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ORIGINAL ARTICLE

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Rapid 3D imaging of the lower airway by MRI in patients with congenital heart disease: A retrospective comparison of delayed volume interpolated breath-hold examination (VIBE) to turbo spin echo (TSE)

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Abstract

Objective: When imaging the lower airway by MRI, the traditional technique turbo spin echo (TSE) results in high quality 2D images, however planning and acquisition times are lengthy. An alternative, delayed volume interpolated breath-holds examination (VIBE), is a 3D gradient echo technique that produces high spatial resolution imaging of the airway in one breath-hold. The objective of this study is to retrospectively evaluate the accuracy of lower airway measurements obtained by delayed VIBE when compared to TSE.

Design: Patients with congenital heart disease who underwent a cardiac MRI (CMR) that included a delayed VIBE sequence from 5/2008 to 9/2013 were included. Standard TSE imaging was performed and delayed VIBE was acquired 5 min after gadolinium contrast administration. Airway measurements were made on both sequences by two observers in a blinded fashion to the other observer and other technique. Intraclass correlations (ICC) were calculated to assess for agreement between both techniques and the observers.

Results: 29 studies met inclusion criteria with a mean patient age of 8.8 years (2 months to 63 years) and mean patient weight of 30.2 kg (3.5-110). All delayed VIBE and TSE sequences were found to be of diagnostic quality. Mean acquisition time was shorter for the delayed VIBE (13.1 seconds) than TSE (949.9 seconds). Overall there was very good agreement between the delayed VIBE and TSE measurements for both observers (ICC 0.78-0.94) with the exception of the distal right bronchus (ICC 0.67) The interobserver agreement was also excellent for both TSE (ICC 0.78-0.96) and VIBE (ICC 0.85-0.96).

Conclusion: Delayed VIBE is rapid and at least as accurate as the alternative TSE imaging for assessment of the lower airway by MRI across a wide spectrum of patients.

KEYWORDS

Airway, cardiac MRI, congenital heart disease, turbo spin echo (TSE), vascular ring, volume interpolated breath-hold examination (VIBE)

1 | INTRODUCTION

Airway anomalies including trachea/bronchomalacia, complete cartilaginous rings, abnormal situs, and extrinsic vascular compression of the lower airway are a relatively common comorbidity in patients with complex congenital heart disease. Therefore, it can be the case that patients with congenital heart disease will require imaging of their lower airway in addition to their heart and vasculature. Some of the more common diagnoses or indications for this evaluation include vascular ring (1%-3% of all congenital cardiac anomalies), tetralogy of Fallot with absent pulmonary valve syndrome, left pulmonary artery sling, innominate artery compression syndrome, midline descending aorta, and postoperative complications (Figure 1).[1,2] For these clinical scenarios where detailed understanding of the airway and great vessels is

FIGURE 1 Volume rendering of the aortic arch and lower airway in a pediatric patient with a double aortic arch. The red arrow highlights the tracheal compression associated with this vascular ring

important, multidetector computed tomography (MDCT) is the imaging modality of choice in some centers. It rapidly produces high resolution, three-dimensional images of both the airway and vasculature. A significant disadvantage of MDCT is the use of ionizing radiation and in this population of young patients who may require multiple diagnostic studies over their lifetime any avoidance of ionizing radiation is desirable.[3]

In our center when there is suspicion of airway anomalies in patients with congenital heart disease, we image the majority of these patients with MRI. For example in our experience, patients with vascular rings and suspected airway anomalies make up 3% of all patients who are referred for CMR.

CMR is preferred because the clinical question may additionally require the evaluation of cardiac function, quantification of shunts, quantification of valve regurgitation, or myocardial characterization. Although echocardiography is the modality of choice for intracardiac anatomy and ventricular function, CMR is uniquely suited to evaluate the airways and answer all these questions in a single study. In our institution a CMR of this kind would require a series of axial, coronal, and sagittal turbo spin echo (TSE) stacks to evaluate the airways, followed by three gadolinium enhanced 3D gradient echo (3D-GRE) acquisitions in addition to the standard functional and anatomical protocol to demonstrate the vascular anatomy. With this combination, the structural impact of vascular anomalies on the pediatric airway can be demonstrated.[4–6]

