Pulmonary Venous Anatomy Imaging With Low-Dose, Prospectively ECG-Triggered, High-Pitch 128-Slice Dual-Source Computed Tomography

Wai-ee Thai, MD; Bryan Wai, MD; Kaity Lin, MD; Teresa Cheng, BS; E. Kevin Heist, MD, PhD; Udo Hoffmann, MD, MPH; Jagmeet P. Singh, MD, DPhil; Quynh A. Truong, MD, MPH

Background—The efforts to reduce radiation from cardiac computed tomography (CT) are essential. Using a prospectively triggered, high-pitch dual-source CT protocol, we aim to determine the radiation dose and image quality in patients undergoing pulmonary vein (PV) imaging.

Methods and Results—In 94 patients (61±9 years; 71% male) who underwent 128-slice dual-source CT (pitch 3.4), radiation dose and image quality were assessed and compared between 69 patients with sinus rhythm and 25 patients with atrial fibrillation. Radiation dose was compared in a subset of 19 patients with prior retrospective or prospectively triggered CT PV scans without high pitch. In a subset of 18 patients with prior magnetic resonance imaging for PV assessment, PV anatomy and scan duration were compared with high-pitch CT. Using the high-pitch protocol, total effective radiation dose was 1.4 (1.3, 1.9) mSv, with no difference between sinus rhythm and atrial fibrillation (1.4 versus 1.5 mSv; P=0.22). No high-pitch CT scans were nondiagnostic or had poor image quality. Radiation dose was reduced with high-pitch (1.6 mSv) compared with standard protocols (19.3 mSv; P<0.0001). This radiation dose reduction was seen with sinus rhythm (1.5 versus 16.7 mSv; P<0.0001) but was more profound with atrial fibrillation (1.9 versus 27.7 mSv; P=0.039). There was excellent agreement of PV anatomy (κ 0.84; P<0.0001) and a shorter CT scan duration (6 minutes) compared with magnetic resonance imaging (41 minutes; P<0.0001).

Conclusions—Using a high-pitch dual-source CT protocol, PV imaging can be performed with minimal radiation dose, short scan acquisition, and excellent image quality in patients with sinus rhythm or atrial fibrillation. This protocol highlights the success of new cardiac CT technology to minimize radiation exposure, giving clinicians a new low-dose imaging alternative to assess PV anatomy. (Circ Arrhythm Electrophysiol. 2012;5:521-530.)

Key Words: arrhythmia (heart rhythm disorders) ■ atrial fibrillation ■ computed tomography ■ imaging ■ pulmonary vein isolation

Radiofrequency catheter ablation of the pulmonary veins (PV) is increasingly used as an interventional treatment strategy for symptomatic atrial fibrillation (AF).1 However, the PV anatomy is variable, and suboptimal visualization of the PV may compromise procedural success.2 Hence a detailed knowledge of the left atrial (LA) and PV anatomy is imperative for accurate targeting and planning during PV isolation as well as follow-up for PV stenosis.3-5

Clinical Perspective on p 530

Both cardiac computed tomography (CT) and magnetic resonance imaging (MRI) are noninvasive imaging modalities that are commonly used to visualize the PV and LA anatomy and for coregistration with electroanatomic mapping (EAM) before radiofrequency PV isolation.3 With regard to cardiac CT, exposure to ionizing radiation is of great concern,4 and efforts to reduce radiation are essential. New CT technology allows for cardiac imaging with single-beat acquisition and minimal radiation exposure. Second-generation 128-slice dual-source CT (DSCT) scanners have improved temporal resolution (75 ms) because of a gantry rotation time of 280 ms compared with single-source CT.7 Spiral acquisition can also be performed with high pitch (up to 3.4), enabling the entire heart to be scanned within 1 cardiac cycle and thus drastically reducing the radiation exposure to submillisievert values for certain coronary artery examinations.7,8 Pitch is defined as the longitudinal distance that the table travels per revolution of the x-ray tube divided by the total nominal irradiated width of the detector. Higher pitch also reduces acquisition of overlapping...
slices, which drastically reduces radiation exposure to the patient.

