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Combined Angiography and Late Gadolinium Enhancement Acquisition to Improve Assessment of Pulmonary Vein Isolation for Atrial Fibrillation

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Abstract

Purpose—To develop a Shared K-space MRI sequence that combines angiographic and late gadolinium enhancement (LGE) acquisitions to improve atrial wall segmentation and scar identification, and to develop a novel visualization method that quantifies scar encirclement of pulmonary veins post-ablation treatment for atrial fibrillation.

Materials and Methods—A Shared K-space (SharK) sequence was developed and used at 3T to image the left atrium in eleven patients post-cryoballoon ablation. The effects of sharing k-space between the angiographic and LGE acquisitions on the accuracy of scar were assessed. The left atrial wall was segmented and points about each pulmonary vein (PV) ostia were projected onto a bullseye to quantitatively compare PV encirclement. The parameters used to quantify encirclement were varied to perform a sensitivity analysis.

Results—Compared to using a complete set of k-space, total atrial scar differences were significant only when sharing > 75% k-space ($p=0.014$), and 90% sensitivity and specificity for identifying scar was achieved when sharing 50% k-space. In patients, the right PVs showed more inter-subject variance in encirclement compared to the left PVs. A 100° anteroinferior portion of the left PVs was always encircled while the superior segments of both right PVs was ablated in only 6/11 patients.

Conclusion—A SharK sequence was developed to combine angiographic and LGE imaging for atrial wall segmentation and scar identification. The PV bullseye quantifies and localizes encirclement about the PVs. The left PVs showed higher amount of scar encirclement and less variability compared to the right PVs.

Keywords

cryoballoon ablation; pulmonary vein isolation; late gadolinium enhancement; atrial fibrillation; cardiovascular MRI

INTRODUCTION

Pulmonary vein isolation (PVI) by catheter ablation has been shown to be effective in treating atrial fibrillation (1). PVI can be performed using a point-by-point radiofrequency (RF) ablation catheter or with application of a cryoballoon at the ostium of the pulmonary veins. Regardless of the method of ablation used, approximately 33% of patients who undergo PVI experience AF recurrence (2–4).

Studies that evaluate scar post-PVI have demonstrated that the continuity of scar encircling the pulmonary veins post ablation is associated with freedom from AF recurrence (5–7). MRI is capable of differentiating between scarred and non-scarred atrial wall by using late gadolinium enhancement (LGE) imaging (8–11). To perform LGE of the atrial wall, a three-dimensional (3D), navigator and electrocardiogram (ECG)-gated, inversion recovery (IR)-prepared fast low angle shot (FLASH) sequence is employed (8,12,13). Imaging is performed 15–25 minutes after contrast injection to allow sufficient time for contrast to accumulate into scar, and slices are acquired in the transverse orientation for full atrial coverage. The atrial wall is then extracted, by manually segmenting the LGE images, or semi-automatically segmenting the angiographic images that are co-registered to the LGE images (14). This segmentation is used to create a 3D reconstruction of the atrium and pixel intensities from the segmentation are projected onto the 3D model. Scar encirclement is assessed by visually inspecting the model to determine whether or not the pulmonary veins are fully encircled by scar or by dividing the region about the pulmonary vein into sectors and visually assessing the presence of LGE (5,6).

These current methods to evaluate scar post-PVI suffer from the cumbersome and subjective nature of atrial wall segmentation, and utilize non-quantitative methods to assess scar continuity or encirclement. Manual segmentation on LGE images is required due to the poor contrast at the blood-atrial wall border. While the inner atrial wall can be easily segmented on contrast-enhanced angiographic images, acquisition of angiography is often not part of the MR protocol. When angiographic images are acquired, a breath held sequence with a lower resolution than the LGE image is used (15). Transferring segmented borders from angiographic images onto the LGE images requires co-registration of both image stacks, a complicated process due to differences in resolution and respiratory position. In addition, the qualitative nature of encirclement assessment fails to describe the spatial heterogeneity in encirclement about the pulmonary veins and does not allow comparison between subjects in a quantitative manner. 3D models also require multiple viewing angles to fully determine the extent of scar encirclement about each pulmonary vein. In order to fully assess scar encirclement from PVI, an MR sequence which allows for more accurate atrial wall segmentation from angiographic images combined with a quantitative method to evaluate the amount of scar encircling the pulmonary veins is necessary.

