AJR FOCUS ON:

Expiratory Volumetric MDCT Evaluation of Air Trapping in Pediatric Patients With and Without Tracheomalacia

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OBJECTIVE. The purpose of this study was to use paired inspiratory–expiratory volumetric MDCT to compare the frequency, severity, and pattern of air trapping in pediatric patients with tracheomalacia with the findings in children without tracheomalacia.

MATERIALS AND METHODS. The study group consisted of 15 consecutively registered pediatric patients (younger than 18 years) who had tracheomalacia, defined as 50% or greater reduction in tracheal cross-sectional luminal area between end inspiration and end expiration, diagnosed with MDCT and confirmed with bronchoscopy. The comparison group consisted of 15 consecutively registered pediatric patients without evidence of tracheomalacia at MDCT and bronchoscopy. Two blinded pediatric radiologists working in consensus interpreted the randomly viewed end-expiratory thin-section CT images of both groups of children for the presence, severity, and pattern of air trapping at three anatomic levels (upper, middle, and lower lung zones). The severity of air trapping was graded visually on a 5-point scale. The total air trapping scores, obtained by summing the values for the three anatomic levels for the study and comparison groups, were compared by Wilcoxon's rank sum test. The pattern of air trapping was categorized as lobular, segmental, lobar, diffuse, or mixed, and the patterns in the two study groups were compared by Pearson's chi-square test.

RESULTS. The study cohort with tracheomalacia consisted of 15 patients (10 boys, five girls; mean age, 2.4 ± 2.8 years; range, 1 month–11.8 years). The comparison group without tracheomalacia consisted of 15 patients (nine boys, six girls; mean age, 2.7 ± 2.4 years; range, 1 month–8.1 years). Air trapping was identified in all 15 patients with tracheomalacia (median score, 5.0; range, 3–11) and in 10 of 15 children (67%) in the comparison group (median score, 3.0; range, 1–4). The median total air trapping score was significantly higher in the study cohort than in the comparison group ($p = 0.002$), but there were no significant differences in the air trapping patterns between the study groups ($p = 0.53$).

CONCLUSION. Pediatric patients with tracheomalacia have a higher frequency and greater severity of air trapping than do children without tracheomalacia.

Keywords: air trapping, children, expiratory volumetric MDCT, infants, tracheomalacia

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Expiratory high-resolution CT is an established, reliable, and accurate technique for assessing air trapping in both pediatric and adult patients [1–3]. In children, expiratory air trapping has been associated with a variety of congenital and acquired pulmonary disease processes, including bronchial atresia, congenital lobar emphysema, pulmonary sequestration, bronchopulmonary dysplasia, Swyer-James syndrome, asthma, bronchiectasis, and bronchiolitis obliterans [4–12]. In adults, expiratory air trapping has been associated with tracheobronchomalacia, a condition characterized by excessive tracheal collapsibility due to weakness of the airway walls or supporting cartilage [13]. In adults with tracheomalacia, air trapping has been postulated to occur as the result of chronic inflammation of the small airways related to downstream effects of central airway mechanical difficulties, including an abnormal coughing mechanism and difficulty clearing secretions [13, 14].

Because of the proposed chronic mechanism in adults, it is uncertain whether air trapping will also be observed in infants and young children with tracheomalacia. Such knowledge is potentially relevant to the diagnosis and management of tracheomalacia in pediatric patients. The purpose of our study was to use paired inspiratory–expiratory volumetric MDCT to compare the frequency, severity, and patterns of air trapping in pediatric

patients with tracheomalacia with the findings in children without tracheomalacia.