There is a paucity of data on the use of this new CT scanner technology for PV imaging. Thus, we aim to determine the radiation dose and to assess the adequacy of image quality (IQ) with this prospectively ECG-triggered, high-pitch scan mode using the 128-slice DSCT scanner in patients who are in sinus rhythm (SR) and AF. In addition, we compare the radiation dose and IQ between this high-pitch scan protocol and previously used standard retrospective or prospectively ECG-triggered CT protocols. Last, we compare the scan duration and PV anatomy between high-pitch CT and MRI.

Methods

Study Population

We performed a retrospective query through our radiology database (RENDER, Massachusetts General Hospital, Boston, MA) for patients who underwent DSCT evaluation for PV imaging between April 2010 and April 2011 and identified 106 consecutive patients. Figure 1 summarizes the study schema and inclusion/exclusion of patients. A total of 94 patients with a history of paroxysmal or persistent AF who underwent PV imaging with this high-pitch CT protocol were included for analysis. Of the 94 patients, 19 patients had previous standard PV CT scans, and 18 patients had an MRI for PV imaging. The local Institutional Review Board approved the study protocol.

Imaging Protocols

High-Pitch 128-Slice DSCT Protocol

All high-pitch CT image acquisitions (pitch 3.4) for LA and PV anatomy were performed at end-expiration using a 128-slice DSCT scanner (Definition Flash, Siemens Healthcare, Forchheim, Germany). CT scan parameters include 2×128×0.6 mm slice collimation, gantry rotation time of 280 ms, half-scan reconstruction for temporal resolution 75 ms, tube voltage of 100 or 120 kV, and effective tube current of 252 to 456 mAs using automated exposure control. β-blocker was not given before scanning, except in 1 patient (metoprolol 5 mg intravenously). Oral barium (15 mL) was given in 88% of patients at the request of the referring electrophysiologist. We used a test bolus protocol, followed by a contrast-enhanced CT scan, with a flow rate of 5 to 6 mL/sec of an iodinated contrast agent and a normal saline solution of 40 mL at the same rate. Scanning was prospectively triggered at 25% of the R-R interval on ECG, and images were acquired in 1 heart beat. Patients with hypoattenuation of the LA appendage on the contrast-enhanced CT scan immediately had a delayed noncontrast CT scan to evaluate for possible LA appendage thrombus.

Standard CT Protocol

Standard non–high-pitch scans (pitch, 0.2–0.38) were performed at end-expiration using a 64-slice single-source multidetector CT scanner (Siemens Sensation 64, gantry rotation time of 330 ms, 32×0.6 mm collimation, tube voltage of 120 kVp, effective tube current of 839–862 mAs), 64-slice

Figure 1. Flow diagram of study schema and population. CT indicates computed tomography; DSCT, dual-source CT; LA, left atrial; and MRI, magnetic resonance imaging.
DSCT scanner (Siemens Definition 64, gantry rotation time of 330 ms, 2x64x0.6 mm collimation, tube voltage of 120 kVp, effective tube current of 158–826 mAs), or 128-slice DSCT scanner (Siemens Definition Flash, gantry rotation time of 280 ms, 2x128x0.6 mm collimation, tube voltage of 100 or 120 kVp, effective tube current of 252–456 mAs) with retrospectively gated or prospectively triggered acquisition (Figure 1). Similar to the high-pitch CT protocol, the standard CT protocols included a test bolus scan, followed by contrast-enhanced CT scan and a delayed noncontrast CT scan if LA appendage thrombus was suspected.

For all high-pitch and standard CT scans, transaxial images were reconstructed with a slice thickness of 0.1 to 1.0 mm and increments of 0.4 to 0.5 mm. A medium smooth tissue convolution kernel was used. CT image data sets were transferred to an offline workstation (Ziostation, Ziosoft Inc, Redwood City, CA), where axial and multiplanar reformatted images of PV and LA anatomy were evaluated.

