A novel approach using volumetric dynamic airway computed tomography to determine positive end-expiratory pressure (PEEP) settings to maintain airway patency in ventilated infants with bronchopulmonary dysplasia

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Abstract

Background Positive end-expiratory pressure (PEEP) is a key mechanical ventilator setting in infants with bronchopulmonary dysplasia (BPD). Excessive PEEP can result in insufficient carbon dioxide elimination and lung damage, while insufficient PEEP can result in impaired gas exchange secondary to airway and alveolar collapse. Determining PEEP settings based on clinical parameters alone is challenging and variable.

Objective The purpose of this study was to describe our experience using dynamic airway CT to determine the lowest PEEP setting sufficient to maintain expiratory central airway patency of at least 50% of the inspiratory cross-sectional area in children with BPD requiring long-term ventilator support.

Materials and methods We retrospectively identified all infants with BPD who underwent volumetric CT with a dynamic airway protocol for PEEP optimization from December 2014 through April 2019. Sixteen infants with BPD underwent 17 CT exams. Each CT exam consisted of acquisitions spanning the trachea and mainstem bronchi. We measured cross-sectional area of the trachea and mainstem bronchi and qualitatively assessed the amount of atelectasis. We documented changes in management as a result of the CT exam.

Results The average effective dose was 0.1–0.8 mSv/scan. Of 17 CT exams, PEEP was increased in 9, decreased in 3 and unchanged after 5 exams.

Conclusion Dynamic airway CT shows promise to assist the clinician in determining PEEP settings to maintain airway patency in infants with BPD requiring long-term ventilator support. Further evaluation of the impact of this maneuver on gas exchange, cardiac output and other physiological measures is needed.

Keywords Airway · Bronchopulmonary dysplasia · Dynamic computed tomography · Infants · Positive end-expiratory pressure · Tracheobronchomalacia

Introduction

Long-term mechanical ventilation is a key support mechanism for survival of many preterm infants. Unfortunately, it can also

contribute to bronchopulmonary dysplasia (BPD). Using the most common definition, oxygen requirement either at 28 postnatal days or 36 weeks' postmenstrual age, BPD is the major cause of chronic lung disease and morbidity in preterm

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neonates, affecting up to 10,000 infants each year in the United States. In the 50 years since BPD was first described, chronic mechanical ventilation, low birthweight, low gestational age and sepsis have continued to be the main risk factors for developing BPD [1, 2]. In addition to the lung parenchyma, the airways can also be severely affected in BPD.

Tracheobronchomalacia continues to be a significant factor inhibiting successful ventilation in this population. One study found airway collapse in their cohort of infants with BPD to be as high as 48% [3]. A key setting in ventilation management for BPD with tracheobronchomalacia is positive end-expiratory pressure (PEEP), whereby continuous pressure is applied by the ventilator to distend the airway throughout the respiratory cycle, maintain lung volumes, and keep small airways open while recruiting alveoli to ensure adequate exchange of oxygen and carbon dioxide [4]. Inappropriately high or low PEEP settings can have deleterious effects. If the PEEP setting is too high, the pressure can impede elimination of carbon dioxide, overdistend the airways and alveoli causing further lung injury, and impede venous return [1, 4, 5]. If the PEEP setting is too low, the airways collapse and atelectasis develops, causing ventilation/perfusion mismatch, poor gas exchange and atelectrauma [4, 5]. Considering the many variables in the complex respiratory status of neonates that include gestational age, corrected age, birth weight and history of infections, an individualized approach to ventilatory management is needed [6].

Typically clinical parameters such as fraction of inspired oxygen (FiO₂), arterial and capillary blood gases, ventilator flow volume loops, and measures of cardiac output are used to determine PEEP settings [4, 7]. Unfortunately there is little evidence-based guidance for selecting optimal PEEP levels in preterm infants [4, 6, 7]. A multicenter international study showed substantial variability in PEEP settings among centers despite accounting for differences in infant characteristics [6]. As an imaging adjunct, chest radiographs are often challenging to use for guiding PEEP management because subtle acute changes related to adjustments in the PEEP settings are often masked by chronic lung disease findings.

