than those with BPD alone, including longer time on mechanical ventilation, longer duration of hospital stay, and increased mortality[10]. A retrospective study of infants with severe bronchopulmonary dysplasia and pulmonary hypertension showed a 35% and 27% incidence of aortopulmonary collaterals and pulmonary vein stenosis, often missed during echocardiographic studies[17], which highlights the role of CT imaging in a selective high-risk population.

Recent developments in imaging, particularly ultrashort echo-time MRI (UTE MRI), are promising. Hyssinger et al[18] evaluated the correlation between flexible bronchoscopy and MRI for the assessment of tracheomalacia. UTE-MRI showed a moderate correlation with tracheomalacia severity and high specificity with a strict definition of tracheomalacia (> 40% change in cross-sectional area). UTE-MRI can decrease the exposure to radiation that infants and children with underlying respiratory disorders are at risk for.

Conclusion

Advances in CT imaging, particularly with protocols that limit radiation exposure, allow for the non-invasive assessment of tracheal AP diameter and collapse, as well as lung field atelectasis at varying PEEP levels and vascular abnormalities. A "Dynamic PEEP" CT protocol allowed us to optimize PEEP in our four BPD patients with a more accurate assessment of the presence or absence of airway collapse, hyperinflation, and atelectasis at varying PEEP levels. This protocol was also effectively combined with non-invasive evaluation of the lung parenchyma and cardiovascular systems.

Abbreviations

BPD – Bronchopulmonary Dysplasia

PEEP – Positive End-Expiratory Pressure

FRC – Functional Residual Capacity

NICU – Neonatal Intensive Care Unit

Declarations

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Author contribution statement

CS, RS, JB, HH, MS, and GFP contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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Figures

