

Dynamic expiratory CT: An effective non-invasive diagnostic exam for fragile children with suspected tracheo-bronchomalacia

Nicola Ullmann MD¹  | Aurelio Secinaro MD² | Laura Menchini MD² |
Serena Caggiano MD¹ | Elisabetta Verrillo MD¹ | Teresa Pia Santangelo MD² |
Renato Cutrera PhD¹ | Paolo Tomà MD²

¹ Respiratory Unit, University Department of Pediatrics (DPUO), Bambino Gesù Children's Hospital, Rome, Italy

² Department of Imaging, Bambino Gesù Children Hospital, IRCCS, Rome, Italy

Correspondence

Nicola Ullmann, MD, Bambino Gesù Children's Hospital, Piazza S. Onofrio 4, 00165, Rome, Italy.

Email: nicola.ullmann@opbg.net/
nicolaullmann@gmail.com

Abstract

Background: Tracheobronchomalacia, defined as variable collapse of the airways, has been recognized as an important cause of respiratory morbidity but still widely underdiagnosed. Bronchoscopy is still considered as the gold standard, but numerous limitations are known, especially for fragile sick children. Moreover, information on parenchymal lung disease cannot be described. There is a real need for a reliable, non-invasive test to help detection of airway and parenchymal malformations in children, specifically when bronchoscopy cannot be performed.

Methods and Results: 34 paediatric patients underwent cine multidetector CT for ongoing respiratory symptoms and were included. All CT images were of good quality and sedation was never needed. Airway disease such as trachea-bronchomalacia with/without stenosis was described in 53% with the first being more frequent. Bronchomalacia alone was described in 10 patients and in 4 patients was associated with tracheomalacia. Moreover, CT allowed identification of parenchymal disease in 10 patients. Airways stenosis alone was detected in seven patients. The majority of patients (85%) underwent also bronchoscopy for clinical decision. The agreement between CT and bronchoscopy was explored. The two examinations did not agree only in two cases. CT dynamic showed an excellent sensitivity of 100% (81.47-100%), a great specificity of 82% (48.22-97.72%), NPV 100%, and PPV 90% (72-96.9%).

Conclusion: Dynamic CT results an effective and highly sensitive diagnostic exam for children with tracheo-bronchomalacia. CT is especially indicated for those small and fragile patients that cannot undergo an invasive investigation. Moreover, CT allows a detailed evaluation both of the airways and the lungs which is useful for the clinical management.

KEYWORDS

bronchoscopy, congenital malformations, imaging

1 | INTRODUCTION

The term malacia is originated from the Greek word "malakia," meaning soft. In tracheobronchomalacia (TBM), the walls of trachea and/or bronchi are weaker than normal, which can lead to partial collapse. The usual inspiratory enlargement and expiratory restricting of the airways due to disparities between intrathoracic and intraluminal pressures is emphasized in tracheomalacia.

Tracheo- and bronchomalacia are clinically similar, with a limited range of clinical expressions. Although TBM has recently been increasingly recognized as an important cause of significant respiratory morbidity, this condition is still widely underdiagnosed.

Diagnostic bronchoscopy (DB) has always been considered as the gold standard exam to investigate airway pathology in all age groups, but it can have many practical and diagnostic limitations especially in young sick children also for invasivity.¹ Therefore, there is a real need for a single, reliable, non-invasive test to help detection of airway and/or parenchymal malformations in children, specifically when bronchoscopy cannot be performed. Chest radiography (inspiratory and expiratory phases), conventional tomography and fluoroscopy have all been unsuccessfully used for non-invasive diagnosis of TM with significant limitations.²

Recent advances in CT imaging offer new opportunities to noninvasively diagnose both tracheomalacia and concomitant lung conditions. About CT, Lee defined the techniques currently used for evaluating TBM.³ Greenberg illustrated a continuous scanning technique by wide-detector scanners, however, literature is still scarce on its accuracy in direct comparison with the reference "gold-standard" of bronchoscopy in children.⁴ A recent study from Ngercham et al reported good correlation between CT and DB in a small selected population with TBM and esophageal atresia.⁵

Thus, the main purpose of this study was to evaluate the role of Dual-Source CT (continuous free-breathing dynamic scan) to study a larger and unselected, thus more reliable, paediatric population, unable to collaborate, with persistent respiratory symptoms for suspected TBM. The main radiological evaluation criteria considered were: image quality, especially regarding the adequacy of a narrow detector array, and radiation dose. Moreover, radiological results were compared with the reference standard bronchoscopy in order to determine whether dynamic CT has the potential to serve as a reliable method for diagnosing airway abnormalities in children with persistent respiratory symptoms.

