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Optimization of Free-Breathing Whole-Heart 3D Cardiac MRI at 3Tesla to Identify Coronary Vein Anatomy and to Compare with Multi-Detector Computed Tomography

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Abstract

Objective—This study optimizes use of 3T MRI to delineate coronary venous anatomy, and compares 3T MRI with MDCT measurements.

Methods—The study population included 37 consecutive subjects (22 men, 19-71 years). Whole-heart contrast-enhanced MRI images at 3T were acquired using segmented k-space gradient echo with inversion recovery prepared technique. MDCT images were obtained using nonionic iodinated contrast.

Results—The coronary sinus, and great cardiac, posterior interventricular, and anterior interventricular veins were visualized in 100% of cases by both MRI and MDCT. Detection of the posterior vein of left ventricle and left marginal vein by MRI was 97% and 81% respectively. Bland Altman plots showed agreement in ostial diameter measured by both modalities with correlation coefficients ranging 0.5-0.76. Vein length and distances also agreed closely.

Conclusion—Free-breathing whole-heart 3D MRI at 3T provides high spatial resolution images and could offer an alternative imaging technique instead of MDCT scans.

Keywords

Coronary Veins; Multidetector Computed Tomography; circulation; magnetic resonance imaging; imaging

Introduction

With the introduction of cardiac resynchronization therapy, non-invasive methods to identify coronary venous anatomy are increasingly important.¹⁻⁴ Resynchronization therapy requires pre-procedural knowledge of venous anatomy to facilitate implantation of pacing leads in

the coronary sinus and right ventricle thus permitting simultaneous biventricular pacing.^{5,6} Similarly, anatomic knowledge is essential in the development of techniques for percutaneous mitral annuloplasty.⁷⁻⁹ Comprehensive knowledge of coronary venous anatomy allows optimal patient selection, and choice of device or lead placement position.

Until recently, balloon-occlusion retrograde venography using conventional X-ray was the standard reference method for visualizing coronary veins.^{10,11} However, this invasive technique is technically challenging, and does not define relationships between the coronary veins or mitral annulus. By comparison, multi-detector computed tomography (MDCT) allows non-invasive assessment of coronary veins^{3,12-16} but requires use of ionizing radiation and a short yet crucial breath hold for success. Alternatively, cardiac magnetic resonance imaging (MRI) has become a powerful non-invasive tool to evaluate cardiovascular structures including coronary arteries¹⁷⁻²¹ and veins.^{1,4,22-25} However, most studies were performed at 1.5T. With the increasing availability of 3T scanners, such MR sequences need to be modified and assessed before widespread implementation. To our knowledge, no studies have compared visualization of the coronary veins by high field MRI at 3T with MDCT. The purpose of this study was to apply and test an MR sequence optimized for 3T in order to evaluate the feasibility of free breathing 3D whole heart sequence to delineate and assess the anatomical features of coronary veins. Additionally, the study is to compare coronary vein measurements obtained using this optimized method for 3T with those from MDCT as the standard non-invasive technique in current clinical practice.

Materials and Methods

Clinical subjects

Thirty seven consecutive subjects (22 men; 19-71 years old) gave written informed consent for cardiac MDCT and 3T MR imaging as part of a research protocol approved by the local Institutional Review Board and compliant with patient privacy rules. All subjects underwent MDCT and 3T MR scans within a 30 day interval. Subjects were in sinus rhythm and did not have any known cardiac or thoracic process that would distort the anatomy of the coronary veins.

MRI acquisition

All participants underwent MR imaging performed using a 3T Intera system (Philips Medical Systems, Best, The Netherlands), a six-element cardiac phased-array receiver coil, and vector electrocardiographic gating²⁶ using preparatory scans and imaging techniques that have been described previously.¹⁹ Intravenous contrast (0.2 mmol/kg of 500 mM Gd-BOPTA) followed by the same volume of normal saline was injected using a power-injector (Spectris, Medrad, Warrendale, PA) at a rate of 0.2cc/sec. A whole-heart acquisition using inversion-recovery preparation (IRprep) pulse was begun 5 minutes after the start of contrast injection, thus allowing steady state conditions. The whole -heart scan utilized respiratory navigator for respiratory gating (acceptance window=5mm) allowing for application of a free breathing acquisition technique. A 3D volume acquisition covering the whole heart segmented gradient echo sequence (TR/TE=4.4/1.4msec, turbo factor=27, 20° flip angle, 60

2-mm-thick partitions interpolated to 120-mm-thick partitions during reformatting) was performed in the transaxial plane, with an acquired voxel size of $1 \times 1 \times 2 \text{ mm}^3$. The inversion time for IRprep was set at 220ms to allow nulling of the myocardium with an acquisition window of 119ms set for diastolic rest period. Parallel imaging was utilized (SENSE factor of 2). The prescribed acquisition time was 4.55 minutes, and completed in approximately 9 minutes with a respiratory navigator efficiency of 50%–60%. Maximum intensity projections and multiplanar reformatted images of coronary veins were obtained to be reviewed by three readers in consensus and in random order.