The angiographic and LGE images are focused on the same anatomical region (the left atrium), but are acquired at different times post-contrast. This suggests that a more effective imaging scheme can be devised to combine acquisition of angiographic and LGE images to create inherently co-registered image stacks. The objectives of this study were to: (1) develop a Shared K-space (SharK) sequence to combine acquisition of angiography and LGE imaging that would create inherently co-registered images for improving visualization of the atrial wall, and (2) develop a novel visualization method that allows simple quantification of scar encirclement post-ablation.

MATERIALS AND METHODS

Sequence Theory

The Shared K-space (SharK) sequence was developed based on a 3D, whole-heart, contrast-enhanced, navigator- and ECG-gated, IR-FLASH sequence using the Siemens Integrated Development Environment for Application and Image Calculation Environment (IDEA/ICE). The SharK sequence employs centric-ordering in both the partition and phase encoding directions in k-space to maximize contrast-to-noise ratio (CNR) during angiographic imaging (Figure 1). The second acquisition of centric k-space is performed in the reverse centric-ordered partition encoding direction to allow imaging of the center portion at ~15 minutes post contrast, the time-point used to start LGE imaging. Outer k-space is shared between the acquisitions to create two full sets of k-space data, one for angiographic images, and one for LGE images. Three dummy pulses were added to drive the magnetization to a steady state prior to data acquisition.

Patient Population

Patients with atrial fibrillation (n = 11, 10 male, age = 61 ± 8 years) who had undergone their first pulmonary vein isolation by cryoballoon ablation underwent a cardiovascular magnetic resonance (MR) exam 1–3 months post ablation therapy. 10/11 patients had paroxysmal AF while one patient had persistent AF. This study was approved by the Emory University Institutional Review Board and was HIPAA compliant; all patients gave written informed consent.

MRI Protocol

All cardiac MR exams were performed on a 3T MRI (TimTrio, Siemens Healthcare, Erlangen, Germany) using a six-element phased-array cardiac coil. Axial and coronal black-blood images were acquired to position the whole heart scans. A double dose of gadobenate dimeblumine at 0.2 mmol/kg (MultiHance, Bracco Diagnostics Inc, NJ, USA) was slowly infused at a rate of 0.3 mL/s followed by an equal amount of saline. The SharK sequence was acquired in the sagittal orientation 90 s after the start of contrast injection. Sagittal orientation minimizes partial volume effects by acquiring slices perpendicular to orientation of the pulmonary veins. Sequence parameters were TR = 3.3 ms, TE = 1.44 ms, flip angle = 15° , inversion time = 200 ms, readout bandwidth = 610 Hz/pixel, GRAPPA acceleration factor = 2. 96–98 partitions were acquired with voxel size $1.36 \times 1.36 \times 1.5 \text{ mm}^3$ and interpolated to 192 – 196 partitions with voxel size $0.68 \times 0.68 \times 0.75 \text{ mm}^3$. A Look-Locker sequence was performed at 15 minutes post-contrast at a mid-short axis slice to determine

the optimal TI to null healthy myocardium. A full set of k-space was acquired in 5/11 patients to allow retrospective sharing of LGE k-space data with angiographic k-space data for validation. The remaining 6/11 patients used a 50% segment of central k-space to create LGE SharK images.

Atrial Wall Segmentation

The inner atrial wall was segmented on the angiographic images by using an intensity-based threshold, then the borders were manually refined to exclude any points in the left ventricle. The angiographic images were co-registered to the LGE or LGE SharK images using a gradient-ascent algorithm to find the maximum cross-correlation between the two image sets. The borders were then directly transferred from the angiographic images to the LGE images. Since the average atrial wall thickness is approximately 2 mm, borders were dilated 3 pixels (~2.1 mm) to cover the majority of the atrial wall (16). This 3 pixel distance was defined as the *epicardial dilation distance*.