2 | MATERIALS AND METHODS

The study was approved by the hospital institutional review board and patients confidentiality were protected. We included in the study all paediatric patients who consecutively underwent cine multidetector CT for evaluation of persistent respiratory symptoms and clinical suspicion for TBM. Dynamic pulmonary CT was adopted to detect excessive ($\geq 50\%$) collapsibility of trachea and/or bronchi.⁵⁻⁷ CT images were analyzed in consensus by two radiologists who were aware of the

clinical suspicion but were blinded to results of DB when previously performed. Young patients of different age were included and clinical data were collected uniformly in all children, focusing specifically on age at onset, type, severity, and persistency of respiratory symptoms, and presence of comorbidities.

All standard examinations were performed using a second-generation dual source CT system (Siemens Somatom Definition Flash, Siemens Erlangen, Germany) with two X-ray tubes and two detectors settled at an angular offset of 95°. Each detector provides for data acquisition with 64 detector rows of 0.6-mm collimation.

Dynamic central airways acquisition was performed using multiple sequential (5-7 temporal phases with Dynamic Serio protocol at table feed 0) at the level of intrathoracic trachea and main bronchi applying the following parameters: 28-60 mA (according to previously published formula related to body weight $\text{mA} = (\text{kg} \times 2.5) + 5/0.35$), 70-80 kVp, cranio-caudal coverage of 38,4 mm on the Z-axis, temporal resolution of 0.28 s. All patient were scanned during free breathing, with no additional Positive End-Expiratory Pressure (PEEP) in case of ventilator support and with a respiratory rate between 30 and 40 min.

Additional entire thorax acquisition was performed using a Flash spiral mode with 458 mm/s when clinically required. The high-pitch modality allowed examinations without breath-hold or sedation in non-cooperative patients. Scan parameters were as follows: pitch = 2, Collimation: 64×0.6 mm, 0.28 s gantry rotation time, ref. mAs (tube current modulation, CARE Dose) adapted to the body weight (60-90 mAs), 80 kV, Scan time: 0.2-0.3 s. Rotation time: 0.28 s.

In 2/2 patients >10 yrs. we performed a 4D SPIRAL acquisition with 1 s of Temporal Resolution, 7 cm coverage, 4-5 acquisition respiratory rate down to about 15 cycles/min. Ref. mAs (tube current modulation, CARE Dose: 90, 100 mAs), 80 kV.

All images were reconstructed with a slice thickness of 1 mm. Kernel/Algorithm: B30, B60.

When indicated a low-osmolality, nonionic contrast agent (from 300 to 400 mgI/mL) at 2 mL/kg up to 125 mL was used. An automatic injector (Stellant, Medrad, Inianola) with the following parameters: 1 mL/s for 24-gauge catheters (rarely, with the greatest caution), 1.5-2.0 mL/s for 22-gauge catheters, 2-3 mL/s for 20-gauge catheters, with a pressure limit adjusted to a maximum of 150 psi (1,034 kPa) was adopted. We empirically begun the scan at the end of the injection. IV contrast enhancement was administered in 28 patients.

Images were transferred to a workstation, which was equipped with a standard image interpretation software (Syngo3D, Siemens Healthcare, Erlangen, Germany). Tools like multiplanar reformations (MPRs), volume rendering techniques (VRTs), Minimum intensity projections (MinIPs) with cine loops in the different phases allowed an integrated advanced visualization.

Airway cross-sectional area was measured by tracing the internal perimeter of the airway on multiplanar reconstructions in both the inspiratory and expiratory phases.

Because different phases of respiration can be identified in the 6-7 temporal reconstructions, lung window images acquired at the greatest degree of inspiration could be reconstructed with thin sections for high resolution analysis of the lung parenchyma.

The majority of patients (85%) underwent also DB for clinical reasons, and, if clinically indicated, a bronchoalveolar lavage was performed. The larynx, trachea, and bronchial systems were visualized and any abnormality of the airways described. The presence of airway malacia was defined on video recordings as >50% reduction in the airway lumen during expiration, which was the same criterion applied for CT.^{2,3,8} Importantly, the two procedures (DB and CT) were performed in the same hospital admission by experienced physicians unaware of other diagnostic findings.