MDCT Acquisition

MDCT angiography was performed on all subjects using a 16-detector CT scanner (Brilliance 16, Philips Healthcare, Andover, MA,US). The MDCT protocol was similar to previously described techniques.²⁷ Briefly, 50–100 mg of metoprolol was administered orally 30–60 minutes before MDCT to lower the heart rate below 65 beats per minute. Nitroglycerin was not used. Single breath hold MDCT was performed using a tube voltage of 120 kV, a current of 400–500 mAs, 220-mm field of view, and retrospective ECG gating. Nonionic vascular contrast enhancement material (120–130 ml of iopamidol, Isovue, Bracco Diagnostics) followed by 50 ml normal saline was injected through an 18- to 20-gauge peripheral venous access at a rate of 4–5 ml/s. Post processing analysis and interpretation of the axial and the multiplanar reformatted images were performed by consensus of three readers.

Coronary Vein Image Analysis

Analysis of both MRI and MDCT images was performed randomly using a dedicated workstation and commercially available imaging analysis software (Virtual Place; AZE, Tokyo, Japan). After anonymization and randomization, image analysis and quantification was performed three readers in consensus. MRI and MDCT measurements were obtained from images with contrast enhancement using the same analysis software. Image quality was classified on a 4-point scale based on detection of coronary veins and quality of vessel edge, similar to previous methods (1=Poor, poorly visible vessel, markedly blurring of edges, uninterpretable; 2=Moderate, visible vein, moderate blurring of edges; 3=Good, visible vein with mild blurring of edges; 4= Excellent, visible vein with sharply defined borders).²⁸ Veins that were not visible or were graded as 1 were not included.

Three-dimensional volume-rendering reconstructions were used to identify the coronary sinus (CS), posterior interventricular vein (PIV), great cardiac vein (GCV), anterior interventricular vein (AIV), posterior vein of left ventricle (PVLV), left marginal vein (LMV), right marginal vein (RMV) (or anterior cardiac vein), and vein of Marshall using standard anatomic classification.²⁹ Multiplanar reformatting images were obtained (Figure 1). Stretch-out multiplanar reformatting was expanded to measure the maximum diameters of the ostia of the coronary vessels, and to determine the distance between the coronary sinus and its tributaries (Figures 2, 3). The length of major coronary veins was measured using multiplanar reformatting by reconstructing the vein axis as a straight line (Figure 2, 3). The whole axis of the CS, GCV, and AIV were measured as a single unit. The origin of the GCV was defined as the vessel originating after insertion of the vein of Marshall if visible,

or otherwise immediately after the bifurcation of the PVLV. The presence of a Thebesian valve at the ostium of coronary sinus was also evaluated.

Statistical Analysis

Bland Altman plots assessed relative bias (mean difference) and limits of agreement (mean difference $\pm$ 2 standard deviations of difference) between MDCT and MRI measures of coronary venous ostia, distance from the coronary sinus ostium to tributaries, and length of coronary veins.³⁰ If differences were observed, further comparison was made between the groups using Student's t test.³¹ Non-parametric correlation coefficients were calculated. All data were expressed as mean $\pm$ standard deviation (SD) or as mean bias $\pm$ 1.96SD for Bland Altman plots. A p value < 0.05 was considered statistically significant. Data were analyzed using STATA statistical software (Version 9.0, College Station, TX).

Results

Both MRI and MDCT scanning were successfully completed for all subjects without complications. The mean scan time for MDCT was 21.4 ± 1.3 seconds. The mean acquisition time for whole heart MR was 11.1 ± 4.5 minutes and the mean value of navigator efficiency was 45%. The mean score of image quality was 3.75 ± 0.5 for MR and 3.80 ± 0.5 for MDCT.

Anatomic Findings

Coronary sinus (CS), great cardiac vein (GCV), posterior interventricular vein (PIV) and anterior interventricular vein (AIV) were identified in all subjects by both modalities. In one subject, the PIV drained separately into right atrium. Due to anatomic variation, other coronary veins were visualized less frequently, but the detection rate was similar for MRI and MDCT (Table 1). The small cardiac vein draining into the coronary sinus was visualized in only 4-5 patients and the veins draining into the AIV were not visualized by either modality.