MRI Protocol
MRI studies were performed using a 1.5-Tesla scanner (Signa HDx, GE Healthcare, Milwaukee, WI) that had an 8-element, phased array cardiac coil. The MRI protocol was performed with respiratory gating and consisted of 3-plane localizer, sequential 2-dimensional steady-state free precession localizer and asset calibration. Subsequent hyperventilation sequences included test bolus scan, followed by 3-dimensional magnetic resonance angiography of the pulmonary vessels with administration of intravenous gadolinium (0.1 or 0.2 mmol/kg, depending on renal function). All images were obtained with breath hold at end-expiration. The 3-dimensional magnetic resonance angiography was acquired at a slice thickness of 2.2 to 2.6 mm. From the 3-dimensional data set, multiple volume-rendered images and endoluminal views were reconstructed using a dedicated workstation (ADW 4.2, GE Healthcare).

Radiation Dose
For all CT scans, we calculated the effective radiation dose for the PV scan alone and for the total scan, which included the cumulative radiation dose from the topogram, test bolus, contrast-enhanced scan, and if performed, the noncontrast delayed scan. The effective radiation dose was calculated by multiplying the dose length product and a conversion coefficient of 0.014 for the chest.9

Image Quality
Two CT readers, blinded to patients’ clinical data, assessed the CT IQ and PV anatomy by consensus. If there was disagreement, a third CT reader reviewed the images together with the 2 readers until a consensus was reached (n=4). IQ was assessed on the basis of 5 categories as determined by the presence of artifacts affecting the LA or PV, image noise, and adequate LA and PV contrast enhancement. IQ was classified as 1=excellent, 2=good, 3=moderate, 4=poor, and 5=nondiagnostic or uninterpretable scan. Assessment of artifacts affecting the PV and LA included slab and breathing artifacts, metal or beam hardening artifacts from pacing wires or mechanical valves, and artifacts from barium in the esophagus or stomach.

PV Anatomy
For both the CT and MRI, the PV ostium was defined as the point of inflection between the walls of the PV and LA.10 The number of separate PV ostia entering the LA was determined in multiple orthogonal planes. On the right, we assessed for the presence of a common, superior, middle, inferior, and top PV. On the left, we assessed for the presence of a common, superior, middle, and inferior PV. For LA size, we report the anterior to posterior LA diameter.

Statistical Analysis
Continuous data are presented as means±SD or median (interquartile range) as appropriate and percentages for categorical variables. For 2 group comparisons, we used Student t test or Wilcoxon rank sum test for continuous variables and χ² or Fisher exact test for categorical data, as appropriate. We classified the heart rate analyses into 5 categories using cut points defined by the 25th, 50th, 75th, and 90th percentiles: <60, 60 to 70, 71 to 85, 86 to 99, ≥100 beats per minute. We compared the radiation dose across the 5 heart rate categories using Kruskal-Wallis 1-way analysis of variance ANOVA. We compared the IQ across the 5 heart rate categories in 2 ways: (1) those with excellent IQ versus those without using χ² test; and (2) as differentiated by the ordinal 5-point IQ categories using Fisher exact tests. For the comparison of high-pitch and standard CT protocols, we tested the difference in radiation dose by using mixed-effects models to account for the within-subject variability. For the subset of patients with CT and MRI, we used a paired t test to compare the difference in scan duration time. For comparison of PV anatomy between CT and MRI, we reported exact agreement and used Cohen κ statistics to determine the degree of agreement between the 2 modalities. P<0.05 was considered statistically significant. Statistical analyses were performed using SAS (version 9.2, SAS Institute Inc, Cary, NC).

Results
Baseline patient characteristics for the total cohort who underwent high-pitch scans are summarized in Table 1. Medications listed represent those taken regularly at the time of CT. Baseline renal function was normal, mean left ventricular ejection fraction was preserved, and mean LA size was increased in the total cohort, with no difference between SR and AF (all P≥0.06). At the time of CT acquisition, 69 (74%) patients were in SR. The distribution of heart rates is shown in Figure 2A. The mean total CT scan duration from the beginning of the test bolus to the end of the PV scan was 6±4 minutes, with no difference between patients in SR or AF (P=0.65).