3 | RESULTS

A total of 34 paediatric patients (mean age 3.6 [SD 6.5] years) underwent cine multidetector CT for clinical reasons and were included in the study. Interestingly, the majority of patients had respiratory distress (RD) within the first months of life (Table 1) and 35% of children had a history of prematurity (≤ 33 weeks). Ongoing respiratory conditions at the time of CT and previous surgical procedures are summarized in Table 1.

CT images of good diagnostic quality were obtained for all children despite any age difference and none of the children needed to be sedated for CT examination. All findings are clearly summarized in Table 2. Four patients presented isolated tracheomalacia (ie, Figure 1). Airway disease such as malacia (BM and/or tracheomalacia) with/without stenosis was described in 18 patients (53%) with BM resulting more frequent than tracheomalacia (14 vs 8 pts). Respectively, BM (right and/or left) alone was detected in 10 patients (ie, Figure 2) and BM associated with tracheomalacia was found only in four patients. A total of 10 patients had left BM and the majority of these (80%) underwent previous cardiologic surgery. In 10 patients pulmonary pathological conditions were described at CT (ie, consolidations, atelectasis, bronchiectasis, and parenchymal ground glass); seven of those patients had also pathologic tracheobronchial findings. Airways stenosis alone was detected in seven patients.

Diagnostic bronchoscopy, performed for clinical reasons to exclude macroscopic abnormalities, was performed in the majority of patients (29/34-85%) and was completely negative in eight cases (28%). We analyzed whether there was an agreement in the diagnosis of airways malacia and/or stenosis between dynamic CT and DB (Table 2). Agreement was clinically classified as complete or partial. The latter was considered when both techniques could describe the same malformation and the location was similar but not identical. In 27 cases (93%) agreement between the two studies was complete or partial, with the latter being only in four patients. In details, in 3/4 patients (pts n° 3, 5, and 16 in tables) CT dynamic and endoscopy described the same malformation but the location was not identical, specifically, CT dynamic identified a larger extension of the pathological condition. In another patient (pt n° 26), CT identified a left BM while DB identified a left bronchus stenosis and a right BM. The two diagnostic examinations did not agree only in two cases when a right BM (pts n° 15, 21) detected by dynamic CT, was not described by the bronchoscopist. Therefore, considering bronchoscopy as gold

standard, CT dynamic showed a great diagnostic sensitivity and a specificity as clearly summarized in Table 3.

Importantly, in three patients with normal airways findings (pts 7, 15, 21), CT was useful in fact allowed detection of parenchymal morbidity such as multiple areas of distelectasis. Differently, in one case (pt n° 29) the two exams agreed, being both negative for tracheal or bronchial malformations, but bronchoscopy allowed identification of laryngomalacia.

In the 18 patients with pathologic radiological findings (TBM and/or airway stenosis), the cine multidetector CT images significantly contributed to final clinical decisions and specific interventions were adopted (Table 2). Tracheostomy was performed in six cases, in one patient the surgical intervention was concomitant with balloon dilatation which was also performed in other four children for significant stenosis. Moreover, non invasive respiratory support (NIV and nasal cPAP) was started in three patients with clinical benefit. In two patients mechanical ventilation was necessary or parameters modified.

In other children the resolution of concomitant comorbidities (ie, recurrent aspiration), an endoscopic laser treatment or a bronchial stent placement were effective to cause cessation of respiratory symptoms. The rest of the patients, even with airways pathologic findings, did not need any modification of their respiratory treatments because they were able to grow out of it.

Mean dose of dynamic scans (the cumulative values of all time points in the total dynamic scan) in patients <10 yrs was DLP 13 mGy.cm, CTDIvol 3.01 mGy (DLP range: 5-27 mGy.cm, CTDIvol range: 1.98-3.43 mGy). Mean dose of complete examination was DLP 33 mGy.cm, CTDIvol 4.35 mGy (DLP range: 10-58 mGy.cm, CTDIvol range: 3.08-5.23 mGy). Mean dose of dynamic scans in few patients >10 yrs was DLP 69 mGy.cm, CTDIvol 7.8 mGy. Mean dose of complete examination was DLP 117 mGy.cm, CTDIvol 19.4 mGy. The use of 4D SPIRAL acquisition explain the high DLP/CTDI ratio.

European DRL (piDRL) for computed tomography of the thorax in children <10 yrs is DLP 45 mGy.cm, CTDIvol 2.7 mGy; in 10-15 yrs DLP 80 mGy.cm, CTDIvol 3.3 mGy.⁹ Of course piDRL are related to a single scan on the same area (single time point). In our series in dynamic scans we acquired 5-7 time points that means an increased irradiation of the human body tissues in the field of view.

