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Post-interventional three-dimensional dark blood MRI in the adult with congenital heart disease

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ABSTRACT

Background: Investigate a novel three-dimensional (3D) turbo spin echo (TSE) magnetic resonance imaging (MRI) sequence to assess stented segments in adults with congenital heart disease (CHD) after transcatheter intervention.

Methods: Adults with CHD referred for computed tomography (CT) after transcatheter intervention underwent MR exam with a 3D respiratory gated TSE sequence. Data obtained at the time of the study included type of CHD, radiation dose, length of time between exams, and luminal diameters of stented segments from each exam. Continuous variables were analyzed using Student's t and Bland–Altman plots performed to analyze measurements obtained from both examinations.

Results: Eleven patients underwent both examinations. Type of defects included coarctation of the aorta ($n = 6$) and tetralogy of Fallot. Average radiation dose was 19.6 mSv and average time between CT and MRI was 99 ± 160 days. Luminal diameters of stented vessels correlated closely between TSE MRI and CT ($r^2 = .85$) with a bias toward overestimation with MRI (mean 22.4 ± 4.3 mm and 20.9 ± 3.7 mm, $p < .01$).

Conclusion: This novel 3D respiratory gated TSE MR technique provides a feasible method to reduce metallic artifact and improve visualization of stented segments and surrounding anatomic structures without exposure to radiation.

1. Introduction

There has been a steady increase in the number of adults with both simple and complex congenital heart disease (CHD).[1] Although successful surgical repairs have been reported for many forms of CHD, long-term evaluation is required in adults with CHD to detect late-onset complications. As a result of ongoing advancements in the field of interventional cardiology, many adults with CHD are often now referred for transcatheter therapies to address these complications. Still, approximately 25% of patients may develop further complications as early as one year after stent placement including intimal hyperplasia, stent fracture, dissection, or aneurysm formation necessitating long-term surveillance [2].

Current non-invasive imaging strategies utilized to assess the adult with CHD after transcatheter interventions include cardiovascular computed tomography (CT) and magnetic resonance imaging (MRI). Cardiovascular CT provides excellent visualization of not only metallic stents but also an evaluation of the surrounding anatomic structures. Limitations of serial cardiovascular CT in the young adult with CHD after transcatheter interventions include cumulative exposure to ionizing radiation. Therefore, cardiovascular MRI has become the modality of choice for the evaluation of adults with complex CHD in most centers. Yet, despite attempts to tailor imaging sequences accordingly, a complete anatomic cardiovascular MR examination of the stented segments is often limited due to stent-induced metallic artifacts (Fig. 1). Spin-echo based imaging techniques are known to have less sensitivity to magnetic susceptibility induced artifacts than steady-state free precession (SSFP) and gradient-echo methods commonly used for MR angiography.

Recently, a newly developed single slab three-dimensional (3D) turbo spin echo (TSE) sequence, known as SPACE (Sampling Perfection with Application optimized Contrast using different flip angle Evolution) has been used to assess large arterial territories. [3,4] SPACE uses spatially selective excitation pulses, variable refocusing

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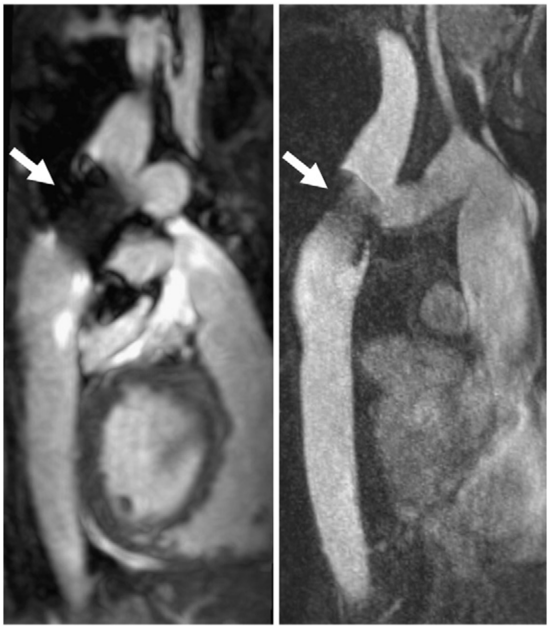

Fig. 1. Gradient echo magnetic resonance imaging sequences demonstrating metallic artifact (arrows) in a young adult with coarctation after transcatheter therapy. Artifact is noted on both the steady state free procession respiratory navigator gated sequence (left) and contrast enhanced magnetic resonance angiogram (right).

flip angle and spatially nonselective refocusing pulses [5,6] that allow for small interecho times and significantly more echoes to be acquired following each excitation compared with conventional 3D-TSE sequence.

In this study, we describe the implementation of the single slab 3D T1 weighted SPACE sequence with respiratory navigator gating to evaluate stented segments and surrounding anatomy in adults with CHD who had undergone prior transcatheter interventions.

2. Materials and methods

2.1. Subject population

Eleven adults; including 6 women, with a history of prior transcatheter intervention referred for a clinical cardiovascular CT examination at our Adolescent and Adult Congenital Heart Disease Center were enrolled. The written informed consent was obtained for participation in this Institutional Review Board-approved protocol. Six patients with coarctation had undergone transcatheter therapy of the aortic arch as a result of recoarctation. The remaining five patients had tetralogy of Fallot and underwent transcatheter therapy for pulmonary artery stenosis (proximal left or right pulmonary artery stenosis). In one patient with tetralogy, 'kissing stents' were deployed for bilateral proximal pulmonary artery stenosis. This allowed for the assessment of a total of 12 stented segments. The subject's age, previous transcatheter intervention, length of time between examinations (CT, and MRI) and effective radiation dose were recorded.