Shared K-Space Assessment

To evaluate the effects from sharing k-space between angiographic and LGE images, different amounts of outer k-space ($1/8^{\text{th}}$, $2/8^{\text{th}}$, $3/8^{\text{th}}$... $7/8^{\text{th}}$) were shared from the 5 patients who had one full set of k-space acquired for angiography and one full set of k-space acquired for LGE images to create retrospective SharK LGE images (Figure 2). The atrial wall on the SharK LGE images were segmented by transferring the segmentation from the LGE images to the SharK LGE images as described previously. Atrial scar was differentiated from healthy atrial tissue by using a *scar intensity threshold*, where an ROI was selected in the LV myocardium, and atrial wall pixels with intensity greater than $\mu \pm 6\sigma$ of the ROI intensity were considered scar (15). The total amount of atrial scar for all LGE and SharK LGE images was calculated multiplying the total number of scarred atrial wall pixels by the voxel size. The same ROI was used for all LGE and SharK LGE images for consistency. The effect of sharing different amounts of k-space was assessed by calculating the absolute scar error as compared to the original full k-space LGE image. A pixel-to-pixel comparison was performed on the atrial wall pixels of the full k-space LGE images compared against the corresponding atrial wall pixels on the SharK LGE images. All atrial wall pixels were classified as scarred or healthy based on whether the pixel intensity was greater than the scar threshold. This allowed the creation of a 2x2 contingency table to perform a sensitivity and specificity analysis on a per-pixel basis. Paired t-tests were used to compare changes in atrial scar burden between the original LGE image and all SharK LGE images.

3D Atrial Reconstruction

All pixels that comprised the inner atrial wall were exported as a point cloud and wrapped in Geomagic (Rock Hill, SC, USA) to create a 3D shell of the atrium. A plane perpendicular to each PV ostia, named the “PV plane”, was manually defined as the opening at the atrial body leading to the PV (Figure 3, top right). The reconstruction was cut at these four planes to create five separate 3D structures (atrial body, LIPV, LSPV, RIPV, RSPV). Files were exported as STL files into MATLAB.

Pulmonary Vein Bullseye Projection

All segmented atrial wall points were classified into one of the five structures (atrial body, LIPV, LSPV, RIPV, RSPV) as defined by the PV planes based on the nearest Euclidean distance. This prevented points that were categorized as part of one anatomical pulmonary vein to be associated with another pulmonary vein in the display. For each pulmonary vein, the PV plane was translated ± 7 mm along its normal direction to create a domain for each bullseye (Figure 3). Atrial wall points within this domain that belonged to either the corresponding pulmonary vein or the atrial body were projected onto a circular grid to create “pulmonary vein bullseye” using a polar projection algorithm. This algorithm projected the anatomical superior direction onto the PV plane, which was then defined as 90° on the bullseye. Atrial wall points on the side of the plane closer to the atrial body were projected outwards toward larger rings onto the bullseye while points on the side of the plane toward the pulmonary vein were projected inwards onto smaller rings on the bullseye. A bullseye grid was then linearly interpolated from the pixel intensities of the projected atrial wall points. The bullseye display assumes one is looking at the pulmonary vein ostia from the pulmonary vein side, outside of the atrial body.

Scar Encirclement Assessment

Encirclement was assessed by quantifying the percentage of scar (out of 360°) encircling each pulmonary vein (Figure 4). Pulmonary vein bullseyes were created using the same *scar intensity threshold* to differentiate scarred from healthy atrial wall. A *radial scar distance threshold* was then applied to quantify the number of degrees of ablation around each pulmonary vein. This value classified each 1° about the PV bullseye as “encircled” or “not encircled” and was set to 2 continuous millimeters of atrial scar in the radial direction on the bullseye for a degree of encirclement. The 2 mm value was chosen based assumption that ~2 connected MR pixels above the scar threshold represented a true region of LGE. The total encirclement was calculated by summing the total degrees of encirclement for each bullseye.

PV Bullseye Comparison

PV bullseyes were combined across patients for each of the four pulmonary veins to compare the frequency of scar encirclement about each pulmonary vein. PV bullseyes were collapsed in the radial direction into a single 360° ring, with each degree classified as ‘encircled’ or ‘non-encircled’ based on the radial scar distance threshold (Figure 4). Rings were combined across patients to determine the most common regions of ablation about each pulmonary vein across patients. A paired t-test assuming equal variances was used to compare encirclement between the pulmonary veins, and $p < 0.05$ was used to determine significance.