4 | DISCUSSION

TBM is a condition characterized by excessive expiratory collapse of the trachea and/or bronchi caused by underlying weakening of the airway walls or supporting cartilage.² Although TBM has recently been increasingly recognized as an important cause of chronic respiratory symptoms, this condition is still widely underdiagnosed because it is a functional abnormality that may escape the detection with routine end-inspiratory CT imaging.¹⁰ Particularly in young children, an early and correct diagnosis is crucial to avoid unnecessary drugs, and medical management can be tailored to minimise frequent respiratory collapses and reduce various concomitant complications.

TABLE 1 Clinical symptoms and surgical background of patients

Patients	First respiratory problems	Previous thoracic surgery	Ongoing respiratory problems
1	RD	ISD, VSD, PDA	Chronic respiratory insufficiency
2	RD	VSD, PFO	Hypercapnia
3	RD, stridor	—	RD
4	RD, pulmonary hypertension	ISD, VSD	RD, mild hypercapnia, atelectasis
5	RD, stridor	Double aortic arch	Exertional dyspnea
6	Stridor	—	Exertional dyspnea, recurrent infections
7	RD	—	RD, cyanosis, mild laryngeal stridor
8	Bronchospasm	—	Recurrent infections and bronchospasm
9	Cyanosis	Right aortic arch, Tetralogy Fallot, PAS	Recurrent bronchospasm/infections
10	RD	—	Hypercapnia
11	RD in respiratory infection	—	RD in respiratory infection
12	RD	VSD, ISD, Pulmonary artery sling	RD, difficult extubation
13	RD	—	RD, hypercapnia
14	RD	VSD, ISD, AV Canal, PAB	Difficult extubation (tracheostomy)
15	Lobar emphysema/Ab ingestis pneumonia	—	RD, difficult extubation (tracheostomy)
16	RD	Lungs transplantation	RD and respiratory infections
17	Stridor	—	Desaturations, hypercapnia
18	Recurrent inhalations	Esophageal atresia with fistula	Recurrent bronchospasm/infections
19	Cyanosis, RD	Tetralogy Fallot, PVR, ISD, VSD	RD
20	Respiratory stridor	—	Respiratory stridor, recurrent bronchospasm and infections
21	RD, Pulmonary hypertension	—	RD
22	RD	Tetralogy Fallot, Vascular ring	RD, chronic respiratory insufficiency
23	RD, Respiratory stridor	—	Respiratory stridor
24	RD	Tetralogy Fallot	Desaturations, atelectasis
25	RD, Respiratory stridor	—	RD
26	RD, neonatal asphyxia	PDA	Respiratory insufficiency
27	RD	TBA, AAI	RD
28	RD	—	RD
29	RD, Respiratory stridor	—	RD
30	RD	—	RD
31	RD	—	Recurrent pulmonary infections, desaturations, atelectasis
32	RD	—	RD
33	RD	PVR	RD
34	RD	—	RD

AAI, aortic arch interruption; AV Canal, atrioventricular canal; ISD, interatrial septal defect; PDA, patent ductus arteriosus; PFO, patent foramen ovale; PAB, pulmonary artery banding; PAS, pulmonary artery stenting; PVR, pulmonary valve replacement; RD, respiratory distress; TBA, transposition of big artery; VSD, ventricular septal defect.

Bronchoscopic visualization of dynamic airway collapse is considered the gold-standard to investigate airway disease in all age groups, but several investigators have highlighted many limitations such as, possible false negative results due to the generation of an endobronchial positive pressure.¹¹ Moreover, DB is an invasive technique and it may

not be clinically feasible or desirable to be performed in little and fragile patients and it does not offer any information on lung parenchymal abnormalities.⁸ Additionally, pulmonary function testing may provide supportive evidence in adults, but it is limited in paediatric patients and it does not give any anatomic information.

