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Single-Shot Coronary Quiescent-Interval Slice-Selective MRA using Compressed Sensing: A Feasibility Study in Patients with Congenital Heart Disease

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Abstract

Objective—To determine whether it is feasible to visualize the coronary origins in patients with congenital heart disease (CHD) using single-shot coronary Quiescent-Interval Slice-Selective (QISS) magnetic resonance angiography (MRA) with compressed sensing (CS).

Methods—This retrospective study leveraged a parent study which was aimed to comparing breath-hold, 2.1-fold accelerated, 2-shot coronary QISS MRA and clinical standard contrast-enhanced (CE) MRA in 14 patients with CHD (mean age = 17.0±8.6 years; 6 females; 8 males). We evaluated the feasibility of single-shot coronary QISS MRA by retrospectively undersampling the 2-shot dataset by an additional factor of 2, performing CS reconstruction, and comparing the retrospectively derived single-shot QISS MRA to 2-shot coronary QISS MRA and clinical standard CE MRA. For quantitative analysis, structural similarity index (SSIM) and normalized root mean square error (NRMSE) were calculated. For qualitative analysis, two experienced readers scored the conspicuity of coronary origins on a 5-point Likert scale (1 = nondiagnostic, 2 = poor, 3 = clinically acceptable, 4 = good, 5 = excellent).

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Conflicts of Interest: None.

Results—Compared with 2-shot QISS, single-shot QISS produced NRMSE of $5.8\pm0.8\%$ and SSIM of $95.4\pm1.6\%$, suggesting high data fidelity by CS reconstruction. Compared with the mean conspicuity scores for clinical CE-MRA (4.2 ± 0.5 and 4.1 ± 0.6 for right and left coronary origins, respectively), the mean conspicuity scores were not significantly different ($P>0.3$) for 2-shot QISS (4.4 ± 0.9 and 4.2 ± 1.1 , respectively) and single-shot QISS with CS (4.3 ± 1.1 and 3.8 ± 1.3 , respectively), and deemed clinically acceptable to good (scores ≥ 3.0).

Conclusion—This study shows that it is feasible to visualize the coronary origins in patients with CHD with clinically acceptable to good image quality using single-shot coronary QISS MRA with CS.

Keywords

compressed sensing (CS); Quiescent-Interval; Slice-Selective (QISS) MRA; congenital heart disease; coronary origins; MRI

Introduction

Congenital heart disease (CHD) is the most common type of birth defect, accounting for nearly 1% of live births in the US (1,2). Non-invasive assessment of coronary origins is critical for planning surgical intervention and cardiac catheterization in patients with CHD. For example, coronary imaging is necessary for patients who undergo an arterial switch operation for transposition of the great arteries along with coronary arteries (3,4). While echocardiography is the first line imaging test for evaluation of coronary origins, its accuracy worsens as the pediatric patients grow in size (5). Computed tomography (CT) and magnetic resonance imaging (MRI) are two available non-invasive imaging tests for coronary angiography. Compared with adults, children have smaller hearts and faster heart rates, both posing greater challenges for producing diagnostically acceptable image quality.

Cardiac CT examination involves ionizing radiation and iodinated contrast agent administration, both of which are concerning for pediatric patients (6,7). While pediatric cardiovascular magnetic resonance angiography (MRA) does not involve radiation, it typically involves gadolinium-based contrast agent (GBCA)(7). Gadolinium has been reported to be deposited in the brain even in the setting of normal renal function (8–12), including in children (13,14). Despite the lack of evidence linking adverse side effects to the gadolinium deposition in the brain (15), it is nevertheless concerning. In addition, MRA examinations may require general anesthesia in young children to obtain high-quality images. Mounting evidence from animal and human studies suggest that general anesthetics may cause neurotoxic changes in the developing brain that lead to adverse neurodevelopmental outcomes later in life. Thus, there is a clinical need to develop pediatric cardiovascular MRA methods that do not require GBCA or anesthesia.

Non-contrast MRA is an alternative test for coronary angiography without requiring administration of GBCA. Among a family of non-contrast MRA methods (16), navigator-gated, T2-prepared balanced steady state free precession (b-SSFP) MRA (17) is the most commonly used method in adults. This 3D coronary MRA pulse sequence has been shown to produce clinically acceptable image quality in adults with a scan time on the order of 10

min (18–20), whereas a breath-hold version is less likely to produce clinically acceptable image quality because of high data acceleration (21). Because a 3D cardiovascular MRA pulse sequence with high spatial resolution generally requires long scan time, it is ill-suited to relax the need for anesthesia during pediatric cardiovascular MRI. This study seeks to test the feasibility of single-shot coronary MRA without requiring GBCA or anesthesia for future use in pediatric patients.