Sensitivity Analysis

A sensitivity analysis was performed by varying: (1) the epicardial dilation distance, (2) number of standard deviations above the mean for the scar intensity threshold, or (3) the radial scar distance threshold to evaluate their sensitivity to encirclement (Table 1). One parameter was changed while the other two parameters held constant. The epicardial dilation was evaluated between 1 – 5 pixels, the scar threshold was evaluated between 1–10 standard

deviations, and the radial encirclement threshold criteria was changed between 1–4 mm. Baseline parameters used were: 3 pixel epicardial dilation distance, 6 standard deviations, and 2 mm radial encirclement threshold. The differences in percent encirclement were determined by subtracting by the percent encirclement when using the default parameters. A paired t-test assuming unequal variances was used to compare differences in percent encirclement between pulmonary veins for each increment tested in the sensitivity analysis. A $p < 0.05$ was used to determine significance.

Follow-Up

Follow-up was performed during routine clinical visits, usually at 1–6 months post-ablation and consisted of monitoring with a Holter monitor (24-hour minimum), history and examination, and an in-office ECG. Freedom from recurrence was defined by Heart Rhythm Society guidelines (17).

RESULTS

All eleven patients successfully completed the cardiac MR imaging protocol. Acquisition time for the angiography portion of the SharK sequence (full k-space) was 9.4 ± 2.3 minutes. Imaging time for the 50% SharK LGE images was 4.1 ± 1.2 minutes. The segmentation, 3D reconstruction, and bullseye creation process took approximately 90 minutes per patient.

Shared K-Space Assessment

Atrial Scar Burden—K-space was successfully retrospectively shared to create different SharK images in the five patients who had two sets of full k-space available (Figure 5). The difference in the total amount of atrial scar between using a full set of k-space and sharing up to 75% of k-space was non-significant ($p = 0.63, 0.43, 0.10, 0.18, 0.29, 0.20, 0.05$ for each 12.5% increment up to 75%), Figure 6. There was an increase in error at 75%, but the increase did not reach significance. Total atrial scar was significantly lower when 88.5% of K-Space was shared ($p = 0.014$).

Sensitivity/Specificity to Scar—Pixel-to-pixel comparisons of atrial wall pixels on the full k-space LGE images to the corresponding atrial wall pixels on SharK LGE images allowed calculation of sensitivity of SharK LGE images for correctly identifying a scarred atrial wall pixel and specificity of SharK LGE images in properly identifying a healthy atrial wall pixels (Figure 7). 90% sensitivity and specificity was achieved for SharK $< 50\%$. While the minimum specificity across all SharK LGE images was 78%, sensitivity decreased to 43% when sharing 87.5% of full k-space.

PV Encirclement Results

The average atrial wall scar burden was $10.7 \pm 5.9 \text{ cm}^3$. Pulmonary vein bullseyes were created for all patients, and an example patient is shown in Figure 8. The average encirclement for the four pulmonary veins was $78\% \pm 28\%$, $88\% \pm 19\%$, $54\% \pm 33\%$, and $58\% \pm 33\%$ for the LSPV, LIPV, RSPV, and RIPV respectively. Both left pulmonary veins

had significantly more scar encirclement than the RSPV ($p = 0.0072$, 0.0006 respectively). The LIPV also had significantly more scar encirclement than the RIPV ($p = 0.006$).

Pulmonary Vein Bullseye Comparison

Pulmonary vein bullseyes were successfully combined across all patients for the four pulmonary veins (Figure 9). The anteroinferior portion of the LSPV and LIPV were most consistently encircled. There was a 100° segment of the anteroinferior portion of the LIPV that was ablated in 10/11 patients and a 35° segment of the anteroinferior portion of the LSPV that was ablated all patients. In contrast, the right PVs were least consistently encircled across patients. The superior portion of the RSPV was encircled in only 5/11 patients. While the posteroinferior portion of the RIPV was encircled in 10/11 patients, the rest of the PV was frequently unsuccessfully ablated in 6/11 patients.

Pulmonary Vein Bullseye Encirclement Sensitivity

Epicardial Dilation Distance—*Encirclement* decreased as the epicardial dilation distance increased (Figure 10a). Differences in encirclement between 1–4 pixel epicardial dilation distances were within 10%. Although the differences in encirclement for 5 pixel epicardial distances were larger, this results in 3.75 mm thick borders, which is beyond the atrial wall border.

Scar Intensity Threshold—Encirclement decreased as the number of standard deviation used in the scar threshold increased (Figure 10b). Near complete encirclement is seen between 1–3 standard deviations as the low threshold does not properly separate healthy atrial wall pixels from scarred atrial wall pixels. Encirclement decays for scar intensity threshold > 3 standard deviations plot.