Radiation Dose
Table 2 shows the CT scan length, total contrast administered, and radiation doses of the high-pitch component, as well as the total scan. The median total effective radiation dose of the total scan was 1.4 (1.3, 1.9) mSv, which includes 15 patients who underwent a delayed noncontrast scan to further investigate for LA appendage thrombus. There was no difference in the median dose length product, volume CT dose index, or effective radiation dose between patients in
SR and AF (all P≥0.22). There was no difference in radiation dose when classified by the 5 heart rate categories (P=0.78; Figure 2B).

When classified by tube voltage, the median effective radiation dose was 1.2 (1.1, 1.3) mSv for 80 patients scanned with 100 kV and 2.5 (2.2, 2.7) mSv for 14 patients scanned with 120 kV (P<0.0001). The mean body mass index (BMI) was 29±6 kg/m² for patients scanned with 100 kV and 34±6 kg/m² for those scanned with 120 kV.

All 15 delayed scans showed no LA appendage thrombus by CT, with subsequent confirmation by transesophageal echocardiography. The median effective radiation dose of the 15 delayed scans was 0.6 (0.5, 0.7) mSv.

**Image Quality**

IQ was assessed as being excellent or good in 93 (99%) patients, and no scans had poor IQ or were nondiagnostic. There was no difference in IQ between patients in SR or AF.
All 80 patients scanned with 100 kV had good to excellent IQ scans. In the 14 remaining patients who were scanned with 120 kV, 13 had good to excellent IQ, and 1 scan was assessed as having moderate IQ because of severe image noise in a patient with BMI of 31 kg/m² and suboptimal LA contrast enhancement (Figure 3). No scans had slab or breathing artifacts. Artifacts affecting IQ of the LA and PV were predominantly because of barium and beam hardening artifacts. Pacing devices or mechanical valve artifacts affected the LA in 7 (7%) scans, the PV in 8 (9%) scans, and LA and PV in 1 (1%) scan. Of the 30 patients in whom there was artifact from barium, the barium artifact affected the LA in 19 (20%) patients, PV in 5 (5%), and both in 6 (6%) patients. Regardless of SR or AF, there was no difference in the number of patients affected by metal (\(P=0.78\)) or barium artifacts (\(P=0.6\)). Image noise level was graded as none to average in the majority of CT scans (n=87; 93%). One (1%) scan was affected by severe noise as mentioned above.

**Table 2. CT Parameters of Total Patient Population and as Classified by Sinus Rhythm or AF**

<table>
<thead>
<tr>
<th></th>
<th>Total (n=94)</th>
<th>Sinus Rhythm (n=69)</th>
<th>AF (n=25)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT features</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scan length, mm</td>
<td>195 (184, 210)</td>
<td>194 (182, 210)</td>
<td>199 (189, 209)</td>
<td>0.62</td>
</tr>
<tr>
<td>Total contrast, mL</td>
<td>84.8±11.0</td>
<td>85.6±11.4</td>
<td>82.6±9.8</td>
<td>0.24</td>
</tr>
<tr>
<td>High-pitch scan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube voltage (%), 100 kV</td>
<td>80 (85)</td>
<td>60 (87)</td>
<td>20 (80)</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>120 kV</td>
<td>14 (15)</td>
<td>9 (13)</td>
<td>5 (20)</td>
</tr>
<tr>
<td>CTDIvol, mGy</td>
<td>3.6 (3.5, 3.6)</td>
<td>3.6 (3.5, 3.6)</td>
<td>3.6 (3.5, 3.6)</td>
<td>0.55</td>
</tr>
<tr>
<td>DLP, mGy×cm</td>
<td>88 (81, 97)</td>
<td>88 (80, 95)</td>
<td>89 (84, 97)</td>
<td>0.43</td>
</tr>
<tr>
<td>Effective dose, mSv</td>
<td>1.2 (1.1, 1.3)</td>
<td>1.2 (1.1, 1.3)</td>
<td>1.3 (1.2, 1.4)</td>
<td>0.43</td>
</tr>
<tr>
<td>Total scan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLP, mGy×cm</td>
<td>103 (94, 135)</td>
<td>103 (92, 122)</td>
<td>104 (99, 138)</td>
<td>0.22</td>
</tr>
<tr>
<td>Effective dose, mSv</td>
<td>1.4 (1.3, 1.9)</td>
<td>1.4 (1.3, 1.7)</td>
<td>1.5 (1.4, 1.9)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

CT, computed tomography; AF indicates atrial fibrillation; CTDIvol, CT dose index volume; and DLP, dose length product.