For patient under 8 years of age, our practice is to perform these CMR studies under general anesthesia. Although general anesthesia is safe, it is not without risk in this patient population.[7,8] Hence it is to the patient's advantage to complete these studies as quickly and accurately as possible to minimize their anesthetic exposure. A modification of the 3D-GRE angiogram, volume interpolated breath-hold examination (VIBE) is a rapid, contrast enhanced, imaging technique which has been described for use in the abdomen, lung parenchyma, and brain.[9] We have found that this technique, when delayed 5 minutes after contrast injection, qualitatively results in excellent visualization of the pediatric airway and thoracic vessels with high spatial resolution in a single breath-hold. Additionally other desired anatomical assessments or phase contrast imaging can be completed during this 5 minutes waiting period. Even with this delay, VIBE is a much quicker overall assessment of the airway then the more timely three plane TSE imaging that is done traditionally which requires planning, multiple breath-holds, and has slower acquisition times.

To assess the delayed VIBE technique as a more rapid alternative to TSE imaging for measuring lower airway size, we undertook a retrospective study comparing the intermethod accuracy and reproducibility of airway measurements using both techniques.

2 | METHODS

This was a retrospective study including patients aged 2 months to 63 years old, who underwent a cardiac MRI from 5/2008 to 9/2013 and had delayed VIBE sequences completed. The institutional review board at our institution approved this retrospective review. Patients who had significant artifact or imaging which did not include the salient anatomy were excluded. Patients who had only the delayed VIBE sequence or incomplete TSE imaging with VIBE sequencing were still included for interuser analysis. Studies were performed on a 1.5-T Siemens Avanto (Siemens Medical Solutions, Erlagen, Germany). The TSE imaging was performed in the axial, sagittal, and modified coronal planes (parallel to the airway) per institutional protocol (in plane resolution of 1-1.5 mm $\times$ 0.9-1.2 mm, slice thickness 4-6 mm, TR 1-3 RR, TE 5-7, flip angle 120, signal averages 1-3). The delayed VIBE images (TR/TE 3.7/1.2 ms, flip angle 15°, voxel 1.5-1.8 $\times$ 0.8-1 $\times$ 1.0-1.2 mm) were acquired in the sagittal plane 5 minutes after gadolinium contrast administration in a sagittal plane identical to the contrast enhanced magnetic resonance angiogram (MRA) so that the images could be fused if the signal in the vessels was insufficient for identification. Variable scanning parameters were necessary to accommodate variations in patient size. A 5-minute delay was chosen by the authors due to qualitative superiority of airway resolution when compared to the sequence being completed at 1, 3, or 10 minutes during several of the earlier studies. A technical description of the VIBE sequence has been described in detail previously by Rofsky et al.[10]

Once identified, studies were analyzed on OsiriX MRI viewer (Pixmeo, Switzerland). Both a pediatric cardiology fellow and a pediatric cardiac MRI attending made measurements on each study. Each individual was blinded to the other observer as well as the other techniques measurements by separating technique analysis temporally. In the axial view the proximal airway measurements were made in the trachea

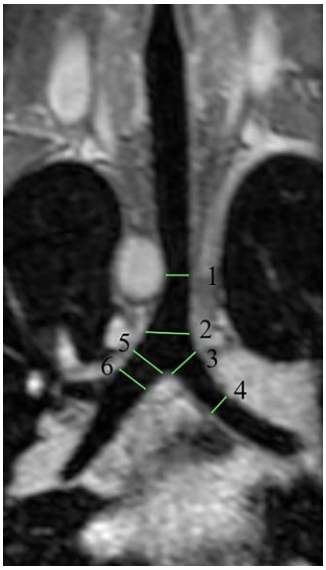

FIGURE 2 The coronal plane measurement locations utilized for this study are highlighted in this image. They are as follows (1) proximal trachea at the level of the transverse aorta, (2) distal trachea just proximal to the airway bifurcation, (3) proximal left bronchus at the carina, (4) distal left bronchus as the airways passes beneath the left pulmonary artery, (5) proximal right bronchus at the carina, (6) distal right bronchus just proximal to the second order branching

at the level of the transverse aortic arch and in the distal trachea just proximal to the carina. These locations were not typically impacted by the presence of an endotracheal tube in the setting of an intubated patient. In the scenario where there was a double aortic arch, the dominant arch was chosen as the landmark to follow. In the coronal view the proximal right and left main bronchi were measured at the carina. The distal right bronchi was measured just proximal to the 2nd order branching and the distal left bronchi was measured where it passed inferiorly to the left pulmonary artery (a normal left pulmonary artery was present in this entire dataset of patients), both taken from the coronal view as well (Figure 2). These measurements were made on both TSE and VIBE sequences as available. Per institutional standard, the VIBE images were reformatted to best approximate the straight axial and modified coronal planes of the TSE imaging before measurements were made. Data was recorded in REDcap, a secure electronic data storage program (NIH/NCRR Colorado CTSI Grant Number UL1 RR025780). Additional subject data collected included patient initials, medical record number, age, sex, weight, study date, indication for study, TSE acquisition time, VIBE acquisition time, and the use of general anesthesia with endotracheal intubation.