Materials and Methods

Patient Population

Our hospital institutional review board approved the review of radiologic and clinical data for this study. Informed consent was not required for this retrospective analysis, but patient confidentiality was protected in accordance with HIPAA guidelines. We used our hospital information system covering the period December 2004 to April 2009 to identify 15 consecutively registered pediatric patients (younger than 18 years) with tracheomalacia detected with paired inspiratory–expiratory volumetric MDCT and confirmed with bronchoscopy. For a comparison group, 15 pediatric patients without CT evidence of tracheomalacia at paired inspiratory–expiratory volumetric MDCT who also underwent bronchoscopy were selected from the same time period and matched with the study group with regard to age, use of sedation and intubation, and type of MDCT scanner. Exclusion criteria were the presence of pleural and parenchymal abnormalities (e.g., infectious pneumonia, mass, pneumothorax, and pleural effusion) that limited evaluation of air trapping in one or both lungs and presence of a central airway condition other than tracheomalacia (e.g., endobronchial foreign body, neoplasm, mucoid impaction, and central airway stenosis).

At our institution, paired inspiratory–expiratory volumetric MDCT is generally performed in the evaluation of pediatric patients when we have high clinical suspicion of tracheomalacia based on unexplained recurrent respiratory symptoms (e.g., stridor, cough, desaturation, and lower airway infection) with or without known risk factors. The decision to perform imaging usually is reached by discussion among pediatric pulmonologists, pediatric radiologists, and pediatric surgeons. It is common for these patients to undergo both MDCT and bronchoscopy.

CT Technique

In the study and the comparison groups, the 13 patients younger than 5 years were sedated and the two patients older than 5 years underwent MDCT without sedation or intubation. All MDCT studies were performed with a 16-MDCT scanner (LightSpeed 16, GE Healthcare) (12 patients) or a 64-MDCT scanner (Sensation 64, Siemens Healthcare) (18 patients).

The CT scan coverage extended from immediately below the vocal cords to the level of the diaphragm. CT parameters included 0.75-mm collimation for 16-MDCT and 0.6-mm collimation for 64 MDCT, weight-based low-dose tube current and kilovoltage, high-speed mode, and a pitch equivalent of 0.55–0.94. CT images were reconstructed with a high-spatial-resolution algorithm (bone algorithm).

All patients underwent imaging with the standard MDCT central airway protocol used in our department. This protocol consists of imaging at two different phases of respiration: the end-inspiratory phase (imaging during suspended end inspiration) and the end-expiratory phase (imaging during suspended end expiration). For the 26 infants and young children who needed general anesthesia and intubation, CT was performed with the patient in the supine position, and positive-pressure ventilation was alternately applied and withheld during inspiration and expiration, respectively [15, 16]. To approximate the physiologic level of end-inspiratory pressure typically generated by nonintubated children, the end-inspiratory pressure in sedated and intubated infants and young children was held at 20 cm water [15, 16]. After end-inspiratory phase CT, positive-pressure ventilation was withheld, which resulted in an end-expiratory pressure close to 0 cm water. The four patients able to follow breathing instructions underwent both end-inspiratory and end-expiratory phase MDCT in the supine position after practicing the inspiratory and expiratory breathing techniques with experienced CT technologists. End-inspiratory CT was performed first for all patients and was followed by end-expiratory CT. CT was performed in the craniocaudal direction for both end-inspiratory and end-expiratory imaging.

CT Image Evaluation

The reviewers evaluated all CT images using a PACS at standard lung window settings (level, –450 to –550 HU; width, 1,600–1,800 HU).

Image quality—Images from all paired inspiratory–expiratory volumetric MDCT examinations were first evaluated by an experienced, board-certified pediatric radiologist for the quality of inspiratory and expiratory CT images and the presence of respiratory motion artifact. The criteria for a diagnostic quality inspiratory CT image included round or oval configuration of the trachea and well-expanded lungs [17]. The criteria for a diagnostic quality expiratory CT image were flattening or anterior bowing of the posterior membranous wall of the trachea, increased attenuation of all or part of the lung parenchyma, and decreased overall lung volume associated with decreased anteroposterior dimension of the chest [17]. Respiratory motion artifact was defined by the presence of one or more double-imaged structures (e.g., doubling of bronchi, vessels, and fissures or doubling of the contours of the trachea, heart, and mediastinum). MDCT examinations with nondiagnostic quality images or respiratory motion artifact were excluded from the final analysis.