**Figure 2.** A, Histogram with distribution of heart rates of the 94 patients. B, Radiation dose as classified by heart rate categories (\(P=0.73\); Table 3). All 80 patients scanned with 100 kV had good to excellent IQ scans. In the 14 remaining patients who were scanned with 120 kV, 13 had good to excellent IQ, and 1 scan was assessed as having moderate IQ because of severe image noise in a patient with BMI of 31 kg/m² and suboptimal LA contrast enhancement (Figure 3). No scans had slab or breathing artifacts. Artifacts affecting IQ of the LA and PV were predominantly because of barium and beam hardening artifacts. Pacing devices or mechanical valve artifacts affected the LA in 7 (7%) scans, the PV in 8 (9%) scans, and LA and PV in 1 (1%) scan. Of the 30 patients in whom there was artifact from barium, the barium artifact affected the LA in 19 (20%) patients, PV in 5 (5%), and both in 6 (6%) patients. Regardless of SR or AF, there was no difference in the number of patients affected by metal (\(P=0.78\)) or barium artifacts (\(P=0.6\)). Image noise level was graded as none to average in the majority of CT scans (n=87; 93%). One (1%) scan was affected by severe noise as mentioned above. Figure 2C depicts the distribution of IQ across the 5 heart rate categories. Across the heart rate categories, there was no difference in the proportion of scans with excellent versus those deemed not excellent in IQ, nor when comparing excellent, good, and moderate IQ (both \(P \geq 0.28\)). Of note, the IQ was either excellent or good at high rates (>85 beats per minute).

**High-Pitch Versus Standard CT Protocols**

A subset of 19 patients (59±9 years; BMI, 29±5 kg/m²) had a high-pitch scan and a previous standard protocol CT scan for PV anatomy assessment, both of which were clinically indicated at the time. The median duration between high-pitch and standard CT scans was 15.8 months (range, 3–52 months). Figure 1 shows the type of CT scanner and protocol used. All 24 standard CT scans were performed with 120 kV. Of the high-pitch scans, 13 (68%) were performed with 100 kV and the remaining 6 scans (32%) with 120 kV.

The median total effective radiation dose was drastically reduced when comparing the standard CT scans with the
High-pitch protocol (19.3 [15.1, 25.4] versus 1.6 [1.3, 2.8] mSv, respectively, \( P<0.0001 \); Figure 4). Similar differences in radiation dose reduction was seen for patients in SR (standard CT: 16.7 [11.2, 20.5] versus high-pitch scan: 1.5 [1.3, 2.7] mSv; \( P<0.0001 \)) and even more pronounced in patients with AF (standard CT: 27.7 [21.9, 31.7] versus high-pitch scan: 1.9 [1.4, 2.9] mSv; \( P=0.039 \)). When comparing radiation dose of scans performed at 120 kV, we found similar marked dose reductions (standard CT: 19.3 [15.1, 25.4] versus high-pitch scan: 2.8 [2.6, 2.9]; \( P=0.01 \)). Only 1 of the standard CT protocols was performed using a prospectively triggered, non–high-pitch, 120-kV acquisition with a radiation dose of 4.5 mSv (patient was in SR).

Although all high-pitch and 92% of standard CT scans were assessed as having excellent or good IQ, 2 (8%) scans performed with the standard protocol were assessed to have poor IQ because of large slab artifacts, 1 in SR (Figure 5) and the other in AF (Figure 6). Additionally, slab artifacts were present in 4 other standard CT scans; however, these slab artifacts did not involve the LA or PV and thus not graded as severely affecting IQ. Notably, there were no slabs or breathing artifacts in the high-pitch subgroup.