Subject characteristics and clinical data were reported as observational data and the mean values, as well as range, were calculated for patient age, weight, and TSE/VIBE acquisition times. Interuser and intrauser variability analysis was performed using intraclass correlation coefficient (ICC) to assess for agreement between measurements from each technique as well as between the two observers. Studies that had only VIBE sequences available were included in the analysis of interuser variability only. Bland-Altman plots were created to demonstrate agreement between TSE and VIBE sequence measurements for individual anatomical locations. Data analysis was completed using SAS software, version 9.3 (SAS Institute, Cary, NC).

3 | RESULTS

Of the 36 CMR studies that were reviewed, 29 studies met inclusion criteria for analysis. Of those 29 studies, 16 had both TSE and delayed VIBE sequences completed. The remaining 13 studies had no TSE imaging of the pertinent airway anatomy but the delayed VIBE measurements were included in the analysis for interobserver variability. All delayed VIBE and TSE sequences were found to be of diagnostic quality and the image quality was comparable between the cases with sedation and without. Table 1 includes the characteristics and clinical data for subjects included in this review. Notable data includes patient age (2 months to 63 years old with a mean age of 8.8 years), weight (3.5-109.9 kg with a mean weight of 30.2 kg) and acquisition times. The mean acquisition time was shorter for the delayed VIBE at 13.1 seconds (7.6-24.9) than TSE at 949.9 seconds (361-2318). 16 of the 29 studies were obtained for the purposes of assessing an arch anomaly for a possible vascular ring. The indication for the remainder of the studies included in the analysis was to assess known congenital heart disease. A majority of the studies were completed under general anesthesia with the patients airway secured by endotracheal intubation.

Table 2 includes the results of the ICC analysis of both technique and observer. Overall, there was very good agreement between the delayed VIBE and TSE measurements with an ICC of 0.78-0.94. The

TABLE 1 Demographics and clinical data

Variable	Mean (range) or N (%)	
Age	8.8 years (2 months-63 years)	
Weight	30.2 kilograms (3.5-109.9)	
Sex	Male 12 (41%)	Female 17 (59%)
Indication for study	Evaluate for arch anomaly 16 studies	Evaluate congenital heart disease 13 studies
TSE acquisition time	949.9 s (361.1-2318.6)	
VIBE acquisition time	13.1 s (7.6-24.9)	
Intubated for study?	Yes 20 (69%)	No 9 (31%)

TABLE 2 Interobserver and intraobserver agreement

	Inter-technique ICC by observer		Interobserver ICC by technique	
Site	BG	BF	TSE	VIBE
Proximal Trachea Major Axis	0.871	0.921	0.897	0.924
Proximal Trachea Minor Axis	0.899	0.919	0.917	0.921
Proximal Trachea Area	0.915	0.782	0.900	0.851
Distal Trachea Major Axis	0.782	0.900	0.938	0.903
Distal Trachea Minor Axis	0.810	0.878	0.886	0.932
Distal Trachea Area	0.783	0.882	0.914	0.948
Proximal Right Bronchus	0.936	0.801	0.956	0.955
Distal Right Bronchus	0.917	0.666	0.803	0.928
Proximal Left Bronchus	0.792	0.855	0.834	0.912
Distal Left Bronchus	0.890	0.795	0.779	0.894

only outlier was measurement of the distal right bronchus that had an ICC of just 0.67. The interobserver agreement between the two observers was also excellent for both TSE (ICC 0.78-0.96) and VIBE (ICC 0.85-0.96). Bland-Altman plots were created for each individual measurement location (Figure 3).