One potential solution for real-time MRA is the recently developed coronary Quiescent-Interval Slice-Selective (QISS) MRA (22) based on 2.1-fold accelerated, radial k-space sampling. The original implementation was evaluated in adults as a breath-hold version, where 10 contiguous 2D images were acquired in a single breath-hold of 20 heart beats (i.e., 2-shots spread over 2 heart beats per 2D image). To date, coronary QISS MRA has not been evaluated in patients with CHD, and single-shot coronary QISS MRA has not been evaluated in any cohort. Compared with previously described 2-shot coronary QISS MRA, advantages of real-time coronary QISS MRA include capability of relaxing the need for anesthesia during pediatric cardiovascular MRI and being less sensitive to irregular heart rhythm or motion. In this study, we sought to test whether it is feasible to visualize the coronary origins in patients with CHD using single-shot coronary QISS MRA with compressed sensing (CS)(23). Success of this study will serve as an important step towards clinical translation of real-time coronary QISS MRA in pediatric patients.

Methods

Patients Demographics

This is a retrospective study involving 14 patients with CHD (mean age = 17.0 ± 8.6 years; 8 males; 6 females; see Table 1 for relevant clinical profiles). This study leveraged a parent study which was aimed to comparing previously described breath-hold coronary QISS MRA and clinical standard contrast-enhanced (CE) MRA. From this point forward, previously described coronary QISS MRA will be referred to as 2-shot QISS MRA. The study was approved by the local ethics board, and informed consent was obtained from all participants (or parents) for QISS MRA. We evaluated the feasibility of single-shot coronary QISS MRA by retrospectively undersampling the raw data of 2-shot coronary QISS MRA dataset by an additional factor of 2, performing CS reconstruction, and comparing the retrospectively derived single-shot QISS MRA to 2-shot coronary QISS MRA and clinical CE MRA. Both general anesthesia and GBCA (0.12 ml/kg of gadofosveset trisodium or ABLAVAR, Lantheus Medical Imaging, MA, USA) were administered using clinical standard protocols, and this research study had no bearing on these clinical protocols.

As a secondary evaluation, we prospectively scanned three adult patients (3 male, mean age = 58.7 ± 6.5 years) who underwent clinical cardiovascular MRI and performed breath-hold, 2-shot QISS MRA (reference) and free-breathing, single-shot coronary QISS MRA with otherwise identical imaging parameters.

Hardware

A prototype 2.1-fold accelerated, two-shot coronary QISS MRA pulse sequence was implemented on a whole-body 1.5T scanner (MAGNETOM Aera, Siemens Healthineers, Erlangen, Germany). This scanner was equipped with a gradient system capable of achieving a maximum gradient strength of 45 mT/m and a slew rate of 200 T/m/s. The RF excitation was performed using the body coil. Standard multi-coil arrays (anterior and spine elements, typically 36 elements total) were employed for signal reception.

Pulse Sequence

Relevant imaging parameters of coronary QISS MRA included: field of view (FOV) = 180 mm $\times$ 180 mm, image acquisition matrix size = 128 $\times$ 128, spatial resolution = 1.4 mm $\times$ 1.4 mm, slice thickness = 2.1 mm, cardiac triggering, 96 rays per 2D image (or 48 rays per shot), 2 shots per 2D image, radial angular sequence starting from 0° with 13.123° steps, flip angle 140°, TE = 1.9 ms, TR = 3.7 ms, receiver bandwidth = 1,000 Hz/pixel, fat suppression, and $\alpha/2$ flip-back pulse immediately before b-SSFP readout, number of slices = 10, inversion time (TI) = 650 ms following in-plane frequency offset corrected inversion (FOCI) pulse (24). For patients with heart rate $\leq$ 80 beats per minute, the two-shot QISS dataset was acquired over 2 heart beats, whereas for patients with heart rate $>$ 80 beats per minute, the two-shot QISS dataset was acquired over 4 heart beats. Using scout images displaying the left ventricular outflow tract, QISS MRA was prescribed perpendicular to the outflow tract and parallel to the aortic valve plane in order to sample the coronary origins. Coronary QISS MRA was always performed before GBCA was administered.