Radial Scar Distance Threshold—Encirclement linearly decreased as the distance used for the radial encirclement threshold increased (Figure 10c). While differences are significant for radial encirclement thresholds between 1–3 mm, encirclement only decreased ~5% for each millimeter increase in the radial encirclement threshold.

Patient Follow Up

The mean follow-up time was 4.9 months (range: 1 – 18 months). 3/10 patients experienced recurrence. The patient with persistent AF was lost to follow-up.

DISCUSSION

We developed a Shared K-space (SharK) sequence for generating angiographic and LGE images from a single acquisition and applied the sequence on patients who have undergone PVI for treatment of AF in this preliminary study. Acquisition of the SharK sequence allowed segmentation of the inner atrial wall borders on angiographic images and direct transfer of borders to LGE images for atrial wall segmentation. A pulmonary vein bullseye was developed to enable scar encirclement quantification about each PV. The sensitivity analysis revealed that the pulmonary vein bullseyes are resistant to changes in the radial encirclement threshold and epicardial pixel dilation amount but are more sensitive to the

number of standard deviations used in determining the scar intensity threshold. Applying the sequence and bullseye analysis to a group of patients post atrial fibrillation ablation treatment showed significant heterogeneity in the distribution of atrial scar at the pulmonary ostia.

Application of the SharK sequence to evaluate scar encirclement for pulmonary vein isolation has benefits over current methods of atrial scar imaging, which often do not acquire or use angiographic images in post-processing. When angiographic images are acquired, a lower resolution ($2 \times 2 \times 4 \text{ mm}^3$) breath-held sequence is often used, complicating the co-registration process for segmentation (6). Sharing k-space with the angiography sequence reduces imaging time proportional to the amount of k-space shared for LGE imaging. As a full set of k-space takes ~10 minutes for acquisition due to navigator-gating, the 50% shared k-space segment acquired for LGE imaging saves 5 minutes of imaging time. The shorter LGE imaging time allows acquisition of multiple LGE image stacks, which ensure successful imaging, in the case the first is inadequate due to poor myocardial nulling, patient movement or insufficient accumulation of gadolinium within atrial scar. Multiple image stacks may also be used to show the time-dependent behavior of enhancement of atrial scar tissue, and can potentially be used for atrial segmentation by classifying pixel intensities changes over time.

The SharK sequence also reduces post-image processing by simplifying image co-registration and potentially improves the accuracy of atrial wall segmentation. Co-registration between angiographic and LGE images can be achieved by performing a cross-correlation because the same sequence is used for both image stacks with only minor respiratory differences. Therefore, segmentation can be performed on angiographic images that have clear delineation of the blood-atrial wall border. The higher CNR between the blood-atrial wall border on angiography images compared to than LGE images has the potential lead to more reliable and consistent segmentation. Borders can be directly transferred to the co-registered LGE images and dilated to extract the atrial wall.

Previous studies that use MRI for left atrial imaging acquire images in the transverse orientation, however this imaging plane orientation is more closely parallel to the atrial wall and pulmonary arteries leading to partial volume effects. We propose that acquiring images in the sagittal orientation minimizes partial volume effects as slices are oriented closer to the plane perpendicular to the pulmonary vein and are subsequently more closely perpendicular to regions of scar. Segmentation is simpler in the sagittal orientation as this splits the left atrium into ellipsoids as opposed to the transverse orientation, which splits the left atrium into irregular shapes.

Previous studies have been qualitative, either using a binary “encircled/not-encircled” classification of pulmonary veins or dividing each PV into six sectors, with graders rating the presence of gaps in LGE around the sectors (5,6). Our novel method of quantification eliminates the subjectivity that comes with qualitative grading, showcases the heterogeneity of ablation about the pulmonary veins, and allows a full assessment of scar encirclement in a single glance. This quantification becomes more important when trying to associate recurrence with lack of encirclement, as simply classifying a vein as encircled or non-

encircled may not be enough to explain the differences between those whose symptoms are recurrent compared to those who are not.