4 | DISCUSSION

MDCT and TSE are well-established techniques for imaging the pediatric lower airway. By using MDCT one trades the suspected costs of exposure to ionizing radiation for a very rapid study that produces a three dimensional dataset that shows both the thoracic vessels and lower airways with excellent resolution.[2,11] Alternatively, TSE imaging does not require the use of ionizing radiation and produces high-resolution images of the thoracic vessels and lower airways. The principle cost of TSE is time, which is an important consideration when the study must be done under general anesthesia. In particular, for small children with faster heart rates, to achieve optimal resolution in multiple planes, more averages and multiple breath-holds are needed which extends acquisition times. We propose that the delayed VIBE techniques offers the best of both worlds with a high resolution three dimensional dataset that demonstrates the thoracic vessels and lower airway in a single breath-hold. Our data also demonstrated that VIBE acquisition times are shorter when compared to TSE and useful for a wide range of patient ages and weights. Given that the majority of the patients included in this study required general anesthesia for image acquisition, utilizing a quicker technique limits anesthesia exposure and risks associated with this. Further, this decreased time under anesthesia does not come at the cost of high image quality given that all of the patients included in the study had images of diagnostic worth.

The VIBE technique, which was originally developed for abdominal imaging, uses a low flip angle, which highlights differences in soft tissues.[10] We postulate that this allows for better visualization of the air trachea interface compared to standard contrast enhanced MRA. We also postulate that delaying the acquisition allows for contrast to enhance the airway wall, which significantly improves the imaging of this interface. Vessel opacification was acceptable during the delayed VIBE acquisition but not as good as during the first pass contrast enhanced MRA. Therefore it is our practice to acquire the contrast enhanced MRA and the delayed VIBE with the same field of view and plane so that fusion images can be produced if so desired (Figure 4).

With the exception of the distal right bronchus, the agreement in our data between VIBE and TSE measurements for key anatomical sites was very good, thus demonstrating the accuracy of the technique when compared to the more traditional standard. The lack of agreement at the distal right bronchus site for one reviewer is likely due to the difficulty in reproducibly measuring the same point in the right bronchus which is not uniform in diameter from carina to the second order branching, especially when blinded to the prior measurement. The left bronchus, which maintains a relatively uniform caliber between the carina and the second-order branching, is less prone to this kind of error. The lack of agreement is also likely compounded by a technical difference between the TSE and delayed VIBE techniques. The coronal TSE plane was most often planned with the carina at its center point, consequently at points distal to the carina a mismatch between the coronal TSE and reformatted delayed VIBE planes is more likely. In addition to high levels of agreement between techniques, we found excellent interobserver agreement. This would suggest that these accurate measurements are both reproducible and easy to obtain.

There are several advantages inherent to the delayed VIBE techniques that are not directly comparable to the TSE imaging. Because it is a three-dimensional technique the delayed VIBE can be reformatted in multiple planes using a multiplanar reformatting tool. Therefore the airway can be reformatted in an optimal coronal plane that is difficult to achieve with a single TSE plane. Additionally, different planes can be reformatted from the same dataset in complex airway disease where no single plane can show the entirety of the anatomy. Lastly, the airway can be measured in short axis, which more accurately describes airway narrowing, a finding that may be exaggerated or underestimated in a single plane. A curved multiplanar reformat tool can also be used to more easily demonstrate caliber changes in the airway while staying in the center of the airway. This can be difficult or impossible to do with traditional single plane reformat (Figure 5).

Utilizing software tools more traditionally used for analysis of CT angiograms (Aquarius iNtuition 3D Workstation, TeraRecon, San Mateo, CA), the delayed VIBE datasets can be reformatted to show