Evaluation for tracheomalacia—The reviewer also evaluated the images from all MDCT examinations for the presence or absence of tracheomalacia. For each examination, the reviewer first carefully assessed the entire trachea on both end-inspiratory and end-expiratory CT images and selected the area of greatest narrowing as a measurement level. The cross-sectional area of the trachea was measured in square millimeters with an electronic tool for tracing the inner wall of the airway at the same anatomic level at both end inspiration and end expiration. If the trachea had a uniform caliber without a focal area of greatest narrowing, the cross-sectional area of the trachea was measured at a level immediately above the aortic arch on both the end-inspiratory and end-expiratory images.

The percentage of expiratory tracheal collapse was calculated by comparison of the reduction in the cross-sectional area between CT images from each end-expiratory phase and the end-inspiratory phase of the breathing cycle at the same anatomic level. A diagnosis of tracheomalacia was defined as 50% or greater reduction in the central airway cross-sectional area at end expiration compared with end inspiration [15–17].

Evaluation for air trapping—Two board-certified pediatric radiologists not involved in the initial selection of MDCT examinations, assessment of the diagnostic quality of the CT images, or evaluation for the presence of tracheomalacia retrospectively reviewed all CT studies in consensus. To decrease the potential for bias, the reviewers were blinded to all other clinical data, previous imaging findings, and bronchoscopic findings. Identifying information was removed from the CT images, and the CT scans with and those without tracheomalacia were reviewed randomly. The reviewers assessed the images from each paired inspiratory–expiratory volumetric MDCT examination for the presence and severity of air trapping and the pattern of air trapping.

The diagnosis of air trapping was made on end-expiratory CT images when lung regions did not exhibit an increase in attenuation or a decrease in volume with regard to the appearance on end-inspiratory CT images [18, 19]. We excluded lung regions of air trapping limited to a single secondary pulmonary lobule because it has been reported [20] that air trapping can be seen in isolated secondary pulmonary lobules in healthy persons.

The end-expiratory and end-inspiratory MDCT images from each examination were compared for evidence of air trapping at the three following anatomic levels: upper lung, defined as the level of

the superior aspect of the aortic arch; middle lung, defined as the level of the carina; and lower lung, defined as the level of the left inferior pulmonary vein. The semiquantitative scoring system used to categorize the severity of air trapping was adapted from previous work [13, 20, 21]. The severity of air trapping at each of the three anatomic levels was graded on a 5-point scale: 0, no visible air trapping; 1, 1–25% of the cross-sectional area affected; 2, 26–50% of the cross-sectional area affected; 3, 51–75% of the cross-sectional area affected; and 4, 76–100% of the cross-sectional area affected [13, 20, 21]. To obtain a total air trapping score for a CT examination, the scores for all three anatomic levels per examination were added (range of possible total air trapping scores, 0–12).

The pattern of air trapping was categorized as lobular, segmental, lobar, diffuse, or mixed [13]. The diagnosis of lobular air trapping was made when areas of air trapping involved less than an entire segment. Lobular air trapping included small foci corresponding to the shape of secondary pulmonary lobules and large foci representing several adjacent lobules with involvement of less than an entire segment. Segmental air trapping was considered present when an entire segment or multiple adjacent segments involved less than an entire lobe. The diagnosis of lobar pattern was based on the involvement of an entire lobe. A diffuse pattern referred to the involvement of more than 50% of the lungs without characteristic distribution of lobules, segments, or lobes. The diagnosis of a mixed pattern was made when more than one type of pattern was present.