Navigator-gated, CE 3D MRA based on inversion recovery with gradient echo readout was performed using the following imaging parameters: FOV = 340 mm $\times$ 319 mm, image acquisition matrix = 224 $\times$ 210, spatial resolution = 1.5 mm $\times$ 1.5 mm, slice thickness = 2.4 mm (interpolated to 1.5 mm as per clinical protocol), slices = 104 (23.1% oversampling), cardiac triggering, GRAPPA parallel imaging factor = 1.9, receiver bandwidth = 485 Hz/pixel, TI = 260 ms, flip angle = 18°, TE = 1.35 ms, TR = 3.3 ms, scan time on the order of 5–15 mins (depended on patient's breathing pattern), and centric k-space ordering. CE-MRA was prescribed in a coronal plane. Standard dose (0.12 ml/kg) of gadofosveset trisodium was administered using a power injector at 2–3 ml/s. Note that inversion-recovery 3D MRA was performed following time-resolved MRA.

Image Reconstruction

Figure 1 illustrates the overall flow chart of the image reconstruction pipeline. The 2.1-fold accelerated, two-shot QISS data were retrospectively undersampled in k-space by an additional factor of two and then reconstructed using CS. This corresponded to a net acceleration of 4.2 relative to Nyquist rate sampling. We used nonuniform Fast Fourier transform (NUFFT)(25) because it produces less blurring than the conventional two-step process with gridding and fast Fourier transform. Coil sensitivities were self-calibrated from the low resolution, zero-padded reconstruction using the method described in reference (26).

We performed two pre-processing steps prior to CS reconstruction. In the first step, we performed gradient trajectory correction during post-processing while assuming identical

gradient shifts around 360° (see Figure S1 in Supplementary Digital Content which summarizes the incremental improvement in artifact suppression following trajectory correction). In the second step, we performed density compensation based on the sampling pattern and NUFFT to ensure a fair comparison of intensity between 2-shot and 1-shot QISS results.

For the iterative CS image reconstruction, an L1-norm optimization was used with spatial total optimization (TV) as the sparsifying transform, where the normalized regularization weight was 0.000025 relative to the maximum signal. This value was determined empirically based on visual analysis of data agreement between 2-shot and 1-shot training data, using a similar approach described previously (27,28). We varied the reconstruction pipeline to determine whether adding soft thresholding (@ 0.02% of maximum intensity) as a pre-step suppresses residual aliasing artifacts more than otherwise. All image reconstructions were done offline in MATLAB R2016a software (Natick, MA, USA) on a standard computer with Windows 7. Image reconstruction time was recorded to determine clinical feasibility.

Image Analysis

We performed both qualitative and quantitative analyses to evaluate results. For quantitative analyses, comparison between 2-shot and 1-shot QISS MRA, we calculated the structural similarity index (SSIM), normalized root mean square error (NRMSE), and edge sharpness to infer data fidelity. Because both 2-shot and 1-shot results share the same data, it was possible to compute SSIM and NRMSE over the entire image. For SSIM and NRMSE calculations, we generated a mask based on thresholding to exclude signal-free pixels. This step was necessary to ensure that these metrics do not include spurious data points from signal-free regions. For edge sharpness estimation, we measured intensity profiles through an aorta or atrium to background. To increase precision in calculating edge profiles, we interpolated each profile by a factor of 20 and measured the spatial distance between 25 percentiles and 75 percentiles of peak intensity value. We calculated the apparent signal-to-noise ratio (SNR) as the mean signal of several regions of interest (ROIs) within cardiovascular structures (yellow ROIs in Fig. 2) divided by standard deviation of signal free background (cyan rectangle in Fig. 2), as previously described (29).

A total of 39 MRA data sets were randomized and de-identified for visual analysis. One pediatric cardiovascular radiologist (CKR) with 17 years of experience and one pediatric cardiologist (JDR) with 9 years of clinical experience, respectively, graded the conspicuity of coronary origins on a 5-point Likert scale (1 = nondiagnostic, 2 = poor, 3 = clinically acceptable, 4 = good, 5 = excellent). The two readers were given training data sets with varying image quality to calibrate their scores together prior to actual grading. Following training, each reader was blinded to image acquisition type (2-shot QISS, 1-shot QISS, contrast-enhanced MRA), the other reader, and clinical history. For fairness, CE MRA data were reformatted using a 3D viewing tool (Leonardo Workstation, Siemens) to match the FOV, orientation, and spatial coverage as QISS MRA. Note that each case (1-shot QISS, 2-shot QISS, CE MRA) was displayed and evaluated separately.