TABLE 2 Diagnostic exams and medical interventions

Patients	Bronchoscopy findings	CT findings	Medical interventions
1	—	Left BM	cPAP
2	—	Tracheo, right and left BM	Tracheostomy
3	Larngo-tracheomalacia	Tracheo and left BM	Tracheostomy
4	Right and left BM	Right and left BM	—
5	Tracheo and right BM	Tracheo, right and left BM	—
6	Negative	Negative	—
7	Negative	Atelectasis	—
8	—	Supernumerary bronchial bud	—
9	—	Right bronchial stenosis	—
10	Right and left BM	Right and left BM	cPAP
11	—	Negative	—
12	Tracheal stenosis	Tracheal stenosis	Tracheostomy and balloon dilation
13	Negative	Negative	—
14	Tracheal stenosis and left BM	Tracheal stenosis, left BM	Balloon dilation
15	Negative	Right BM, atelectasis	Tracheostomy
16	Left bronchial stenosis	Bilateral bronchial stenosis	Balloon dilation
17	Tracheo and left stenosis	Tracheo and left stenosis	—
18	Tracheomalacia and stenosis	Tracheomalacia and stenosis	—
19	Tracheal stenosis, right and left BM	Tracheal stenosis, right and left BM	Changed Mechanical Ventilation
20	Tracheal stenosis	Tracheal stenosis	Balloon dilation
21	Negative	Right BM, atelectasis	—
22	Left bronchial stenosis ^a	Left bronchial stenosis, Partial LIL consolidation	Laser treatment
23	Negative	Negative	—
24	Tracheomalacia	Tracheomalacia, atelectasis	—
25	Negative	Negative	Tracheostomy
26	Right bronchus malacia, left bronchus stenosis	Left BM	Left superior lobectomy
27	Bronchial stenosis	Bronchial stenosis	—
28	Left bronchial stenosis	Left bronchial stenosis	Left bronchial stent
29	Laryngomalacia	Negative	Ariepiglottoplasty for laryngomalacia
30	BM	BM	Nocturnal NIV
31	TEF	TEF, BM	TEF correction
32	BM, Tracheomalacia	BM, Tracheomalacia	Tracheostomy, VMI
33	TM	TM	—
34	Negative	Negative	—

BM, bronchomalacia; LS, laryngeal stenosis; TB, tracheal bronchus; LIL, left inferior lobe; TEF, tracheoesophageal fistula.

^aIn another Hospital.

Therefore, there is a need for a single, reliable, non-invasive test to help detection of airway and/or parenchymal malformations in children, specifically when DB cannot be performed.

MDCT seems to be a promising non-invasive method to assess airway pathological conditions. Both inspiratory and expiratory MDCT images should be performed in children with suspected TBM.¹² Different types of MDCT techniques are currently used for

evaluating TBM: (I) paired end-inspiratory and -expiratory MDCT in uncooperative children following intubation by alternatively applying and withholding positive pressure; (II) paired end-inspiratory and dynamic expiratory MDCT (forceful exhalation) which is the method of choice for imaging adults and children older than 5 years; and (III) cine MDCT combined with or without a coughing manoeuvre.⁴

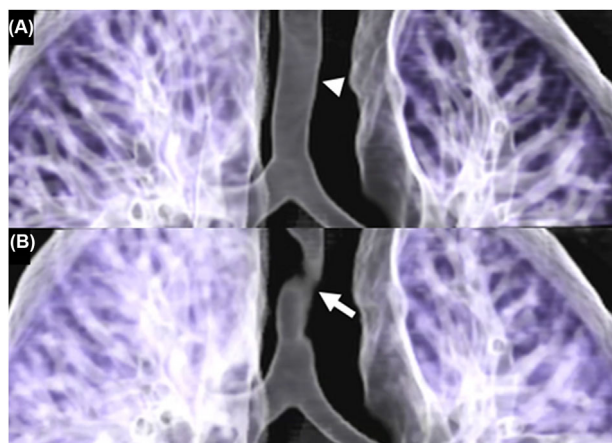


FIGURE 1 3D volume rendering "shaded" reconstruction of central airways and lungs shows normal tracheal caliber during inspiration (1A arrowhead) and significant collapse of tracheal wall during expiration in keeping with tracheomalacia (1B arrow)

We analyzed the potential of a dynamic free breathing technique with the highest temporal resolution, but with the drawback of a narrow anatomic coverage (4 cm) that limits the range of vision—the extent is age dependent—to the trachea and proximal main bronchi.

In two patients over 10 we performed a 4D SPIRAL acquisition of 7 cm coverage.

When airway malacia is present, bronchomalacia (left and/or right) appeared to be the most frequent condition in children with ongoing respiratory symptoms. As previously suggested by Greenberg S.B. et al, our study confirmed that congenital heart disease is often associated with airway abnormalities and in particular left bronchomalacia was described for almost all children previously surgically treated.⁴

In the majority of cases (89%) the agreement between DB and the dynamic CT scan was great and both agreed when negative or described the same airway malformation. This encouraging result