Given the paucity of evidence-based clinical guidelines and the limited utility of chest radiographs, novel methods are needed to better guide PEEP settings. Airway CT is an established technique for evaluating airway foreign bodies, tracheobronchomalacia and extrinsic airway compression by vascular anomalies, but it has not been investigated for the role of optimizing PEEP settings in infants [8]. Ciet et al. [9] showed that central cross-sectional airway measurements of the trachea and mainstem bronchi to assess for expiratory airway collapse can accurately be performed on dynamic airway CT of adults. Lee et al. [10] and Ullmann et al. [11] showed that dynamic CT can be an effective noninvasive tool in the evaluation of tracheobronchomalacia in infants and fragile pediatric patients with good correlation with the

reference standard of bronchoscopy. We hypothesized that dynamic airway CT performed at varying PEEP settings in infants with BPD might be helpful to the clinician by providing quantitative measurement of central airway cross-sectional area for assessing lung atelectasis at inspiration and expiration at each trialed PEEP setting.

Materials and methods

Our institutional review board approved this study, which complied with the Health Insurance Portability and Accountability Act. At our institution, dynamic airway CT for PEEP titration is reserved for a small subset of chronically ventilated infants with BPD and complex ventilation physiology not responding to standard ventilation management strategies given the utility of dynamic CT to reliably assess the central tracheobronchial tree for tracheobronchomalacia as well as the lung parenchyma for atelectasis. To evaluate the use of CT for PEEP titration in neonates, we performed a retrospective review by searching the picture archiving and communication system (PACS) at Texas Children's Hospital to identify all dynamic airway chest CT exams performed on infants from December 2014 through April 2019. Inclusion criteria were a clinical diagnosis of BPD and an exam indication to guide titration of the PEEP setting. We collected clinical data including age, gender, additional clinical diagnoses, and PEEP settings used prior, during, and after the CT exam.

CT exams were performed on an Aquilion ONE (Canon Medical Systems, Tochigi, Japan) 320-detector CT scanner with a pediatric cardiac radiologist and neonatology team present throughout the exam. All exams were performed without sedation. Exams were acquired in volumetric mode with low-dose technique utilizing 80 kVp, 20–30 mA, gantry rotation time of 0.35 s, and scan field of view (FOV) of 24 cm. Rapid sequential volumetric acquisitions were acquired during free breathing over at least two respiratory cycles continuously. Images were reconstructed in the axial plane using the “body standard volume” reconstruction kernel with lung window settings, a slice thickness of 0.5 mm, slice increment of 0.5 mm, matrix of 512×512, and display FOV tailored to each infant (typically 10–15 cm). Three-dimensional volume-rendered images were also generated. No intravenous contrast agent was administered. An initial dynamic CT spanning the trachea and mainstem bronchi was performed at the child's usual PEEP setting. Axial images of the tracheobronchial airway and lungs were evaluated at the scanner in real time for end-expiratory collapse and atelectasis. The locations of maximal collapse of the trachea and bronchi during end-expiration were identified for measurement purposes. Subsequent dynamic CT acquisitions were obtained with each trialed PEEP setting, either higher or lower depending on the findings on the initial scan. Re-scanning was delayed for at least 5 min

after a change in PEEP settings to allow the lungs and airways to adjust to the new PEEP setting. For each dynamic CT data set, multiplanar minimum-intensity projection reconstructed images were reviewed to obtain true long-axis views of the airways, and the cross-sectional area of the trachea and mainstem bronchi was measured utilizing double oblique angle correction. The cross-sectional area of the trachea and mainstem bronchi during expiratory phase imaging was compared to the corresponding inspiratory cross-sectional area with a primary goal of identifying the lowest PEEP setting necessary to maintain an end-expiratory cross-sectional area of the trachea and mainstem bronchi of at least 50% of the inspiratory trachea and mainstem bronchi cross-sectional area. A reduction in 50% cross-sectional area was chosen because this value has been reported as the standard criterion for tracheobronchomalacia in adults and children when evaluated with CT and during direct visualization on bronchoscopy [12–15]. Additionally, a reduction of 50% cross-sectional area might serve as a proxy for patency of smaller distal airways, which are opened by PEEP but not quantitatively assessed because of the spatial resolution of CT.