Statistical Analysis

For each of three metrics (SSIM, NRMSE, edge profiles), the two groups (2-shot vs. 1-shot QISS) were compared using a paired (two-tail) t-test. For the conspicuity score, the mean reader score for each coronary origin (left and right) was compared between the three groups (2-shot QISS, 1-shot QISS, CE-MRA) using the Kruskal-Wallis test, where Fisher's least significant difference was used to compare each pair. The Bland-Altman analysis was used to compute reader agreement. A p value < 0.05 was considered significant for all statistical tests.

Results

All 14 cases included coronary origins, except for 1 case where the origins were missed due to scanning operator mistake. This one case with limited spatial coverage was excluded for qualitative evaluation of image quality of coronary origins but included for quantitative evaluation of image quality. Four patients had heart rates greater than 80 beats per minute, so their 2-shot coronary QISS MRA data were acquired over 4 heart beats.

Figure 2 shows representative images comparing 2-shot QISS, 1-shot QISS with zero padding (i.e., without CS), 1-shot CS with TV alone, and 1-shot QISS with TV plus soft thresholding. As shown in Fig. 2, the mean apparent SNR was 24.9, 16.8, 26.4, and 30.6 for 2-shot QISS, 1-shot QISS with zero padding, 1-shot QISS with TV, and 1-shot QISS with TV plus soft thresholding, respectively. Note that an increase in apparent SNR with CS is due to noise filtering and is not to be confused with intrinsic SNR. Starting from this point, the remaining 1-shot QISS results correspond to CS with spatial TV plus soft thresholding.

Figure 3 shows representative edge profiles through blood and background from another subject. These profiles show that the results are comparable. Summarizing the results over 14 patients with CHD, the mean edge sharpness values were not significantly different ($P > 0.6$) between 2-shot QISS (1.2 ± 0.3 mm) and 1-shot QISS (1.3 ± 0.3 mm). Compared with 2-shot QISS, 1-shot QISS produced NRMSE of 5.8 ± 0.8 % and SSIM of 95.4 ± 1.6 %, suggesting high data fidelity produced by CS reconstruction. Compared with 2-shot QISS (offline reconstruction time = 16.0 ± 0.1 s per 2D image accounting for pre-processing steps and multi-coil NUFFT), 1-shot QISS required significantly ($P < 0.05$) longer offline reconstruction time (77.4 ± 0.7 s per 2D image accounting for pre-processing steps, multi-coil NUFFT, and CS).

Figure 4 shows representative QISS and CE MRA maximum-intensity-projections (MIP)s in the same orientation and FOV, where both coronary origins are visible. Summarizing the results over 13 patients (Table 2), compared with conspicuity scores for clinical CE-MRA (4.2 ± 0.5 and 4.1 ± 0.6 for right and left coronary origins, respectively), the mean conspicuity scores were not significantly different ($P > 0.3$) for 2-shot QISS (4.4 ± 0.9 and 4.2 ± 1.1 , respectively) and single-shot QISS (4.3 ± 1.1 and 3.8 ± 1.3 , respectively) and deemed clinically acceptable to good (scores ≥ 3.0). The reader agreement was similar between CE-MRA and coronary QISS MRA (Table 3).

Figure 5 shows representative breath-hold, 2-shot QISS (reference) and prospectively acquired free-breathing 1-shot QISS MRA obtained from three adult patients. In patients labeled 1 and 2, the 2-shot and 1-shot QISS images produced similar image quality, whereas in patient 3 who had intermittent arrhythmia during MRI, single-shot QISS produced better image quality than 2-shot QISS. Consistent with retrospective results from pediatric patients, these prospective examples in adults suggest that it is feasible to produce diagnostically acceptable image quality with real-time coronary QISS MRA.

Discussion

This retrospective study shows that it is feasible to visualize the coronary origins in patients with CHD with clinically acceptable to good image quality using single-shot, coronary QISS MRA with CS. Compared with 2-shot QISS and clinical CE-MRA images, single-shot, QISS images obtained with CS reconstruction produced reader scores that were not significantly different. Clinically acceptable to good image quality scores are supported by quantitative image metrics such as SSIM, NRMSE, and edge sharpness. A rapid NC-MRA method that does not require general anesthesia or GBCA has important clinical implications for pediatric cardiovascular MRI, because it reduces cost by eliminating MR-compatible anesthesia equipment, specialized personnel, anesthetics, and GBCA, as well as risks associated with anesthesia.