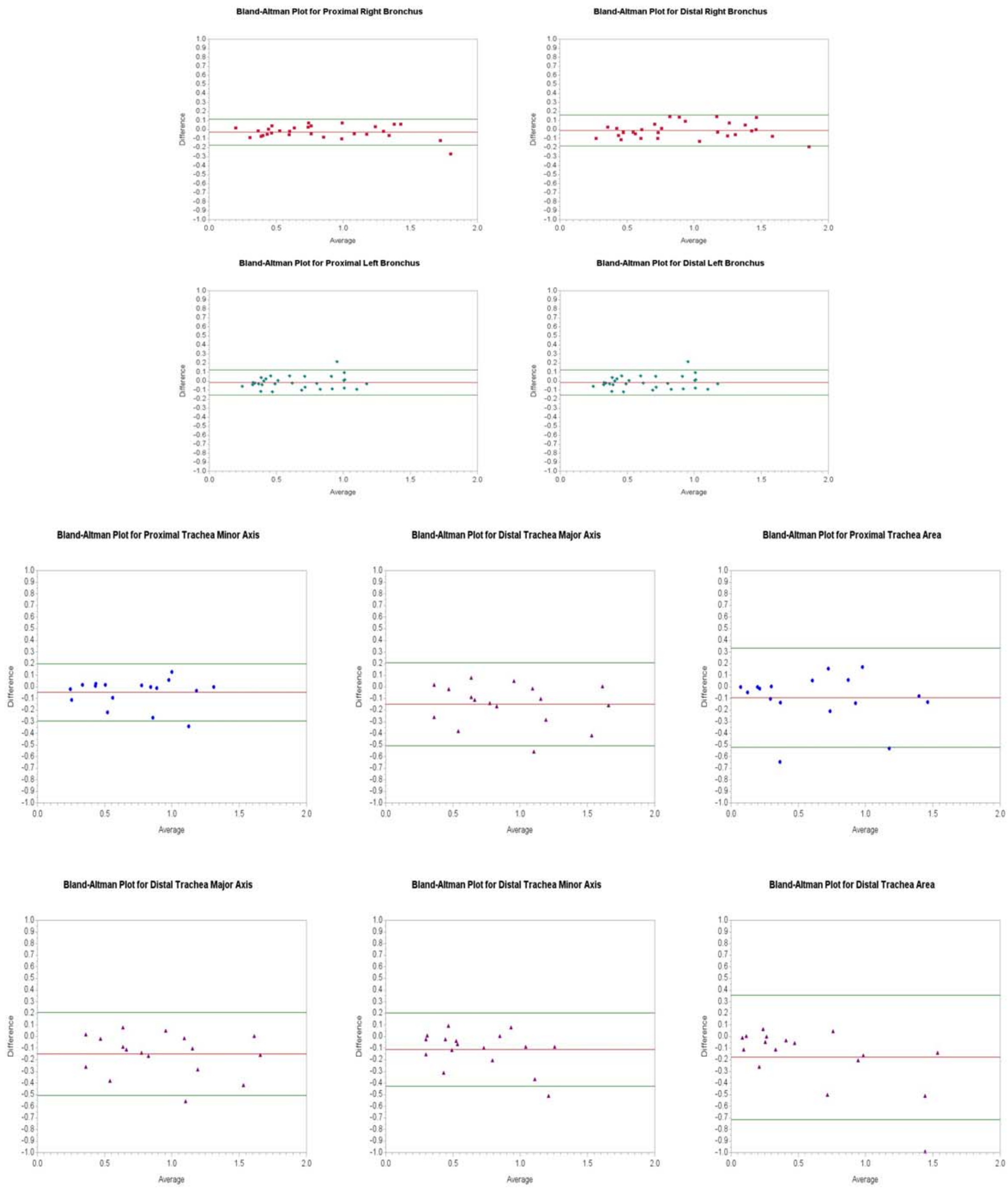

FIGURE 3 Bland-Altman plots which demonstrate the level of agreement between TSE and VIBE measurements at each chosen anatomical site

volume rendering of both the airway and the vessels. Using the same tools, a virtual bronchoscopy can also be extracted from the dataset providing another perspective of the lower airways (Figure 6).

Clinically this is useful information in patients with complex airway and vascular anatomy in terms of how the two interact. As indicated in our patient population for this study, many of the scans where delayed VIBE was utilized were completed as part of the evaluation for a vascular ring. Prior to any surgical intervention for a vascular anomaly, the exact anatomy and relationship between vasculature and airway should be confirmed and evaluated. Further there will be uses in other patients with congenital heart disease as research suggests an association between cardiac defects and anomalies of the lower airways.[12,13] In specific lesions such as tetralogy of Fallot with absent pulmonary valve or in those with a significantly dilated great vessel secondary to valvar lesions or prior interventions, patients should be evaluated as there are implications for the lower airways. Additionally, as previously mentioned, avoiding the radiation from MDCT is a significant advantage for these patients who may require multiple studies in their lifetime.