TABLE 1: Results on Air Trapping in Pediatric Patients With and Without Tracheomalacia

Patient No.	Patient Characteristics			Total Air Trapping Score	Pattern of Air Trapping
	Age (mo)	Sex	Clinical Symptom		
Tracheomalacia					
1	5	M	Stridor	9	Mixed (lobular, segmental)
2	53	F	Stridor	10	Mixed (lobular, segmental)
3	80	F	Cough	3	Lobular
4	143	M	Recurrent infection	5	Lobular
5	50	M	Stridor	5	Lobular
6	13	F	Recurrent infection	11	Mixed (lobular, segmental)
7	2	M	Desaturation	3	Diffuse
8	7	M	Stridor	5	Lobular
9	6	M	Stridor	6	Mixed (lobular, segmental)
10	4	M	Desaturation	3	Lobular
11	15	F	Stridor	6	Lobular
12	6	M	Stridor	4	Lobular
13	38	M	Cough	8	Mixed (lobular, segmental)
14	4	F	Stridor	5	Lobular
15	1	M	Stridor	3	Lobular
No tracheomalacia					
1	8	F	Desaturation	N/A	N/A
2	75	M	Stridor	3	Lobular
3	55	M	Recurrent infection	2	Lobular
4	3	F	Stridor	4	Mixed (lobular, segmental)
5	39	F	Recurrent infection	N/A	N/A
6	14	F	Cough	N/A	N/A
7	8	M	Stridor	4	Segmental
8	2	F	Desaturation	3	Lobular
9	8	M	Stridor	2	Lobular
10	51	M	Cough	N/A	N/A
11	59	F	Cough	N/A	N/A
12	98	M	Stridor	1	Lobular
13	24	M	Stridor	1	Lobular
14	26	M	Stridor	4	Mixed (lobular, segmental)
15	15	M	Stridor	4	Mixed (lobular, segmental)

Note—N/A = not applicable.

Bronchoscopic Evaluation

All patients underwent bronchoscopy, 18 patients before and 12 patients after CT examinations. The diagnosis of tracheomalacia was made at bronchoscopy when 50% or greater reduction in the caliber of the trachea was found during expiration.

Follow-Up Information

For each patient, the hospital information system was used to determine the presence of clinical diagnoses such as asthma and other respiratory conditions, which may have contributed to the patient's clinical symptoms and imaging findings. This information was reviewed for the time leading up to and for up to 2 months after the date of the paired inspiratory–expiratory volumetric MDCT examination included in our study.

Statistical Analysis

Normally distributed variables, including age and percentage of tracheal collapse, were compared by two-sample Student's *t* test. Sex and symptoms were compared by Fisher's exact test for binomial proportions. Air trapping scores (0–11 points) exhibited skewness and were therefore compared by nonparametric Wilcoxon's rank sum test [22]. The patterns of air trapping in the two study groups were compared by Pearson's chi-square test. Two-tailed $p < 0.05$ was considered statistically significant. Statistical analysis was performed with a software package (SPSS version 16.0, SPSS).

Results

Study Cohort

Information regarding age, sex, and symptoms is listed in Table 1. The study group consisted of 15 patients (10 boys, five girls; mean age, 2.4 ± 2.8 [SD] years; range, 1 month–11.8 years) with the CT and bronchoscopic diagnosis of tracheomalacia. The comparison group without CT and bronchoscopic evidence of tracheomalacia consisted of 15 patients (nine boys, six girls; mean age, 2.7 ± 2.4 years; range, 1 month–8.1 years). The 15 patients in the tracheomalacia group

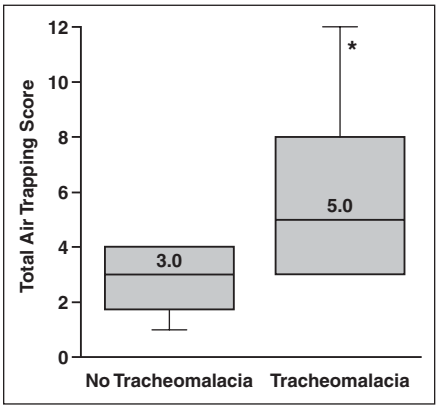

Fig. 1—Box-and-whisker plot shows total air trapping scores for two groups. Median score in tracheomalacia group (5.0 points; range, 3–11 points) was significantly higher than score in comparison group (median score, 3.0 points; range, 1–4 points) (p = 0.002, Wilcoxon's rank sum test [*asterisk*]). Interquartile ranges (25th to 75th percentile of scores) as indicated by length of boxes were 3–8 points in tracheomalacia group and 2–4 points in comparison group.