This study warrants several discussion points. First, SNR measurements need to be interpreted with caution because CS filters noise and changes the spatial distribution of noise. As such, SNR values reported in this study should not be confused with intrinsic SNR. Second, we did not explore an optimal radial angle for CS reconstruction, because this study was designed as a sub-study of a parent study, and we did not have access to the source codes to modify the pulse sequence. Additional analysis is needed to determine which radial angle optimally balances signal homogeneity and artifacts arising from eddy currents in b-SSFP readout. Third, for clinical translation, it is important to consider image reconstruction time with CS. Strategies to reduce the reconstruction time in future work may include leveraging graphics processing unit (GPU) computing, software coil compression (30), and Split Bregman methods to efficiently solve the L-1 norm (31). Rapid CS reconstruction is an active area of research within the MRI community, and MR vendors are beginning to advertise CS as a future product. Thus, it is likely that a rapid image reconstruction pipeline could become commercially available. Fourth, this study used spatial TV and soft thresholding to suppress noise-like aliasing artifacts in 4.2-fold undersampled, single-shot QISS dataset. It may be possible to further suppress aliasing artifacts using different constraints and filters. Fifth, advantages of 4.2-fold accelerated, single-shot coronary QISS MRA over 2.1-fold accelerated, 2-shot coronary MRA include capability to relax the need for anesthesia during pediatric cardiovascular MRI and insensitivity to arrhythmia or cardiac motion. Alternatively, the 4.2-accelerated QISS MRA could be performed as 2-shot acquisition with 103 ms readout duration (i.e., 24 rays per shot) to minimize its sensitivity of coronary motion.

This study also includes several limitations. First, the primary analysis included only 14 patients with CHD. Additional investigation in a larger cohort of patients is needed to

evaluate the clinical utility of single-shot, coronary QISS MRA. Second, in this study, we performed gradient trajectory correction using a simple empirical approach, because we had no access to the source codes for implementing a pre- or post-scan calibration scan. Another study is warranted to evaluate the advantages (possibly better artifact suppression) and disadvantages (additional scan time) of different phase correction strategies. Third, the primary data analysis was performed on retrospective reconstruction of breath-hold, 2-shot coronary QISS MRA in patients with CHD. While this restriction is a limitation, it is worth noting that a retrospective analysis also made it possible to compute quantitative metrics such as SSIM and NRMSE because the 2-shot and single-shot data sets are inherently registered. Fourth, the proposed free-breathing, single-shot coronary QISS MRA was prospectively evaluated in only three adult patients. A future study is warranted to confirm this finding in patients with CHD. Fifth, this study did not evaluate the sharpness of coronary vessels using advanced visualization tools such as “Soap-Bubble” (32), because coronary origins in patients with CHD are small. Developing another visualization tool is beyond the scope of this study. Sixth, this study did not compare the proposed radial reconstruction method with other investigational non-Cartesian reconstruction methods proposed for general applications (33,34) and specifically for cardiovascular MRI (35–40), because they are not commercially available. A future collaborative study is warranted to determine which investigational radial reconstruction methods are optimal for coronary QISS MRA.

In conclusion, it is feasible to visualize the coronary origins in patients with CHD with clinically acceptable to good image quality using single-shot coronary QISS MRA with CS.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

A schematic flowchart illustrating the image reconstruction pipeline. Step 1: 2.1-fold accelerated, two-shot radial QISS data were undersampled in k-space by an additional factor of 2. Step 2: an iterative CS algorithm was used to reconstruct the results, where spatial TV was used as the sparsifying transform. Soft thresholding was used as a pre-step to improve artifact suppression. Radial k-space sampling patterns are displayed after downsampling by a factor of 4 for better visualization with less clumping.

Figure 2.

(Top Row) Representative images of 2-shot QISS (first column), single-shot QISS with zero padding (second column), single-shot QISS with spatial TV denoising (third column), single-shot QISS with spatial TV denoising plus soft thresholding (fourth column). Superimposed yellow ROIs represent areas used to calculate mean signal. Superimposed cyan rectangle represents a background region used to calculate noise. (Bottom Row) Corresponding images displayed with a narrow grayscale to bring out background signal.

Figure 3.

Spatial intensity profiles (yellow lines) through blood and background to represent edge sharpness: 2-shot QISS (left column) and single-shot QISS with spatial TV plus soft thresholding (right column). Edge sharpness was defined as the distance between 25 and 75 percentiles of peak intensity value.