As with any retrospective evaluation there are inherent limitations, which also apply to this study. Given the retrospective nature of this study design, not every study included both techniques for comparison against the other sequence. Additionally, not every study included TSE images focusing on the desired key anatomical locations since each evaluation was targeted at the diagnostic question for that patient. For

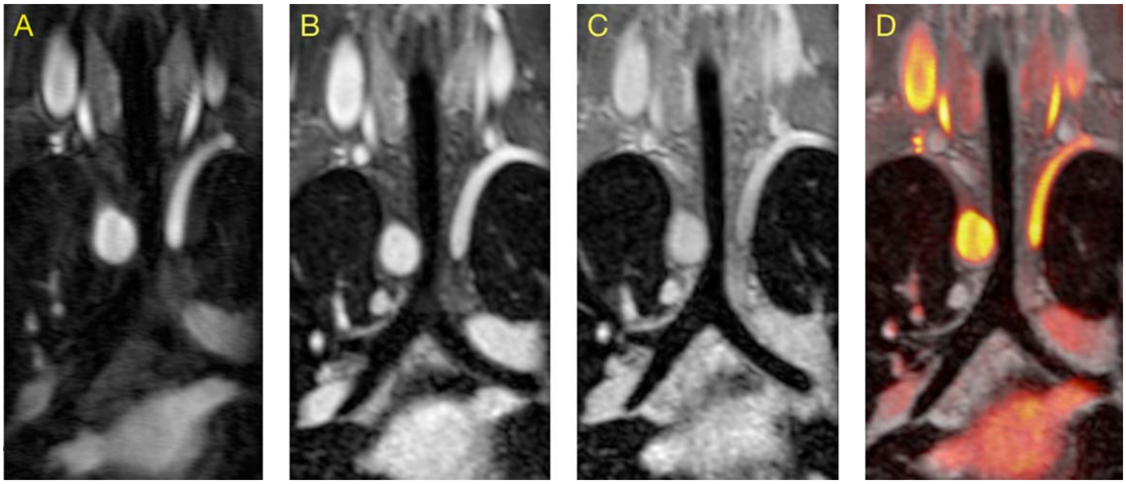

FIGURE 4 (A–D) demonstrates the impact of the magnetic resonance angiogram (MRA) acquisition technique on visualization of the lower airway. These MRAs were obtained sequentially in the patient also shown in Figure 1 with double aortic arch. (A) Conventional 3D-GRE acquisition with excellent enhancement of the aortic arch but poor definition of the lower airway. (B) VIBE acquisition with good enhancement of the aorta and better visualization of the lower airway, however there is a lack of airway edge detail. (C) Delayed VIBE acquisition. The enhancement of the aorta is less than the previous two acquisitions but the edge detail is much improved compared to panels A and B. (D) Fusion image of the 3D-GRE and the delayed VIBE acquisitions, giving an image with optimal enhancement of the aorta and excellent detail of the lower airway

example, if the focus was regarding tracheal compression, imaging was not optimized for the distal bronchi. Third, given the design of this study, there is no "gold standard" known true values for comparison with the analysis. A phantom study would provide this and may be considered for future studies involving the use of VIBE to measure airway size. Next, there was variation in our patient population with some patients being intubated while others were spontaneously breathing. While the presence of an endotracheal tube may distort any tracheal abnormalities present in those patients, the objective of this study was to compare measurements of the same anatomical structure by two modalities. This objective is not impacted by a normal or abnormal airway as long as the authors remained consistent in their location of measurements. Lastly, with a relatively low number of patients in the study it is more prone to bias based on our patient population and patient selection. There was also a large age and weight range in our study group, however the image quality was subjectively comparable among the different sized patients.

Despite these limitations, data from this study suggests that VIBE is a comparable tool to traditional TSE in measuring the proximal portions of the lower airways. Ideally this technique should provide quicker assessment of the pediatric patient and future analysis/use of this sequence will include identifying normative data for bronchial anatomy of the pediatric population.