Quantitative Analysis of Coronary Veins

Coronary Vein Diameter Measurements—Comparing MRI and MDCT, Bland Altman analysis demonstrated good agreement between ostial diameter measurements for the large veins measured (Table 2 and figure 4). There was a small positive bias in MRI measures for the CS, PIV, AIV, vein of Marshall, and right marginal vein. There was a small negative bias in GCV, PVLV, and left marginal vein (Table 2 and figure 4). There was a significant correlation between measures by MRI and MDCT except for smaller veins such as the right marginal vein. Results for the small cardiac vein were not analyzed because there were few measurements.

Coronary Vein Distance Measurements—Bland Altman analysis demonstrated a mean small negative bias in all MRI measures. However, there was no significant difference between MRI and MDCT measurements in the distance between CS and its tributaries: CS-PIV, CS-PVLV, CS-GCV, and CS-LMV (Table 3 and figure 5). The distance measurements by MRI and MDCT were significantly correlated (Table 3).

Length measurements—Using Bland Altman analysis, there was no significant difference between MRI and MDCT measurements of the length of coronary veins (Table 4 and figure 6). There was a mean positive bias in all MRI measures (Table 4 and figure 6). The length measurements by MRI and MDCT were significantly correlated (table 4).

Discussion

Most studies have reported use of 1.5T MRI scanners for coronary vein anatomic mapping.^{1,4,23,24} As 3T MRI units become more common in clinical practice, optimization of pulse sequences dedicated to higher field strengths has permitted faster speed, higher resolution, and improved image quality.^{19,32} Pulse sequences are adapted to 3T due to Specific Absorption Rate (SAR) limits, susceptibility and motion artifacts and relaxometries of tissue and thus contrast at 3T. Compared with 1.5T MRI, the use of higher magnetic field strength with a lower T1 relaxation curve allows more accurate determination of inversion time and shortens the delay time from 20 minutes with 1.5T to 5 minutes before starting the IR prepared 3D whole heart scan.^{19,24} Moreover, the higher signal-to-noise ratio (SNR) inherent at 3T can be used to offset the relative SNR loss that results from reduction in voxel size and the use of parallel imaging to shorten scan times. Use of parallel imaging facilitates scanning within a practical time of approximately 9 minutes. This allows higher resolution scans with voxel size of $1 \times 1 \times 2 \text{ mm}^3$ at 3T, compared to voxel size of $1.5 \times 1.5 \times 5 \text{ mm}^3$ at 1.5T as reported previously for a 3D whole heart technique analogous to MDCT.²⁴ This study demonstrates the feasibility of performing free-breathing 3D whole-heart IR prepared technique at 3T MR for the assessment of coronary veins.

There are many advantages in use of this technique including excellent image quality, flexible post-processing options,³³ improved patient convenience with an alternative high resolution imaging technique for those who do not tolerate breath-holding for MDCT. Additionally, beta blockade is unnecessary as preparation for MRI examination.

This study demonstrates that 3T MRI is a feasible method to detect and evaluate the coronary venous system when compared with non-invasive coronary vein examination using MDCT. There was no significant difference between MRI and MDCT measures of ostial diameters for the larger coronary veins. There was also no significant difference in distances between coronary sinus ostium and its branches, and the length of the coronary veins measured by MDCT and MRI.

Most studies report utility of a single imaging modality (MDCT or 1.5T MRI) to delineate coronary venous anatomy.^{4,13,34,35} In some studies, identification of the coronary sinus and great cardiac vein was 100% while detection of the posterior inter-ventricular vein ranged between 75 -100%.^{1,4,11} Other coronary veins were visualized less frequently: PVLV 50-88%, LMV 69-75%, and AIV 65-79%.^{1,4,11} Our detection rates were higher and this may be attributed to the higher SNR and improvements in spatial and temporal resolution associated with the higher magnetic field strength (3T).

In our study, it was possible to visualize the Thebesian valve with MRI and MDCT in 27% and 24% of cases respectively. The Thebesian valve is frequently found at the CS ostium³⁶

and could hinder insertion of catheters in the CS. Improving the ability to identify the valve would enable the operator to anticipate and prevent possible complications.³⁷

Published reports describe some variability in the mean ostial diameter measurements: 11-13.9 mm for the CS, 4-5.9 mm for the PIV, 3-5.4 mm for the PVLV, 2-4.7 mm for the LMV, and 3-4.4 mm for the AIV.^{1,4,11} Our point estimates for mean vessel diameter lie within these reported ranges.