Imaging data collected included the number of scan acquisitions per exam, cross-sectional area measurements of the trachea and mainstem bronchi during end-expiration on each PEEP setting, cross-sectional area measurements at the same location during peak inspiration, lung parenchymal findings including atelectasis, and radiation dose measurements (CT dose index [CTDI] and dose–length product [DLP]). Once the lowest PEEP setting maintaining the desired end-expiratory cross-sectional area was identified, the exam was concluded. No additional respiratory measures were recorded at the time of CT acquisitions.

Results

Sixteen infants underwent 17 CT exams to determine desired PEEP settings during the study period. Mean patient age was 172 days (range 64–433 days). There were nine males, six females, and one child with ambiguous phenotypic sex. Additional clinically relevant diagnoses were pulmonary hypertension ($n=7$), tracheobronchomalacia ($n=6$), congenital heart disease ($n=2$), congenital diaphragmatic hernia ($n=1$) and congenital pulmonary airway malformation ($n=1$). Infants had a tracheostomy tube during 10 CT exams and an endotracheal tube during 7 CT exams.

All infants underwent one to four dynamic acquisitions at varying PEEP settings, with the period on the CT scanner varying 15–30 min, depending on how many PEEP adjustments were made. The authors are not aware of any serious adverse events during the CT scans, although events such as vital sign changes,

desaturation events, and extubations might not have been recorded in the medical records and are therefore unknown on retrospective review. Table 1 shows the trialed PEEP settings for each exam and the corresponding cross-sectional area measurements as a percentage of the peak inspiratory cross-sectional area measurement of the trachea and mainstem bronchi. As a result of the changes in cross-sectional area on dynamic airway CT, the PEEP setting was increased after nine CT exams, decreased after three CT exams, and was left unchanged after five exams. Changes in lung parenchyma as a result of trialed PEEP settings were noted in nine exams, including seven that demonstrated changes in atelectasis and two that demonstrated changes in air-trapping. One child was scanned only once and therefore changes in lung parenchyma could not be assessed.

Figure 1 illustrates the measurements trialed in one child as an example. At the child's lowest PEEP setting of 6 cm H₂O, the expiratory tracheal cross-sectional area decreased by 83% relative to the inspiratory cross-sectional area, and the right and left mainstem bronchi cross-sectional areas decreased by 75% and 78%, respectively. During the course of the CT exam, PEEP settings of 8 cm H₂O, 10 cm H₂O and 12 cm H₂O were trialed. The PEEP setting of 12 cm H₂O demonstrated cross-sectional area measurements on end-expiration closely approximating the imaging goal of a 50% cross-sectional area of peak inspiration. Figure 2 shows a 3-D rendering of the airways demonstrating diffuse narrowing of the trachea and mainstem bronchi at the lower PEEP settings, which improved at the two higher PEEP settings. The infant also had multiple bands of fibrosis or chronic atelectasis that did not change with the increases in PEEP. Taking into account the lung parenchymal findings and the airway measurements as well as other complex clinical factors, the clinical team ultimately chose to use a PEEP setting of 10 cm H₂O, an increase of 4 cm H₂O from the baseline PEEP setting at the beginning of the exam.

Mean volumetric CT dose index (CTDI_{vol}) per scan was 1.7 mGy with a range of 0.5 mGy to 2.7 mGy. Mean dose–length product (DLP) per scan was 12.3 mGy·cm with a range of 3.3 mGy·cm to 24.6 mGy·cm. Using the size-specific dose estimates (SSDE) in the pediatric and adult body CT examinations report by the American Association of Physicists in Medicine Task Group 204, the mean effective dose was 0.4 mSv/scan with a range of 0.1 mSv to 0.8 mSv per scan [16].