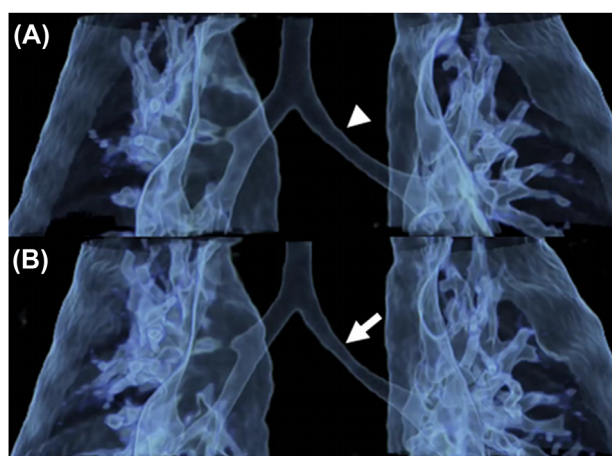


FIGURE 2 3D volume rendering "shaded" reconstruction of central airways and lungs shows normal left main bronchus caliber during inspiration (1A) and end-expirational reduction in caliber of the bronchial lumen due to bronchomalacia (1B)

TABLE 3 Agreement between Dynamic Expiratory CT and Bronchoscopy for diagnosing airway abnormalities in children with persistent respiratory symptoms

Dynamic Expiratory CT vs Bronchoscopy	
Sensitivity	100% (81.47-100%)
Specificity	81.8% (48.22-97.72%)
NPV	100%
PPV	90% (72-96.9%)

Values expressed as: % (95%CI).

NPV, negative predictive value; PPV, positive predictive value.

confirms in children what previously described in 29 adults by Lee K.S. et al.¹³

In a very small number of patients the two exams described the same pathological condition but CT dynamic identified a larger extension of the malformation. However, the small difference between the two exams in the description of the airway malformation, if only one examination was performed, it would have not affected the final clinical decision in fact, both examinations agreed on the same diagnosis. Similar small discrepancy was described in previous adults studies¹⁴ and the authors commented over the uncertainty whether this could reflect an overdiagnosis at CT or an underdiagnosis at DB. In another patient, CT identified a left bronchial stenosis while DB described it as a malacia. As previously suggested, the small discrepancy between the two exams might be due to the more subjective assessment of DB. Interestingly though, three of the four cases with partial agreement underwent a previous thoracic surgery that, we hypothesize, contributed to complicate a clear definition of the airway malformation. Unfortunately, we could not identify any specific clinical feature or element that could predict the only two cases of poor agreement between the two diagnostic assessments when malacic airways detected by dynamic CT, were not described by DB. In one of these patients unfortunately a tracheostomy was necessary for poor clinical reasons, possibly not only related to the detected airway malformation. However, we speculate that these few differences were possibly due to the subjective evaluation of DB and we believe that in our experience the objective and dynamic airways measurement of CT offered an essential support for the final treatment plan. A previous report comparing volumetric dynamic CT with bronchoscopy in only four patients, interpreted a single discordant diagnosis between the two examinations as a false bronchoscopic diagnosis.¹⁵

When airways pathologic radiological findings were detected, cine multidetector CT images contributed to subsequent clinical decisions and specific interventions were adopted as non-invasive respiratory support, balloon dilatation or tracheostomy. In all patients, interventions improved clinical symptoms and children could be finally dismissed. As previously indicated in a published treatment algorithm for TBM, in some of our patients, the medical management of comorbidities was sufficient to determine the resolution of symptoms.¹⁶

Although it was not the main aim of this study, it should be highlighted that CT examination in 29% of the patients could

simultaneously assess for concomitant abnormalities of the lungs. It is well known that parenchymal pathological conditions are often associated with TBM in children and can significantly contribute to clinical symptoms.¹⁷ Therefore, the concomitant evaluation of pulmonary causes for persistent respiratory symptoms is essential for a correct clinical management. Moreover, CT images can offer a good opportunity to identify direct consequences or parenchymal damages of an inappropriate ventilation in severe patients.¹⁸ More importantly, in some patients with normal tracheobronchial findings at DB, parenchymal abnormalities detected by CT, which contributed to a more precise management of the patient, would have been missed. In fact, as said earlier, thanks to CT images, anatomic assessment of airways' adjacent structures can be simultaneously obtained.¹⁵

Considering bronchoscopy as the gold standard, CT dynamic showed an excellent sensitivity of 100% and a very good specificity of 82% with NPV of 100% and PPV of 90%. Therefore, our study suggests that MDCT could be considered a safe and reliable diagnostic exam in a multi-specialistic paediatric Center in those patients with clinical condition that preclude invasive test.