Similarly, there are published reports describing the distance between the CS and its branches: 5.4-12 mm for distance to the PIV, 15.2-32.6 mm to the PVLV, 49.7-68.8 mm to the LMV, and 98.9-146.5 mm to the AIV.^{1,4,11} Our data report higher mean values for the distance between the CS and its branches. This could be a sampling issue, because the previously reported mean values fall within 1-2 standard deviations of our means.

Prior studies also report length of the coronary veins: 31-42.4 mm for the PIV vein, 21-42 mm for the PVLV, 21-38.8 mm for the LMV, and 23.9-45 mm for the AIV.^{1,4,11} Our data describes markedly longer coronary vein measurements. One possible explanation may be the higher magnetic field which increases the signal to noise (SNR) ratio and achieves higher spatial resolution in a shorter acquisition time (improved temporal resolution). These effects would improve the visualization of coronary veins, especially the most distal parts of the vein.

One limitation of the study is the use of a MDCT scanner which has been superseded by new technology with more detector rows. However, this change affects acquisition time, coverage, and temporal resolution. Spatial resolution is not significantly affected by increasing the detector rows and therefore coronary venous imaging is acceptable using our MDCT equipment as the veins tend to be larger in size than coronary arteries.¹⁵ In a previous study, coronary venous imaging with 4-slice MDCT correlated well with occlusive venography.¹⁶ Another limitation is the lack of conventional angiography as a gold standard, but we correlated MRI and MDCT, the standard non-invasive techniques in current practice. Finally, this study has a small sample size, but MRI and MDCT measures are compared in the same subjects.

In conclusion, free-breathing whole-heart 3D technique at high field MRI (3T) is a feasible technique for assessment of the coronary venous system. Identification and measurements of the coronary venous system by MRI was highly correlated with the standard MDCT measurements in the same subject.

Acknowledgments

none

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Figure 1.

Multiplanar reformatted images of the coronary veins by MDCT (A) and MRI (B) in the same patient. MRI was able to identify the whole venous tree that was recognized using MDCT.

(AIV, Anterior Inter-ventricular Vein; CS, Coronary Sinus; GCV, Great Cardiac Vein; LMV, Left Marginal Vein; PIV, Posterior Inter-ventricular Vein; PVLV, Posterior Vein of Left Ventricle)

Figure 2.

Stretched-out multi-planar reconstruction of coronary veins imaged by MDCT (top) and MRI (bottom). These reconstructed images were used to perform the quantitative analysis of the coronary venous system.

(AIV, Anterior Inter-ventricular Vein; CS, Coronary Sinus; GCV, Great Cardiac Vein; LMV, Left Marginal Vein; PIV, Posterior Inter-ventricular Vein; PVLV, Posterior Vein of Left Ventricle)

Figure 3. Stretched-out multi-planar reconstruction of coronary veins imaged by MDCT (top) and MRI (bottom). These reconstructed images were used to perform the quantitative analysis of the coronary venous system.
(AIV, Anterior Inter-ventricular Vein; CS, Coronary Sinus; GCV, Great Cardiac Vein; LMV, Left Marginal Vein; PIV, Posterior Inter-ventricular Vein; PVLV, Posterior Vein of Left Ventricle)

Figure 4.

Bland Altman plots for ostial diameters of coronary veins measured by MDCT and 3T MRI. All measures are expressed in mm.

Figure 5. Bland Altman plots of distance from coronary sinus to various coronary veins measured by MDCT and 3T MR. All measures are expressed in mm

Figure 6.

Bland Altman plots of length of various coronary veins measured by MDCT and 3T MR. All measures are expressed in mm.

Table 1

Recognition of Coronary Veins by Imaging Modality

	MRI N (%)	MDCT N (%)	p *
Coronary Sinus	37 (100%)	37 (100%)	ns
Posterior Inter-ventricular Vein	37 (100%)	37 (100%)	ns
Great Cardiac Vein	37 (100%)	37 (100%)	ns
Posterior Vein of Left Ventricle	36 (97.3%)	36 (97.3%)	ns
Left Marginal Vein	30 (81%)	29 (78.4%)	ns
Anterior Inter-ventricular Vein	37 (100%)	37 (100%)	ns
Small Cardiac Vein	5 (13.5%)	4 (10.8%)	**
Vein of Marshall	9 (24.3%)	12 (32.4%)	ns
Right Marginal Vein	27 (73%)	25 (67.6%)	ns
Thebesian Valve	10 (27%)	9 (24.3%)	ns