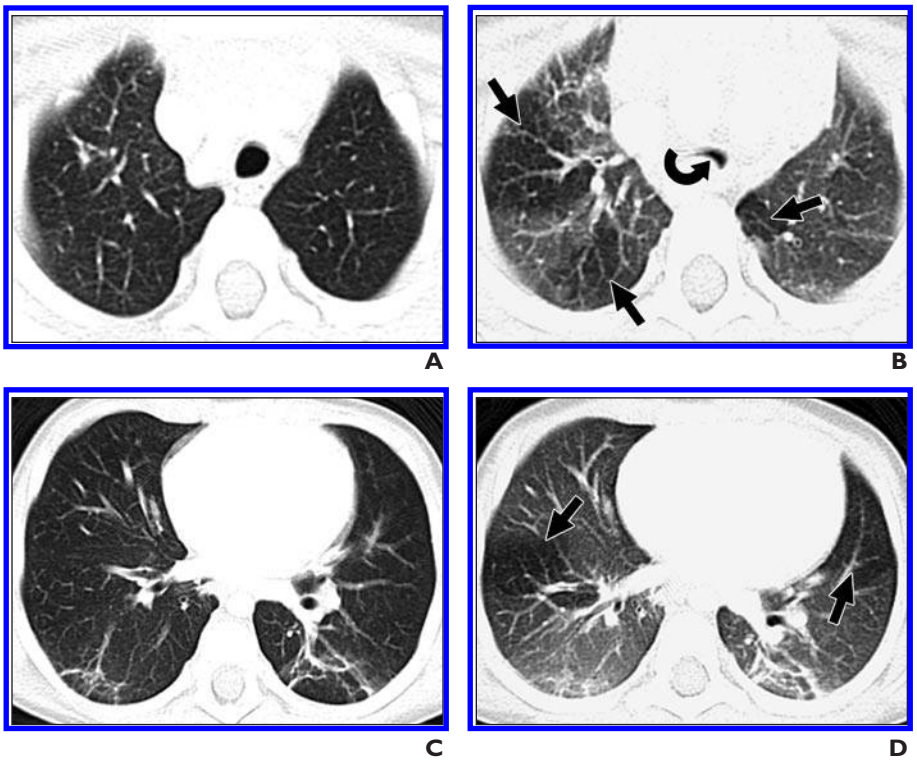

Fig. 2—4-year-old girl with recurrent cough. Paired inspiratory–expiratory volumetric MDCT was performed for evaluation for possible underlying tracheomalacia.
A, Axial end-inspiratory CT image obtained with lung window shows normal appearance of trachea and lung parenchyma.
B, Axial end-expiratory CT image obtained with lung window at same level as **A** shows excessive collapse of trachea (*curved arrow*) consistent with tracheomalacia. Areas of geographically marginated radiolucency (*straight arrows*) in both lungs are consistent with air trapping.
C, Axial end-inspiratory CT image obtained with lung window at level of left inferior pulmonary vein shows normal appearance of lung parenchyma. Linear atelectasis is present in posterior aspect of lower lobes.
D, Axial end-expiratory CT image obtained with lung window at same level as **C** shows geographically marginated radiolucency (*arrows*) in both lungs consistent with air trapping. Dependent atelectasis is present in posterior aspect of lower lobes.

came to medical attention with respiratory symptoms, including stridor in nine patients and cough, desaturation, and recurrent infection in two patients each. The 15 patients without tracheomalacia also had respiratory symptoms, including stridor in eight patients, cough in three patients, and desaturation and recurrent infection in two patients each. There were no significant differences between the groups with respect to age (p = 0.22, two-sample Student's t test), sex (p = 0.99, Fisher's exact test), and presenting symptoms (all $p > 0.99$, Fisher's exact test).