**High-Pitch CT Versus MRI**

When comparing the 18 patients (61±9 years; BMI, 30±6 kg/m\(^2\)) with both CT and MRI, the CT scan duration was strikingly shorter from the time of first image acquisition to the final image acquired (CT: 6±1 versus MRI: 41±16 minutes; \( P<0.0001 \)). The median duration between high-pitch CT and MRI was 24.5 (range, 0.5–102) months.

In total, CT identified 72 PV (right, 38; left, 34), and MRI identified 71 PV (right, 39; left, 32). There was excellent agreement of PV anatomy (presence or absence of each PV).
PV) between CT and MRI ($\kappa$ 0.84; $P<0.0001$). There was near-perfect agreement between the 2 modalities when assessing right-sided PV ($\kappa$ 0.98; $P<0.0001$) and good agreement for left-sided PV anatomy ($\kappa$ 0.66; $P<0.0001$). Table 4 shows the excellent agreement between CT and MRI for the assessment of PV anatomy. More specifically, the main discordance between the 2 modalities was with MRI classifying 3 left common ostia, whereas CT distinguished these as 2 separate ostia.

CT technology continues to rapidly evolve, especially in the area of reducing radiation dose while preserving IQ. In the present study, we used a high-pitch, ECG-triggered scan mode on a second-generation DSCT scanner to assess PV and LA anatomy in patients with SR or AF. Our results show that PV imaging can be performed with a low median radiation dose of 1.4 mSv and achieves good to excellent CT IQ. CT scanning is feasible, with no difference in IQ between patients in AF compared with SR, without the need for heart rate-lowering agents. When compared with prior standard CT protocols, we observed a remarkable reduction in radiation dose for both patients with SR and AF with this high-pitch CT protocol. Scan time acquisition was much faster with this low radiation CT scanning technique compared with MRI, with excellent agreement of PV anatomy between the 2 imaging modalities.

Thorough assessment of PV and LA anatomy with a noninvasive imaging modality, such as CT, is important in patients with paroxysmal or persistent AF before PV isolation. Anatomic information from the CT data set can be integrated into a 3-dimensional reconstruction of the PV and LA using EAM systems for guidance during radiofrequency PV ablation.5,11 However, minimizing radiation exposure during CT while maintaining good to excellent IQ is essential. Although CT and EAM integration has been shown to result in reduced procedural duration and radiation exposure,11 patients can receive radiation doses of between 15 and 20 mSv from procedural fluoroscopy alone.12,13 Moreover, recurrence of AF is common, and as high as 56% after ablation therapy,
repeat procedures are often necessary.\textsuperscript{14,15} Hence, minimizing CT radiation dose remains a priority because patients may be further exposed to ionizing radiation during postprocedural follow-up scans and need for repeat ablation procedures, which includes reimaging the PV anatomy beforehand.

Various CT techniques and modes are available for the imaging of PV anatomy, including the use of nongated and ECG gating. Although nongated scans historically involve much less radiation than gated scans (4.6 mSv for nongated scans and 13.4 mSv for gated scans), both may be used for integration with EAM,\textsuperscript{16} although in our experience gated CT scans have less motion artifact and better IQ. ECG-gated CT scans can be acquired with retrospective gating or prospectively triggered, at the expense of much higher radiation dose when retrospective gating is used.\textsuperscript{16,17} In our study, the median total radiation dose of the standard CT protocol subgroup was 19.3 mSv, which was inclusive of the test bolus, PV scan, and delayed scans if required and, most importantly, included patients in SR and AF. If we exclude patients in AF, our median radiation dose with the retrospective gated scans was 16.7 mSv, which is comparable with that reported by Wagner et al,\textsuperscript{16} which included only patients in SR. Alternatively, prospectively triggered scanning can also be used to lower radiation dose during CT scan acquisition,\textsuperscript{17} as with our 1 patient who was scanned using the non–high-pitch prospective mode with a radiation dose of 4.5 mSv. However, this prospective scan mode is used mainly in patients with regular and low heart rates and, in our institution, is no longer implemented for PV imaging because it can be performed with the newer and much lower radiation high-pitch CT protocol. Noncontrast-enhanced prospective ECG-triggered scans using a 64-slice multidetector CT have also been investigated for the feasibility to assess PV anatomy accurately before radiofrequency ablation with low-radiation dose of 1.3 mSv. However, the CT scan protocol used in the study by Lee et al\textsuperscript{18} was the low-dose noncontrast calcium score scan (which was not used to coregister with EAM), followed by a contrast-enhanced retrospectively gated CT angiography scan with a mean radiation dose of 8.5 mSv. The noncontrast scans were