On the other hand, we acknowledge the important benefit of a direct visualization of airways' mucosa and the unique role of DB when bronchoalveolar lavage and/or bronchial biopsies are needed.

According to radiation exposure, the dynamic study in itself with a satisfactory reliability for parenchymal lung (cranio-caudal coverage of about 4 cm) in children <10 years implicates an acceptable dose according to DRLs. If a vascular study and/or a complete view of the lungs are necessary, the sum of doses is beyond the European standards but these (cine airway vs cardiac) are two scans for separate indications. The integration with the dynamic approach causes a 68% increase of the CTDIvol and only in seriously ill patients could be clearly indicated. Besides, we compare the dose administered to the lung with a dose concentrated in 4 (7) cm of human body. The radiation exposure evaluation, evident in previous studies, was reported in mSv4.^{19,20}

To our best knowledge, this is the largest study analyzing clinical and radiological results of the use of dynamic CT scan on paediatric patients with suspected airway abnormalities, including a direct comparison with the gold-standard DB.

Our cohort showed a high prevalence (59%) of airway malformations due to the severity of patients referred to a tertiary hospital and healthy control subjects were not included. However, this limitation is unlikely to be corrected in any other future paediatric study for ethical reasons. Furthermore, we believe that MDCT should be taken into account for children with significant and unexplained persistent respiratory symptoms only after multi-disciplinary discussion between specialist paediatricians. We believe it is important to highlight that in the only patient with a negative MDCT and no available DB, the decision not to perform DB was only clinically driven and not due to radiological results. This point rules out possible errors of sensitivity overestimation. Finally, it would be important to confirm our results with future prospective studies with a larger number of paediatric patients.

From an ethical standpoint CT must be subject to a cost/benefit balance which means the correct evaluation of dose/diagnosis ratio. Radioprotection is the main limit with potential population health damage,

besides all, with difficulties in a correct quantification. However, according to WHO (World Health Organization Communicable radiation risks in paediatric imaging) the added extra level risk of cancer for standard chest CT is very "low," approximately around 0.12%.²¹

5 | CONCLUSION

The excellent agreement with the gold standard DB, suggests that MDCT is an effective and highly sensitive diagnostic exam to diagnose tracheo-bronchomalacia in children experiencing persistent respiratory symptoms. MDCT is especially indicated for those small and fragile patients that cannot undergo an invasive investigation under general anaesthesia. Moreover, MDCT allows a useful and detailed evaluation both of the airways and the lungs which is often essential for a correct clinical management. Finally, even if MDCT implicates a limited increase of radiation exposure, we believe that the examination should always be indicated by a respiratory paediatrician after a multidisciplinary approach in consideration of an appropriate cost/benefit balance.

AUTHORS' CONTRIBUTIONS

Nicola Ullmann, Aurelio Secinaro, Renato Cutrera and Paolo Tomà conceived and designed the study; Nicola Ullmann, Serena Caggiano, Elisabetta Verrillo contributed to data collection and analysis; Aurelio Secinaro, Laura Menchini, Teresa Pia Santangelo and Paolo Tomà performed all the dynamic CTs, analysed radiological data; Nicola Ullmann, Serena Caggiano and Elisabetta Verrillo collaborated to the clinical follow up of patients, analyzed clinical data; Nicola Ullmann, Serena Caggiano, Aurelio Secinaro and Laura Menchini wrote the paper, Paolo Tomà and Renato Cutrera interpreted results and revised the text.

ACKNOWLEDGMENTS

No funding to be declared

CONFLICT OF INTEREST

We declare no conflicts of interest for all the specified authors: Nicola Ullmann, Aurelio Secinaro, Laura Menchini, Serena Caggiano, Elisabetta Verrillo, Teresa Pia Santangelo, Renato Cutrera and Paolo Tomà.

ORCID

Nicola Ullmann  <http://orcid.org/0000-0003-1111-5690>

REFERENCES

1. Mok Q, Negus S, McLaren CA, et al. Computed tomography versus bronchography in the diagnosis and management of tracheobronchomalacia in ventilator dependent infants. *Arch Dis Child Fetal Neonatal Ed.* 2005;90:F290–F293.