2.2. CT protocol

All cardiovascular CT scans were performed during a single breath hold on a 64-slice scanner (Somatom Sensation, Siemens, Germany). After scout images were obtained, a single axial slice in the ascending aorta was selected. A region of interest in the ascending aorta was selected and a bolus tracking system was used to initiate the scan at 110 HU density. The helical scan, starting above the aortic arch extending to the diaphragm, was then performed with retrospective ECG gating and ECG tube current modulation to minimize radiation exposure [7,8] and peripheral intravenous injection of 90–100 ml of contrast at 4 to 5 ml/s (Visipaque, GE Healthcare,Waukesha, WI). Patients were instructed to breathhold during helical scan acquisition, which lasted 15 to 20 s.

The effective radiation dose was recorded from each scan and calculated from the dose length product (DLP) and a conversion coefficient used for the chest wall, averaged for males and females: Effective Radiation Dose (mSv) = (Dose Length Product * 0.017) [7].

2.3. MRI protocol

All scans were performed on a standard 1.5T 32-channel whole body MR system (MAGNETOM Avanto, Siemens, Erlangen- Germany) with a maximum gradient amplitude of 45 mT/m and a slew rate of 200 mT/m/ms. After obtaining routine single-shot steady state free procession (SSFP) scout images, dark blood images obtained using the SPACE sequence; described below, were incorporated into our standard CMR examination of the adult with CHD. Although each protocol prescribed is determined by the underlying congenital lesion, typical sequences performed in each study included axial, sagittal and coronal single shot spin echo (HASTE), SSFP cines in the short-axis, vertical and horizontal long-axis, three-chamber and ventricular outflow views, and either SSFP respiratory gated navigator and/or contrast enhanced MR angiogram.

The 3D T1-weighted SPACE sagittal-oblique, isotropic, cardiac gated acquisition has the following scan parameters: echo time 24 ms, repetition time equal to the R–R interval, trigger delay 30 ms, spatial resolution of 1.2 mm isotropic (uninterpolated), bandwidth 610 Hz/pixel, number of averages 2, parallel acceleration factor 2 (GRAPPA), turbo factor 45, echo spacing 2.95 ms, and echo train duration 136 ms. In the technique used here, a selective excitation pulse is used for volume excitation. [5,6] Nonselective refocusing pulses with variable flip angles tailored to a prescribed signal evolution are used to allow for long echo trains. Both the long echo train and short echo spacing improve sampling efficiency. The nonselective refocusing pulses reduce the technique's sensitivity to bulk motion as compared to standard TSE. The field of view and number of slices were adjusted to cover the region of interest of individual patients. The respiratory navigator acceptance window was set to ±3 mm.

2.4. Image analysis

All images were analyzed on a standard clinical workstation (Leonardo, Siemens, Germany). The CT and SPACE three-dimensional data sets were spatially registered using vendor supplied software (Syngo Fusion, Siemens Healthcare, Germany). With this software, the MR and CT data can be visually aligned in all three dimensions [9,10] (Fig. 2). Luminal diameters were measured at the proximal, mid, and distal portions of each stent in two perpendicular directions from both the MR and CT images (Fig. 3). Measurements from the two imaging modalities were compared using Bland–Altman analysis, as well as linear regression analysis for the calculation of the intraclass correlation coefficient.

3. Results

All 11 patients; average age 34 years ± 8 years, successfully completed the imaging protocol. The average effective radiation dose measured 19.57 ± 1.5 mSv. The average length of time between CT and MR was 99 ± 160 days.

With this technique, no significant artifact from the stent was seen on the SPACE images. The average scan time averaged 15.76 ± 6.02 min. The acceptance rate for this sequence was 51.2 ± 16.2%. Surrounding anatomic structures in close proximity to stented segments were clearly visualized in the SPACE images. The SPACE sequence provided image quality that would yield a three-dimensional assessment of cardiothoracic anatomy in all cases (Fig. 4). Luminal diameters were measured in 33 of 36 locations. Measurements were not made in three locations due to lack of stent apposition with the vessel wall. This occurred with branch pulmonary artery stents that extended to the main pulmonary artery segment.

There was strong correlation between the luminal diameters obtained via MRI and CT ($r^2 = 0.85$) with a bias toward overestimation with MRI (mean 22.4 +/− 4.3 mm and 20.9 +/− 3.7 mm, $p < .01$). Luminal diameters were overestimated by 1.5 mm (±3 mm) by MRI when compared to CT (Fig. 5).

4. Discussion

Adults with CHD continue to represent a growing population who require long term care. Those who have undergone previous transcatheter interventions as a result of prior surgical sequelae require serial non-invasive imaging studies to assess late-onset complications. Serial evaluation with cardiovascular CT is limited by the use of potentially harmful radiation. While the exact risk posed by low levels of radiation remains difficult to predict, exposure should be minimized particularly in those with chronic disease who may be at an increased risk from lifelong exposure from repeated non-invasive