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|}
\hline
\textbf{Concordance} & \textbf{Discordance} & \textbf{Agreement (\%)} \\
\hline
\textbf{Right PV branch} & & & & \\
\hline
Common & 0 & 18 & 0 & 0 & 100 (18/18) \\
Superior & 18 & 0 & 0 & 0 & 100 (18/18) \\
Middle & 2 & 15 & 0 & 1 & 94 (17/18) \\
Inferior & 18 & 0 & 0 & 0 & 100 (18/18) \\
Top & 0 & 18 & 0 & 0 & 100 (18/18) \\
\hline
\textbf{Left PV branch} & & & & \\
\hline
Common & 1 & 13 & 1 & 3 & 78 (14/18) \\
Superior & 13 & 1 & 3 & 1 & 78 (14/18) \\
Middle & 0 & 18 & 0 & 0 & 100 (18/18) \\
Inferior & 13 & 1 & 3 & 1 & 78 (14/18) \\
\hline
\end{tabular}
\caption{Agreement of PV Anatomy Between High-Pitch CT and MRI (n=18 Patients)}
\end{table}

PV, pulmonary vein; CT indicates computed tomography; and MRI, magnetic resonance imaging.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{Computed tomography (CT) oblique sagittal and volume-rendered images from a patient who had a previous standard retrospective scan (A, C) and subsequently a high-pitch CT scan (B, D). Both CT scans were performed on the 128-slice dual-source CT with the patient in atrial fibrillation. Note the slab artifact (arrow) in the retrospective CT scan resulting in a grading of poor image quality but not in the high-pitch scan, which was graded as excellent in image quality. The radiation dose was 25 mSv for the retrospective scan and 2.9 mSv for the high-pitch scan.}
\end{figure}
assessed as having high-diagnostic performance for identifying variations in PV in patients with renal dysfunction. However, although the 3-dimensional volume-rendered reconstructions with the noncontrast CT scans were possible, they were unable to be used to coregister with EAM before PV isolation, thus limiting the clinical use of noncontrast CT scans in this patient cohort.

Newer CT scanner technology using single-beat acquisition with prospective triggering can be performed with either >64-slice multidetector CT or DSCT scanners.7,19 The radiation dose for a 320-detector row, single-source CT has yielded low radiation doses for PV imaging of 1.9 mSv for patients with BMI≤25 kg/m² using 100 kV and 3.8 mSv for patients with BMI>25 kg/m² using 120 kV.19 When comparing our findings with that of 320-detector row CT with prospective scanning for PV anatomy, our radiation dose for patients scanned at 100 kV was lower at 1.2 mSv with the 128-slice DSCT high-pitch protocol, despite a higher mean BMI of 29 kg/m². Similarly, when using 120 kV (mean BMI, 34 kg/m²), CT scanning with the DSCT high-pitch mode resulted in lower radiation dose (2.5 mSv) than that reported with the 320-slice single-source scanner. Not only does our study show that this high-pitch DSCT scan mode for imaging of PV anatomy is feasible, but also this can be achieved with low radiation dose (median, 1.4 mSv). This value is remarkably lower than other previously reported radiation doses for PV imaging without the use of high-pitch scanning.16,19 To put the radiation dose into perspective, the average annual background radiation amounts to ≈3 mSv.20 We were able to achieve such low radiation dose because of the high-pitch factor of 3.4 on the second-generation DSCT, which allows image acquisition of the entire thorax within 1 heart beat.