Discussion

Determining the optimal PEEP setting in infants with BPD is a challenging task requiring an individualized approach to

Table 1 Large airway changes as a result of trialed positive end-expiratory pressure (PEEP) settings

Age	Gender	Relevant diagnoses	Initial PEEP setting (cm)	Trialed PEEP settings ^a (cm)	Tracheal collapse	Right bronchus collapse	Left bronchus collapse	PEEP setting used after CT (cm)	CTDI (mGy)	DLP (mGy·cm)
2 m 3d	F	Bronchopulmonary dysplasia	7	7	10–20%	10–20%	10–20%	7	2.6	15.6
2 m 13d ^b	F	Bronchopulmonary dysplasia	9	5	10–20%	10–20%	10–20%	9	2.6	15.6
		Tracheobronchomalacia		9	<20%	<20%	<20%		1.8	10.9
		Pulmonary hypertension		6	40%	30–40%	30–40%		1.8	10.9
2 m 15d	M	Bronchopulmonary dysplasia	10	10	10–20%	10–20%	10–20%	13	2.7	16.0
		Pulmonary hypertension		12	10–20%	10–20%	10–20%		2.7	16.0
				14	5–10%	5–10%	5–10%		2.7	16.0
2 m 25d	U	Bronchopulmonary dysplasia	8	8	70–80%	50–60%	70–80%	10	1.9	11.4
				10	70–80%	80–90%	50–60%		1.9	11.4
				6	80–90%	70–80%	70–80%		1.9	11.4
				12	60–70%	50–60%	50–60%		1.9	11.4
2 m 26d	F	Bronchopulmonary dysplasia	12	12	30%	30–40%	30–40%	10	1.1	6.3
				10	40–50%	40–50%	40–50%		1.1	6.3
				8	50%	40–50%	40–50%		1.1	6.3
3 m 27d	M	Bronchopulmonary dysplasia	10	10	10%	10%	10%	10	1.2	7.0
		Right middle lobectomy for CPAM		9	10–20%	20–30%	20–30%		1.2	7.0
				8	10–20%	20–30%	20–30%		1.2	7.0
4 m 9d	M	Bronchopulmonary dysplasia	13	13	50–60%	60–70%	50%	18	2.5	20.2
		Congenital heart disease		15	30–50%	55–60%	35%		2.3	18.2
				17	35–50%	50–60%	35%		2.3	18.2
4 m 20d	M	Bronchopulmonary dysplasia	14	14	Minimal	Minimal	60–70%	7	0.6	3.3
		Pulmonary hypertension		12	Minimal	Minimal	60%		0.6	3.3
				10	Minimal	Minimal	80%		0.6	3.3
				8	Minimal	Minimal	70%		0.5	4.3
5 m 7d	M	Bronchopulmonary dysplasia	10	10	70%	50–60%	50–60%	16	1.5	14.8
		Tracheobronchomalacia		12	40%	10–20%	10–20%		1.1	11.1
		Pulmonary hypertension		14	20%	10–20%	10–20%		1.1	11.1
5 m 13d ^b	F	Bronchopulmonary dysplasia	11	11	No expiration	No expiration	50–60%	13	1.4	11.4
		Tracheobronchomalacia		13	60%	50–60%	50–60%		1.4	11.4
		Pulmonary hypertension		15	18%	20–30%	20–30%		1.4	11.4

Table 1 (continued)

Age	Gender	Relevant diagnoses	Initial PEEP setting (cm)	Tried PEEP settings ^a (cm)	Tracheal collapse	Right bronchus collapse	Left bronchus collapse	PEEP setting used after CT (cm)	CTDI (mGy)	DLP (mGy·cm)
5 m 22d	M	Bronchopulmonary dysplasia	6	6	70–80%	70–80%	70–80%	16	0.9	7.5
		Congenital diaphragmatic hernia		9	50%	50%	50%		0.9	7.5
				12	40–50%	40–50%	40–50%		0.9	7.5
				14	40–50%	40–50%	40–50%		0.9	7.5
5 m 23d	M	Bronchopulmonary dysplasia	12	12	Minimal	Minimal	Minimal	12	1.4	11.2
		Tracheobronchomalacia								
6 m 10d	F	Bronchopulmonary dysplasia	8	8	40%	40%	<20%	8	2.5	24.6
		Pulmonary hypertension		5	60%	60%	<20%		2.6	15.6
6 m 29d	F	Bronchopulmonary dysplasia	8	8	50%	40–50%	50%	10	1.8	18.0
				10	30%	20–30%	30%		1.8	18.0
				11	<20%	<20%	<20%		1.8	18.0
9 m 22d	M	Bronchopulmonary dysplasia	12	12	50–60%	60–70%	60–70%	14	2.3	18.2
		Bronchoconstrictive events		10	50–60%	60–70%	60–70%		2.3	18.2
				14	50–60%	60–70%	60–70%		2.3	18.2
11 m 10d	M	Bronchopulmonary dysplasia	11	11	60–70%	60–70%	60–70%	12	1.7	17.1
		Tracheobronchomalacia		13	10%	10%	10%		1.7	17.1
				12	30%	30%	30%		1.7	17.1
1y 2 m8d	F	Bronchopulmonary dysplasia	15	15	30%	5%	5%	13	1.8	10.8
		Tracheobronchomalacia		13	30–40%	30–40%	30–40%		1.8	10.8
		Pulmonary hypertension		11	30–40%	30–40%	30–40%		1.8	10.8
		Congenital heart disease								