Figure 4. Representative maximum-intensity-projections (MIPs) displaying the coronary origins: 2-shot QISS (left column), single-shot QISS with spatial TV plus soft thresholding (middle column), and CE MRA reformatted to match the orientation of QISS MRA (right column). Yellow arrows point to the coronary origins.

Figure 5.

Images comparing prospectively acquired free-breathing, 1-shot coronary QISS (right column) to breath-hold, 2-shot QISS (left column) obtained from three adult patients. Yellow arrows point to the coronary origins. The hearts were in different positions between breath-hold and free-breathing acquisitions as shown.

Table 1

Pertinent clinical profiles of 14 patients enrolled in this study. BAV: Bicuspid aortic valve; VSD: Ventricular septal defect; TOF: tetralogy of Fallot; DOVR: Double outlet right ventricle.

Characteristic	
<i>Age</i>	17.0 ± 8.6 years
<i>Females</i>	6/14 (42.9%)
<i>Heart Rate</i>	80.8 ± 19.7 bpm
<i>RV dilatation</i>	5/14 (36%)
<i>Aortic root dilatation</i>	4/14 (29%)
<i>BAV</i>	2/14 (14%)
<i>Pulmonary atresia</i>	2/14 (14%)
<i>VSD</i>	2/14 (14%)
<i>TOF</i>	2/14 (14%)
<i>Ascending Aorta dilatation</i>	2/14 (14%)
<i>RPA abnormality</i>	2/14 (14%)
<i>LV hypoplasia</i>	2/14 (14%)
<i>Pulmonary regurgitation</i>	2/14 (14%)
<i>Aortic coarctation</i>	2/14 (14%)
<i>Tricuspid valve hypoplasia</i>	1/14 (7%)
<i>Right ventricular outflow tract obstruction</i>	1/14 (7%)
<i>Marfan</i>	1/14 (7%)
<i>Thoracolumbar scoliosis</i>	1/14 (7%)
<i>Pectus excavatum</i>	1/14 (7%)
<i>DORV</i>	1/14 (7%)
<i>Mitral valve atresia</i>	1/14 (7%)
<i>Myocardial hypertrophy</i>	1/14 (7%)
<i>Tricuspid valve prolapse</i>	1/14 (7%)
<i>LPA dilatation</i>	1/14 (7%)
<i>Mitral valve prolapse</i>	1/14 (7%)
<i>Double Outlet Left Ventricle</i>	1/14 (7%)

Table 2

A summary of reader scores from 13 patients with CHD. According to the Kruskal-Wallis test, the three groups (2-shot QISS, 1-shot QISS, and CE-MRA) were not significantly different ($P > 0.2$) for each coronary origin per reader, as well as combined. The reported values represent mean $\pm$ standard deviation. RCA: right coronary artery; LMCA: left main coronary artery. A 5-point Likert scale (1 = nondiagnostic, 2 = poor, 3 = clinically acceptable, 4 = good, 5 = excellent).

Region	Category	Reader 1	Reader 2
<i>Origin of RCA</i>	<i>2-Shot QISS</i>	4.5 $\pm$ 0.8	4.3 $\pm$ 1.2
	<i>1-Shot QISS CS</i>	4.4 $\pm$ 1.0	4.2 $\pm$ 1.2
	<i>CE-MRA</i>	4.2 $\pm$ 0.8	4.3 $\pm$ 0.5
<i>Origin of LMCA</i>	<i>2-Shot QISS</i>	4.2 $\pm$ 1.2	4.2 $\pm$ 1.1
	<i>1-Shot QISS CS</i>	3.8 $\pm$ 1.2	3.8 $\pm$ 1.4
	<i>CE-MRA</i>	4.0 $\pm$ 0.9	4.2 $\pm$ 0.6

Table 3

A summary of reader agreement as per Bland-Altman analysis. The reader scores were in good agreement (i.e., low bias) with similar confidence intervals between 2-shot QISS, 1-shot QISS, and CE-MRA.

Region	Parameter	Mean	Mean Difference	Lower 95% Limit	Upper 95% Limit
Origin of RCA	2-Shot QISS	4.4	-0.2	-1.5	1.2
	1-Shot QISS CS	4.3	-0.2	-0.9	0.6
	CE-MRA	4.3	0.2	-1.4	1.7
Origin of LMCA	2-Shot QISS	4.2	0.0	-0.8	0.8
	1-Shot QISS CS	3.8	0.0	-1.1	1.1
	CE-MRA	4.1	0.2	-1.6	2.0