CT Findings

Image quality—All paired inspiratory–expiratory volumetric MDCT examinations of the study and comparison groups yielded diagnostic quality images without respiratory motion artifact.

Tracheomalacia—The mean percentage tracheal collapse in the tracheomalacia group was 81.6% ± 12.9% (range, 62.5–100%). The mean percentage tracheal collapse in the group without tracheomalacia was 5.4% ± 3.0% (range, 2.1–11.5%).

Air trapping—The presence and severity of air trapping diagnosed with MDCT in patients with and those without tracheomalacia are summarized in Table 1 and illustrated in Figure 1. All 15 of the patients in the tracheomalacia group had evidence of air trapping, having a median score of 5.0 points (range, 3–11 points) (Fig. 2). In the comparison group, 10 of 15 patients (67%) had air trapping, having a median score of 3.0 points (range, 1–4 points) (Fig. 3). Total air trapping scores were significantly higher (p = 0.002, Wilcoxon's rank sum test) in patients with tracheomalacia than in those without tracheomalacia.

The air trapping patterns are listed in Table 1, which shows the common patterns of air trapping in patients with tracheomalacia were lobular (60%), mixed (33%), and diffuse (7%). The most common patterns in the 10 patients without tracheomalacia who had air trapping were lobular (60%), mixed (30%), and segmental (10%). There were no significant differences between the air trapping patterns of the two study groups (p = 0.53, Pearson's chi-square test).

Follow-Up Information

Follow-up information was available for all 30 patients in the study. Three of the 15 patients with tracheomalacia (20%) had potential causes of the clinical symptoms other than tracheomalacia, including asthma in one patient, chronic lung disease in one, and laryngeal cleft in the third. In the comparison group, seven patients (47%) were found to have respiratory conditions that could have explained the symptoms, including asthma in six patients and laryngeal cleft in one patient. No documented potential cause of the respiratory symptoms was found in the other eight patients (53%) in the comparison group.

Discussion

The results of our study show that children with tracheomalacia have a significantly higher frequency and greater severity of air trapping than children without tracheomalacia. This association has potential implications for the diagnosis and management of tracheomalacia in infants and children. It also raises essential

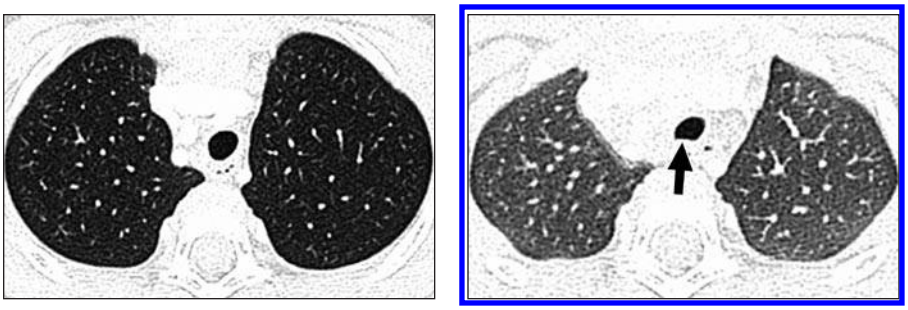

Fig. 3—5-year-old girl with recurrent cough. Paired inspiratory–expiratory volumetric MDCT was performed for evaluation of possible underlying tracheomalacia.
A, Axial end-inspiratory CT image obtained with lung window shows normal appearance of trachea.
B, Axial end-expiratory CT image obtained with lung window at same level as **A** shows flattening (*arrow*) of posterior membranous wall of trachea, which is normal finding at end expiration. Mild expiratory decrease in caliber of tracheal lumen does not meet CT criteria for tracheomalacia. Generalized increased attenuation of lung parenchyma is present without evidence of air trapping. Decreased lung volume associated with decreased anteroposterior dimension of chest also is evident. These findings are normal at end expiration.

questions about the potential mechanism of combined large and small airways disease in infants and children with tracheomalacia.