CPAM Congenital Pulmonary Airway Malformation, CTDI CT dose index, *d* days, *DLP* dose–length product, *F* female, *M* male, *m* months, *U* ambiguous gender, *y* years^a Initial PEEP setting listed followed by PEEP settings trialed during CT^b Same patient

accommodate the complex airway and pulmonary physiology of these children with multiple comorbidities. Dynamic CT shows promise as an objective and quantitative tool to optimize PEEP settings. In our study, 12 of 17 (71%) dynamic

airway CT exams resulted in a change of the PEEP setting. While many of the changes in PEEP setting were on the order of 1–2 cm H₂O, an increase of 10 cm H₂O was made in one child and a decrease of 7 cm H₂O was made in another.

Fig. 1 Dynamic airway CT in a neonate age 2 months 25 days who was born at 26 3/7 weeks of gestational age with bronchopulmonary dysplasia (BPD). **a–c** Inspiratory cross-sectional area measurements were performed of the trachea (**a**), right mainstem bronchus (**b**) and left mainstem bronchus (**c**) for reference. **d–f** Expiratory cross-sectional area measurements at a positive end-expiratory pressure (PEEP) setting of 6 cm H₂O within the trachea (**d**), right mainstem bronchus (**e**) and left mainstem bronchus (**f**) demonstrate decreases in expiratory cross-sectional area compared to inspiratory cross-sectional area of 83% (cross-sectional area: 23 mm² inspiratory, 4 mm² expiratory), 75% (cross-sectional area: 12 mm² inspiratory, 3 mm² expiratory) and 78% (cross-sectional area: 9 mm² inspiratory, 2 mm² expiratory), respectively. **g–i** PEEP setting of 8 cm H₂O. Expiratory cross-sectional area measurements within the trachea (**g**), right mainstem bronchus (**h**) and left mainstem bronchus (**i**) demonstrate decreases in expiratory cross-sectional area compared to inspiratory cross-sectional area of 71% (21 mm² inspiratory, 6 mm² expiratory), 60% (10 mm² inspiratory, 4 mm² expiratory) and 75% (8 mm² inspiratory, 2 mm² expiratory), respectively. **j–l** PEEP setting of 10 cm H₂O. Expiratory cross-sectional area measurements within the trachea (**j**), right mainstem bronchus (**k**) and left mainstem bronchus (**l**) demonstrate decreases in expiratory cross-sectional area compared to inspiratory cross-sectional area of 71% (21 mm² inspiratory, 6 mm² expiratory), 85% (13 mm² inspiratory, 2 mm² expiratory) and 60% (10 mm² inspiratory, 4 mm² expiratory), respectively. **m–o** PEEP setting of 12 cm H₂O. Expiratory cross-sectional area measurements within the trachea (**m**), right mainstem bronchus (**n**) and left mainstem bronchus (**o**) demonstrate decreases in expiratory cross-sectional area compared to inspiratory cross-sectional area of 64% (25 mm² inspiratory, 9 mm² expiratory), 57% (14 mm² inspiratory, 6 mm² expiratory) and 55% (11 mm² inspiratory, 5 mm² expiratory), respectively