2. Carden KA, Boiselle PM, Waltz DA, Ernst A. Tracheomalacia and tracheobronchomalacia in children and adults: an in-depth review. *Chest*. 2005;127:984–1005.
3. Lee EY, Boiselle PM, Cleveland RH. Multidetector CT evaluation of congenital lung anomalies. *Radiology*. 2008;247:632–648.
4. Greenberg SB. Dynamic pulmonary CT of children. *AJR Am J Roentgenol*. 2012;199:435–440.
5. Ngercham M, Lee EY, Zurakowski D, Tracy DA, Jennings R. Tracheobronchomalacia in pediatric patients with esophageal atresia: comparison of diagnostic laryngoscopy/bronchoscopy and dynamic airway multidetector computed tomography. *J Pediatr Surg*. 2015;50:402–407.
6. Boiselle PM, Feller-Kopman D, Ashiku S, Weeks D, Ernst A. Tracheobronchomalacia: evolving role of dynamic multislice helical CT. *Radiol Clin North Am*. 2003;41:627–36. Review.
7. Ferretti GR, Jankowski A, Perrin MA, et al. Multi-detector CT evaluation in patients suspected of tracheobronchomalacia: comparison of end-expiratory with dynamic expiratory volumetric acquisitions. *Eur J Radiol*. 2008;68:340–346.
8. Lee KS, Sun MRM, Ernst A, Feller-Kopman D, Majid A, Boiselle PM. Comparison of Dynamic Expiratory CT with bronchoscopy for diagnosing airway malacia. *Chest*. 2007;131:758–764.
9. European Guidelines on DRLs for Paediatric Imaging Final complete draft for PiDRL Workshop 9, 30 September 2015. http://www.eurosafeimaging.org/wp/wp-content/uploads/2015/09/European-Guidelines-on-DRLs-for-Paediatric-Imaging_FINAL-for-workshop_30-Sept-2015.pdf
10. Lee EY, Boiselle PM. Tracheobronchomalacia in infants and children: multidetector CT evaluation. *Radiology*. 2009;252: 7–22.
11. Burden RJ, Shann F, Bult W, et al. Tracheobronchial malacia and stenosis in children in intensive care: bronchograms help to predict outcome. *Thorax*. 1999;54:5811–5817.
12. Lee EY, Greenberg SB, Boiselle PM. Multidetector computed tomography of pediatric large airway diseases: state of the art. *Radiol Clin N Am*. 2011;49:869–893.
13. Lee Karen S, Sun Maryellen RM, Ernst Armin, Feller-Kopman David, Majid Adnan, Boiselle Phillip M. Comparison of dynamic expiratory CT with bronchoscopy for diagnosing airway malacia: a pilot evaluation. *Chest*. 2007;131:758–764.
14. Baroni RH, Feller-Kopman D, Nishino M, et al. Tracheobronchomalacia: comparison between end-expiratory and dynamic expiratory CT for evaluation of central airway collapse. *Radiology*. 2005;235:635–641.
15. Judith Zhi-Yie Tan, Marcus Crossett, Michael Ditchfield. Dynamic volumetric computed tomographic assessment of the young paediatric airway: initial experience of rapid, non-invasive, four-dimensional technique. *J Med Imaging Radiat Oncol*. 57:141–148.
16. Choo EM, Seaman JC, Musani AI. Tracheomalacia/tracheobronchomalacia and hyperdynamic airway collapse. *Innumol Allergy Clin N Am*. 33:23–24.
17. Lee EY, Tracy DA, Bastos M, et al. Expiratory volumetric MDCT evaluation of air trapping in pediatric patients with and without tracheomalacia. *AJR Am J Roentgenol*. 2010;194:1210.
18. Tan JZ, Crossett M, Ditchfield M. Dynamic volumetric computed tomographic assessment of the young paediatric airway: initial experience of rapid, non-invasive, four-dimensional technique. *J Med Imaging Radiat Oncol*. 2013;57:141–148.
19. Paul JF, Rohnean A, Elfassy E, Sigal-Cinqualbre A. Radiation dose for thoracic and coronary step-and-shoot CT using a 128-slice dual-source machine in infants and small children with congenital heart disease. *Pediatr Radiol*. 2011;41:244–249.
20. Heyer C, Nuesslein T, Jung D, et al. Tracheobronchial anomalies and stenoses: detection with low-dose multidetector CT with virtual tracheobronchoscopy comparison with flexible tracheobronchoscopy. *Radiology*. 2007;242:542–549.
21. Communicating radiation risks in paediatric imaging, 2016. Available on http://www.who.int/ionizing_radiation/pub_meet/radiation-risks-paediatric-imaging/en

How to cite this article: Ullmann N, Secinaro A, Menchini L, et al. Dynamic expiratory CT: An effective non-invasive diagnostic exam for fragile children with suspected tracheobronchomalacia. *Pediatric Pulmonology*. 2018;53:73–80. <https://doi.org/10.1002/ppul.23831>