The main issue with poor IQ is the potential for artifacts to adversely affect the coregistration process with EAM. For the high-pitch scans, rate-slowing agents were not required for heart rate control in patients with either SR or AF. Regardless of the heart rate or rhythm, we found that IQ was preserved, and good to excellent IQ was possible, even at overall high heart rates. Notably, because the entire LA and PV ostia are captured within 1 cardiac cycle on a high-pitch CT scan, slab and breathing artifacts are not present. Interestingly, with the non–high-pitch CT scans, we had 2 cases of 24 with slab artifacts, despite a much higher radiation dose (Figures 5 and 6).

MRI is another option for imaging PV anatomy and has the benefit of not requiring ionizing radiation. However, this imaging modality is time intensive, with a mean total examination time of 48 minutes to complete a PV imaging protocol.21 In our study, the median total scan duration from the beginning of the test bolus to the end of the CT scan was 6 minutes compared with 41 minutes for MRI, which is an advantage of CT and an important alternative imaging option for patients with claustrophobia, an inability to lie supine for prolonged periods, or those unable to perform long breath holds because of dyspnea or musculoskeletal issues because of its much shorter scan duration.

Additionally, CT can be performed in patients with cardiac devices, such as pacemakers, defibrillators, or cardiac resynchronization therapy. Metal from device therapy did not adversely affect IQ or the ability to assess PV anatomy on CT. Specifically, 17% of patients in our study had device therapy and underwent CT instead of MRI because of safety concerns, although there are now increasing reports of the safety of MRI in patients with cardiac devices.22,23

With respect to PV anatomy, we found great agreement between CT and MRI (κ 0.84), with near–perfect agreement for the right-sided PV (κ 0.98). The slight difference in the number of PV between CT and MRI likely reflects the subjective nature of differentiating a short common trunk of a PV from 2 separate ostia. This discordance between the 2 modalities may be explained by the better spatial resolution in the z axis with CT, where images were acquired with a thinner slice thickness of 0.6 to 0.75 mm, in comparison with 2.2 to 2.6 mm with MRI. For this reason, the isotropic spatial resolution of CT provides greater detail of PV anatomy than MRI. Delineating a common ostium correctly is important because it may impact the ablation strategy.

Limitations

The number of patients who had standard CT/MRI for comparison with high-pitch CT scans is small. The choice in PV imaging is dependent on the local expertise and equipment available. CT scans were performed for clinical indications, with variations in PV and LA protocols dictated by individual cardiac CT imagers. However, this reflects real-world practice in a single tertiary center.

Conclusions

Low-radiation dose (median 1.4 mSv) and good to excellent IQ are achievable with prospectively ECG-triggered, high-pitch DSCT for PV imaging in patients with either SR or AF at comparable doses. This radiation dose is drastically lower in comparison with the non–high-pitch scan protocol. Scan times are significantly shorter than MRI, with excellent agreement of PV anatomy between the 2 imaging modalities. This protocol highlights the success of new cardiac CT technology to minimize radiation exposure, giving clinicians a new low-dose imaging alternative to assess PV anatomy.

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Cardiac computed tomography (CT) is often used to noninvasively define left atrial and pulmonary venous anatomy before atrial fibrillation ablation procedures. Exposure to ionizing radiation from CT is of concern, and efforts to reduce radiation dose, while maintaining excellent image quality, are imperative. Second-generation 128-slice dual-source CT scanners enable ECG-triggered, single heart beat image acquisition. In the present study, use of a high-pitch protocol with dual-source CT is shown to obtain excellent quality scans with a minimal radiation dose of 1.4 mSv and scan acquisition time of only 6 seconds during sinus rhythm or atrial fibrillation. Radiation dose was markedly lower than prior non-high-pitch retrospective or prospectively triggered CT pulmonary vein scans. CT scan duration was shorter than magnetic resonance imaging, with excellent agreement of anatomy between the 2 imaging modalities. This new cardiac CT technology minimizes radiation exposure, providing a new low-dose imaging alternative to assess pulmonary vein anatomy.
Pulmonary Venous Anatomy Imaging With Low-Dose, Prospectively ECG-Triggered, High-Pitch 128-Slice Dual-Source Computed Tomography
Wai-ee Thai, Bryan Wai, Kaity Lin, Teresa Cheng, E. Kevin Heist, Udo Hoffmann, Jagmeet P. Singh and Quynh A. Truong

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