There is a paucity of rigorous studies to provide evidence-based guidelines for determining optimal PEEP settings in infants [4, 6]. One retrospective study evaluating the use of flexible bronchoscopy in infants with BPD found nearly half of the infants had airway collapse [3]. They found flexible bronchoscopy to be safe and effective in diagnosing tracheomalacia and bronchomalacia, which can be treated with PEEP [3]. Bronchoscopy does not provide information on the state of lung inflation and CT has the benefit of simultaneously evaluating the lung parenchyma in addition to the airways. Knowledge of the state of overall lung inflation, such as areas of overinflation or atelectasis, can guide the clinician in making changes to the ventilator settings other than PEEP. In a cross-sectional study of neonatal intensive care units involving 173 units and 457 neonates (not specifically evaluating neonates with bronchopulmonary dysplasia), Van Kaam et al. [6] found that generic orders for PEEP settings of 4–6 cm H₂O were commonly placed despite evidence suggesting that higher levels of PEEP might be protective and other literature stressing the importance of an individualized approach. Another study of 17 neonatal intensive care units with a total of 278 extremely low birthweight infants showed that variation of PEEP settings in neonates was predominantly a product of differences in centers rather than clinical characteristics of the

neonates [4]. Ours is the first study to demonstrate the utility of dynamic airway CT in infants with BPD to determine the lowest PEEP setting necessary to maintain a specified end-expiratory cross-sectional area of the trachea and mainstem bronchi relative to the inspiratory cross-sectional area. Dynamic airway CT offers the advantage of real-time quantitative assessment of central airway patency, thereby allowing the PEEP setting to be tailored to the unique pulmonary physiology requirements of the each infant, as is advised by the neonatology literature [6].

At our institution, dynamic airway CT for PEEP titration is reserved for a small subset of chronically ventilated infants with BPD and complex ventilation physiology not responding to standard ventilation management strategies. Because tracheobronchomalacia is associated with increased morbidity in infants with bronchopulmonary dysplasia, it is important to have reliable methods to diagnose and assess treatment strategies for airway collapse in this fragile population [17]. CT offers a reliable assessment of the central tracheobronchial tree and is especially helpful in children with tracheobronchomalacia as a cause of non-response. Response of the smaller airways to changes in PEEP might also be indirectly assessed by the presence of atelectasis or air-trapping, although this might be underestimated in this study because of the relatively short interval between scans obtained at different PEEP settings. Further evaluation is needed to assess the impact of this maneuver on improving airway resistance, lung expansion, and potential end-organ injury.

The radiation dose for our dynamic airway CT exam protocol (mean CTDI_{vol} 1.7 mGy and DLP 12.3 mGy·cm) compares very favorably to published reference standards for chest CT exams in pediatric patients weighing less than 10 kg (CTDI_{vol} 1.8 mGy and DLP 28 mGy·cm), despite the multiple acquisitions that were obtained [18]. Three main factors allowed for radiation dose savings in our population. First, because of the specificity of the clinical question, the scan field of view was limited to the central airways rather than the entire thorax. Second, high inherent contrast between intraluminal air, central airway walls and lung parenchyma allows for very low kVp and mA while still permitting diagnostic quality. Third, CT scans were performed with volumetric technique, eliminating over-ranging associated with helical technique.

The authors acknowledge several limitations to this study. First, this is a small retrospective pilot study with only 16 patients and 17 CT exams. Second, the decision to obtain a dynamic airway CT was made by the neonatology team on the basis of a general indication of difficulty with ventilator management rather than specific referral criteria. The infant BPD

Fig. 2 Three-dimensional airway CT rendering in a neonate age 2 months 25 days who was born at 26 3/7 weeks of gestational age with bronchopulmonary dysplasia. **a** Initial image demonstrates patent central airways on inspiration. **b** The first expiratory-phase CT acquisition at a positive end-expiratory pressure (PEEP) setting of 6 cm H₂O demonstrates marked narrowing of the trachea and mainstem bronchi. **c–e** Central airway patency is increased as the trialed PEEP setting is increased to 8 cm H₂O (**c**), 10 cm H₂O (**d**) and 12 cm H₂O (**e**)

population is a complex, heterogeneous set of children with multiple comorbidities, limiting the ability to generalize the results. Most infants with BPD in our neonatal intensive care unit were not evaluated with dynamic airway CT, so the study patients likely represent more challenging cases with higher pretest probability of a suboptimal PEEP setting. However, this is precisely the patient sub-population that would benefit most from dynamic CT airway evaluation. A third limitation of this study is that measurements of small airways in neonates can be challenging given spatial resolution of CT and interobserver variability. Automation of measurements, though not performed in this study, might be helpful to improve small airway measurements. Although the purpose of this study was to demonstrate the capability of dynamic airway CT to determine the PEEP settings needed to achieve a specified degree of central airway patency, further evaluation in the form of prospective studies with larger patient cohorts is needed to determine the effect of PEEP changes instituted as a result

of dynamic airway CT on measures of oxygenation, ventilation, cardiac output and other physiological measures as well as long-term clinical outcome.