To our knowledge, our study is the first to show a significant association between air trapping and tracheomalacia in the pediatric population. From a practical diagnostic standpoint, our results suggest that the presence of air trapping in the lungs on expiratory CT images should alert radiologists to carefully assess the change in tracheal caliber between end-inspiratory and end-expiratory CT images of children for possible concomitant tracheomalacia. This practice has the potential to enhance the detection of tracheomalacia, which is widely considered to be underdiagnosed in both children and adults [23, 24].

Although the precise cause of air trapping in patients with tracheomalacia has not been established, it has been postulated that in adults with tracheomalacia, small airways disease develops as a result of recurrent infections and chronic inflammation in the small airways due to an impaired coughing mechanism and difficulty clearing secretions associated with malacia of the central airways [13, 14]. Unlike adults with tracheomalacia, who generally come to medical attention with a chronic course of respiratory symptoms, infants, who made up most of the group with tracheomalacia in our study, are not expected to develop small airways disease by such a long-standing mechanism. Our findings therefore raise the possibility that some infants and children with tracheomalacia may have concomitant, intrinsically weak, thus easily collapsible small airways. A future study aimed at investigating the precise underlying pathophysiologic mechanism leading to the development of air trapping in pediatric patients with tracheomalacia is needed.

An interesting finding was that nearly two thirds of our comparison group had some degree of air trapping, but only approximately one third had a known risk factor such as asthma. In interpreting our results, it is important to consider the spectrum of air trapping that has been reported in healthy adults. For example, in a group of healthy adult volunteers with normal pulmonary function and no symptoms described by Tanaka et al. [25], nearly two thirds had air trapping. As in a previously reported study of adult patients with tracheomalacia [13], we found that the pattern of air trapping did not differentiate children with tracheomalacia from those without tracheomalacia. On the basis of these findings, we emphasize that the severity of air trapping, not simply its presence or pattern, is the most important factor in differentiating patients with tracheomalacia from those without tracheomalacia.

A conservative approach is currently the preferred initial treatment of infants and young children with mild to moderate tracheomalacia, because the symptoms can resolve by the age of 1–2 years owing to strengthening and stiffening of the tracheal cartilage with normal growth and development [17, 24, 26–29]. However, for patients whose condition does not improve with conservative treatment and for those with more severe symptoms, several minimally invasive and invasive treatment options are available. These include continuous positive airway pressure, tracheostomy placement, stent placement, and surgical intervention such as aortopexy [17, 24, 27–39]. Future clinical studies are necessary to determine whether the presence of severe air trapping requires treatment aimed at the small airways in addition to these standard therapies for tracheomalacia.

We acknowledge several limitations of our study. First, the retrospective nature of our study design prevented us from fully controlling for all variables that can result in air trapping, such as asthma. Thus the presence of patients with asthma among our comparison group may have led to underestimation of the degree of difference between the two groups. Second, our assessment of air trapping relied on a subjective visual grading system. We emphasize that visual grading has been validated with quantitative measures [40]. Third, our study lacked pathologic data on the histologic findings in the small airways of patients with air trapping. Such information would be helpful for determining the pathophysiologic basis for the observation of air trapping in our study sample. Fourth, our study design was limited to a one-time assessment. Follow-up data would be helpful for determining whether small airways disease is reversible after resolution of tracheomalacia due to surgical correction or to strengthening of the cartilage with maturity. Despite the limitations, we believe that our data represent an important incremental step toward larger prospective studies that are necessary to more fully elucidate the questions raised in our work.

We conclude that pediatric patients with tracheomalacia have both a higher frequency and greater severity of air trapping than do children without tracheomalacia. Therefore, the presence of air trapping on expiratory CT images of children should alert radiologists to carefully assess the change in tracheal caliber between end-inspiratory and end-expiratory CT images for possible concomitant tracheomalacia.

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