MRI: Magnetic Resonance Imaging; MDCT: Multi-Detector Computed Tomography; %: Percentage; N: number of cases; ns, not significant;

*
p value calculated using Fisher's exact test;

**
too few to analyze

Table 2

Correlation between MRI and MDCT Measures of Ostial Diameter of Coronary Veins

Ostial Diameter (mm) mean (sd)	MRI	MDCT	Mean difference*	Limits of agreement*	r [†]	p [‡]
Coronary Sinus	10.1 (2.5)	9.9 (2.6)	0.15	-3.0, 3.28	0.76	<0.001
Posterior Inter-ventricular Vein	5.1 (1.1)	5 (1.2)	0.11	1.11, 2.29	0.5	0.003
Greater Cardiac Vein	6.3 (2)	6.5 (1.8)	-0.23	-3.00, 2.55	0.62	<0.001
Posterior Vein of Left Ventricle	3.7 (1.2)	3.9 (1.3)	-0.18	-1.89, 1.52	0.57	<0.001
Left Marginal Vein	2.7 (0.9)	2.8 (1.0)	-0.07	-1.43, 1.30	0.57	<0.001
Anterior Inter-ventricular Vein	3.9 (0.9)	3.5 (0.7)	0.40	-1.20, 1.99	0.5	0.003
Vein of Marshall	2.1 (0.8)	1.7 (0.4)	0.36	-0.72, 1.43	0.75	0.05
Right Marginal Vein	2.5 (0.6)	2.2 (0.7)	0.41	-1.37, 2.19	0.08	0.7

MRI: Magnetic Resonance Imaging; MDCT: Multi-Detector Computed Tomography; sd: Standard Deviation; mm: millimeter;

* Mean difference and limits of agreement determined from Bland Altman plots;

† Spearman correlation coefficient for MDCT and MR measures;

‡ p values for correlation coefficient

Table 3
Correlation between MRI and MDCT Measures of Distance between Coronary Sinus Ostium and Ostia of Tributaries

Distance: Coronary Sinus (CS) to Tributaries (mm; mean (sd))	MRI	MDCT	Mean difference *	Limits of agreement *	r †	p ‡
CS → Posterior Inter-ventricular vein	12.8 (5.8)	15 (6.4)	-2.19	-13.77, 9.40	0.63	<0.001
CS → Posterior vein of Left ventricle	38.8 (20.3)	40.8 (18.8)	-2.06	-25.84, 21.71	0.73	<0.001
CS → Great cardiac vein	43.2 (19.9)	47.1 (19.6)	-3.83	-29.09, 21.42	0.62	<0.001
CS → Left marginal vein	75.7 (19.6)	82.5 (19.3)	-7.33	-34.74, 20.08	0.53	0.004
CS → Anterior inter-ventricular vein	121.1 (15.6)	125.1 (15)	-4.33	-32.59, 23.94	0.53	0.001

MRI: Magnetic Resonance Imaging; MDCT: Multi-Detector Computed Tomography; sd: Standard Deviation; mm: millimeter;

* Mean difference and limits of agreement determined from Bland Altman plots;

† Spearman correlation coefficient for MDCT and MRI measures;

‡ p values for correlation coefficient

Table 4

Correlation between MRI and MDCT Measures of Length of Coronary Veins.

Length of Coronary Vein (mm; mean (sd))	MRI	MDCT	Mean difference*	Limits of agreement*	r [†]	p [‡]
Coronary Sinus + Greater Cardiac Vein + Anterior Interventricular Vein **	226.6 (46.6)	208.5 (37)	18.10	-68.83, 105.04	0.52	<0.001
Posterior Inter-ventricular Vein	98.4 (26.2)	94.9 (21.2)	3.43	-40.26, 47.11	0.53	<0.001
Posterior Vein of Left Ventricle	75.9 (34.9)	68.7 (31.3)	7.28	-44.46, 59.02	0.72	<0.001
Left Marginal Vein	53.1 (30.3)	41.4 (23.2)	8.73	-33.97, 51.42	0.68	<0.001

* Mean difference and limits of agreement determined from Bland Altman plots;

[†] Spearman correlation coefficient for MDCT and MRI measures;

[‡] p values for correlation coefficient;

sd: standard deviation; mm: millimeter. MRI: Magnetic Resonance Imaging; MDCT: Multi-Detector Computed Tomography.

** Coronary sinus (CS), Great cardiac vein, and anterior inter-ventricular vein measured as a single long segment from CS ostium to distal anterior inter-ventricular vein.