Conclusion

Mechanical ventilation in infants with BPD involves titration of PEEP settings to optimize ventilation and gas exchange while avoiding barotrauma. Determining the optimal PEEP setting in infants with BPD is challenging because of the paucity of evidence-based guidelines and need for an individualized approach to accommodate the complex physiology of each child, many of whom have several comorbidities. Dynamic CT shows promise as an objective and quantitative tool for the clinician to optimize PEEP settings.

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Compliance with ethical standards

Conflicts of interest None

References

- Kalikkot Thekkevedu R, Guaman MC, Shivanna B (2017) Bronchopulmonary dysplasia: a review of pathogenesis and pathophysiology. *Respir Med* 132:170–177
- Voynow JA (2017) “New” bronchopulmonary dysplasia and chronic lung disease. *Pediatr Respir Rev* 24:17–18
- Hysinger E, Friedman N, Jensen E et al (2018) Bronchoscopy in neonates with severe bronchopulmonary dysplasia in the NICU. *J Perinatol* 39:263–268
- Bamat NA, Guevara JP, Bryan M et al (2018) Variation in positive end-expiratory pressure levels for mechanically ventilated extremely low birth weight infants. *J Pediatr* 194:28–33
- Slutsky AS, Ranieri VM (2014) Ventilator-induced lung injury. *N Engl J Med* 370:2126–2136
- van Kaam AH, Rimensberger PC, Borensztajn D et al (2010) Ventilation practices in the neonatal intensive care unit: a cross-sectional Study. *J Pediatr* 157:767–771
- Jobe AH (2009) Lung recruitment for ventilation: does it work, and is it safe? *J Pediatr* 154:635–636
- Greenberg (2012) Dynamic pulmonary CT of children. *AJR Am J Roentgenol* 199:435–440
- Ciet P, Boiselle PM, Michaud G et al (2016) Optimal imaging protocol for measuring dynamic expiratory collapse of the central airways. *Clin Radiol* 71:e49–e55
- Lee S, Im SA, Yoon JS (2014) Tracheobronchomalacia in infants: the use of non-breath held 3D CT bronchoscopy. *Pediatr Pulmonol* 49:1028–1035
- Ullmann N, Secinaro A, Menchini L et al (2018) Dynamic expiratory CT: an effective non-invasive diagnostic exam for fragile children with suspected tracheo-bronchomalacia. *Pediatr Pulmonol* 53:73–80
- Lee EY, Boiselle PM (2009) Tracheobronchomalacia in infants and children: multidetector CT evaluation. *Radiology* 252:7–22
- Boiselle PM, Feller-Kopman D, Ashiku S et al (2003) Tracheobronchomalacia: evolving role of dynamic multislice helical CT. *Radiol Clin N Am* 41:627–636
- Newth CJ, Lipton MJ, Gould RG, Stretton M (1990) Varying tracheal cross-sectional area during respiration in infants and children with suspected upper airway obstruction by computed cinetomography scanning. *Pediatr Pulmonol* 9:224–232
- Gilkeson RC, Ciancibello LM, Hejal RB et al (2001) Tracheobronchomalacia: dynamic airway evaluation with multidetector CT. *AJR Am J Roentgenol* 176:205–210
- American Association of Physicists in Medicine Task Group 204 (2011) Size specific dose estimates (SSDE) in pediatric and adult body CT examinations. American Association of Physicists in Medicine, Alexandria
- Hysinger EB, Friedman NL, Padula MA et al (2017) Tracheobronchomalacia is associated with increased morbidity in bronchopulmonary dysplasia. *Ann Am Thorac Soc* 14:1428–1435
- Strauss KJ, Goske MJ, Towbin AJ et al (2017) Pediatric chest CT diagnostic reference ranges. *Radiology* 284:219–227

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