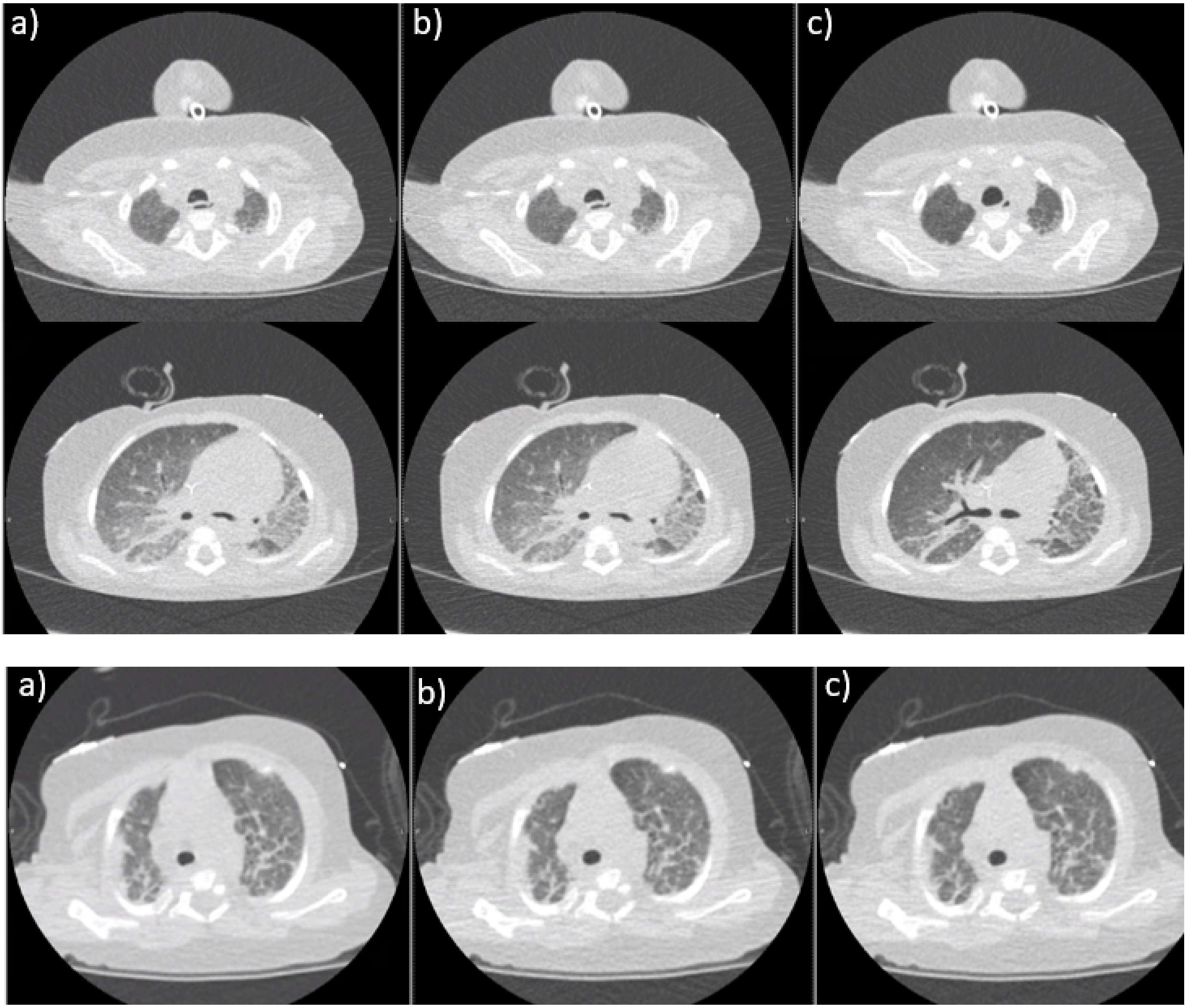

Figure 1

Top Case 1. Maximal AP dimension of the trachea at a) PEEP 8 cm H20, b) PEEP 10 cmH2O and c) PEEP 12 cmH2O: 4.1 mm : 4.5 mm : 9.7mm respectively. Atelectatic changes are also progressed within the visualized lungs with the lower PEEP values Bottom Case 2. Maximal AP dimension of the trachea at a) PEEP 5 cm H20, b) PEEP 7 cmH2O and c) PEEP 9 cmH2O6.7 x 5.3 mm, 7.6 x 6.1 mm and 7.2 x 5.3 mm respectively

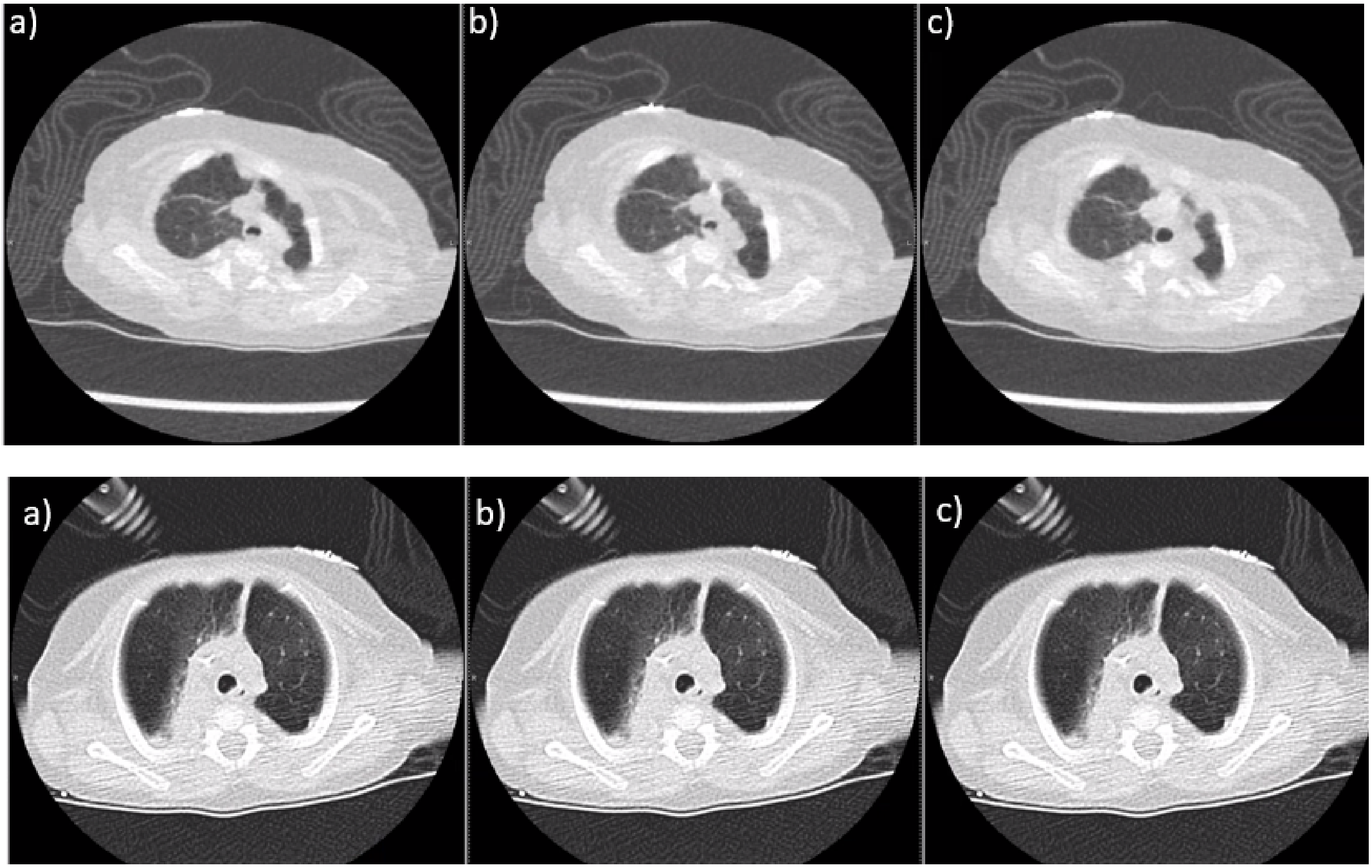

Figure 2

Top Case 3. Maximal AP dimension of the trachea at a) PEEP 9 cm H20, b) PEEP 11 cmH2O and c) PEEP 13 cmH2O 6 mm, 3 mm and 3 mm respectively Bottom Case 4 Maximal AP dimension of the trachea at a) PEEP 7 cm H20, b) PEEP 9 cmH2O and c) PEEP 11 7 x 7 mm, 6 x 8 mm and 8 x 6 mm respectively