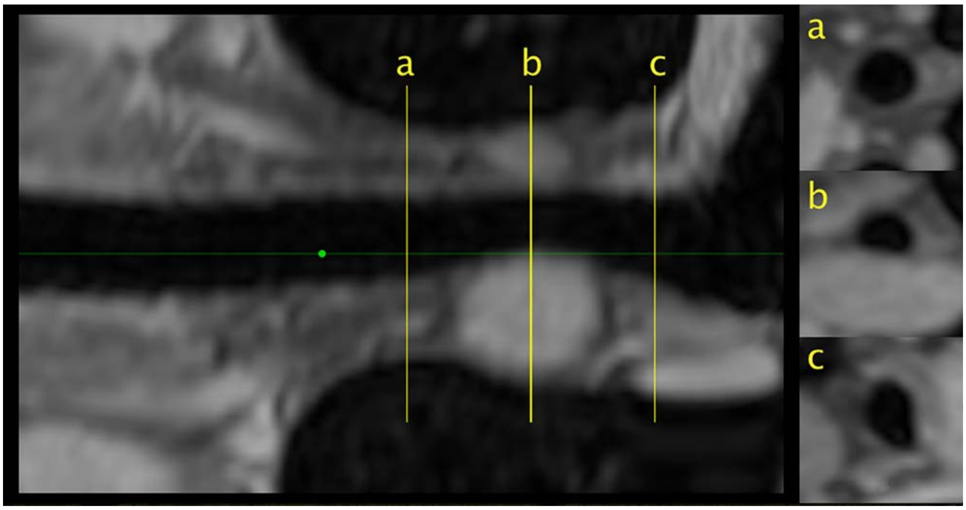

FIGURE 5 The curved multiplanar reconstruction (MPR) is another tool to help visualize airway anatomy and compression. This example is from the patient with double aortic arch in Figure 1. This tool simplifies obtaining cross-sectional measurements of the airway at multiple levels simultaneously. In this example there is a normal airway caliber and shape in the mid trachea (A) followed by vascular compression at the level of the transverse aorta (B) and return to normal caliber at the carina (C)

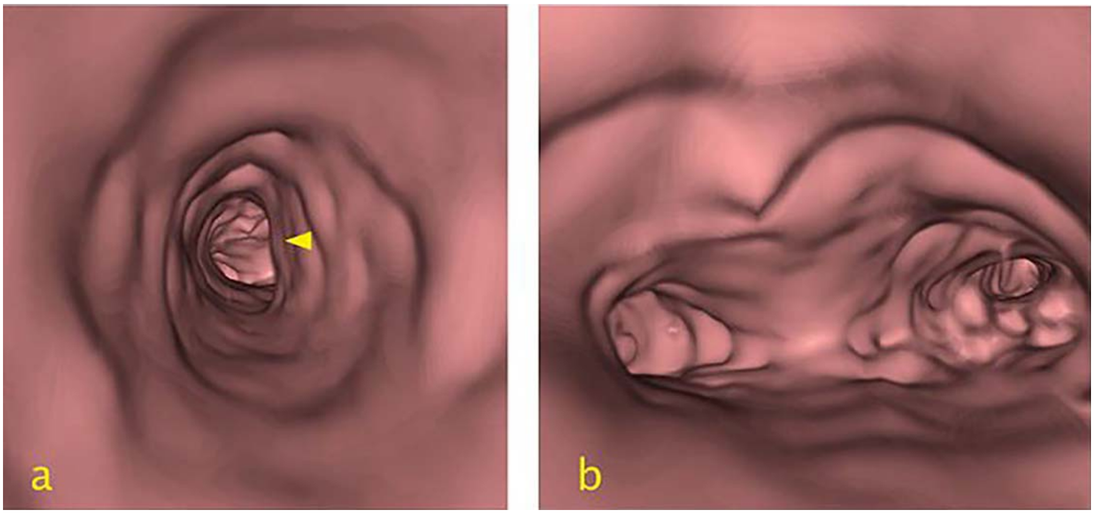

FIGURE 6 The delayed VIBE dataset from the patient with double aortic arch observed in prior figures was used to create virtual bronchoscopy images of the tracheal compression (A) and the carina (B). The yellow arrow highlights the area of compression. This can be an excellent communication tool to easily demonstrate airway anomalies to referring physician and surgeons

5 | CONCLUSION

Delayed volume interpolated breath-hold examination is a rapid, reproducible, and accurate cardiac magnetic resonance technique for imaging the lower airway in a wide variety of patient sizes and ages with congenital heart disease when compared to tradition TSE. Additionally, the three-dimensional nature of this technique confers multiple advantages that were previously only realized by CT scan, however these come without the use of ionizing radiation in the vulnerable pediatric population.

CONFLICT OF INTERESTS

There are no conflicts of interest to report for any of the authors.

DISCLOSURE

None of the authors have grant funding or funding from another source to report.

AUTHOR CONTRIBUTIONS

BG and BF designed the study and carried out data collection. BG and BF also participated in both abstract and manuscript preparation. SP completed the statistical analysis and assisted in drafting the abstract and manuscript.

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