Our results for encirclement are similar to what has been shown previously, though these studies focus on LGE imaging post-RF ablation. The LIPV has been shown to have the fewest gaps in LGE and the most scar volume as compared to the other PVs, consistent with our results which showed that the LIPV is the most completely encircled pulmonary vein (6,7). In addition, a previous study showed that quantification of total scar volume about each pulmonary vein showed that the only vein with significantly less scar volume between non-recurrent and recurrent AF patients was the RIPV (7). While our study does not currently have enough patients to predict AF recurrence based on scar encirclement percentage, we expect similar results as we found the RIPV as the PV with the most variance in scar encirclement and expect this to be an important predictor for AF recurrence.

The sensitivity analysis revealed that the scar encirclement is resistant to changes to epicardial dilation distance and radial encirclement threshold. The differences in percent encirclement when using a 1–2 pixel dilation distance are non-significant suggest that regions of the atrial wall that have been ablated are nearly fully transmurally scarred. The percent encirclement experienced only about a 5% decrease as the radial encirclement threshold was incremented for each additional pixel. The number of standard deviations used for the scar threshold was most sensitive to change and decayed linearly as the number of standard deviations used in the scar intensity threshold increased. However, it is not possible to determine the physiologically correct threshold without performing an animal study to directly compare MR images to histology.

There are several limitations for this study. There was insufficient number of patients to draw any conclusions regarding recurrence. The scar intensity threshold used ($\mu \pm 6\sigma$), while based off a previous study, and does not have validation by *ex-vivo* imaging or histology (15). In addition, the threshold used is different from the majority of other studies, which uses three standard deviations above the mean (5,18). Differences in the LGE sequence such as inversion time or flip angle may be attributed to using different number of standard deviations as the scar threshold. Our inversion times were typically in the range of 300–370 ms while others studies have used TI times of ranging from 230–280ms (8,9). It is important to note that the bullseye mesh resolution is higher than the MR image resolution. The interpolation performed to achieve the bullseye resolution smooths the MR image data. Lastly, patient numbers were not large enough to make statistical associations between encirclement and recurrence. Additional studies will be necessary to confirm the clinical utility of the pulmonary vein bullseyes.

In conclusion, a Shared K-Space sequence can be used to produce images for simpler atrial wall segmentation and the developed pulmonary vein bullseye is a tool to quantify the degree of pulmonary vein encirclement from ablation. Application of the sequence and image processing methodology in patients post-ablation in this preliminary study showed significant variation in the distribution of atrial scar at the PV ostia. The RSPV and RIPV had twice as much variance in overall encirclement and that a 30° anteroinferior segment of the RSPV was ablated in fewer than half of all patients.

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Figure 1.

Shared K-space (SharK) sequence. (a): K-space partition acquisition is shown versus time. The sequence uses a centric-ordered partition encoding ordering. Centric k-space is acquired during slow infusion of contrast and again after full acquisition of k-space. (b): Reconstruction methodology used to create angiographic and LGE images. The initially acquired centric k-space (red) is used for angiographic reconstruction while the later acquired centric k-space (blue) is used for LGE reconstruction. Outer k-space (purple) is shared between the two images.

Figure 2.

Workflow showing of steps used to prepare SharK LGE images to evaluate tradeoff from sharing different amounts of k-space. This was done in the five subjects where two complete sets of k-space data were acquired.

Figure 3. Pulmonary vein bullseye projection from segmented atrial wall points on LGE images. The four PV planes positioned at the PV ostia are shown on the top right. The blue plane on the magnified pulmonary vein represents the PV plane at the ostia, while the two white planes represent the bounding domain for atrial wall points to include on the pulmonary vein bullseye. The bullseye is aligned with the anatomical superior/inferior and anterior/posterior orientations.

Figure 4.

Sample pulmonary vein bullseye. Blue represents regions of healthy atrial wall while red represents regions of scarred atrial wall. A degree is considered encircled when it contains greater than 2 mm of continuous scar radially.

Figure 5.
SharK variations for two different slices are shown. Sharpness decreases as SharK increases.
Red arrows notate regions of atrial scar.

Figure 6.

Percent error in assessing total atrial scar across various SharK LGE images. No significant differences were found in total atrial scar between a full set of k-space and sharing up to 75% of k-space. (* = $p < 0.05$ when compared to a fully sampled LGE image, or 0% Shared K-space)

Figure 7. Sensitivity (top) and specificity (bottom) for detection of scarred atrial wall when comparing fully sample LGE images to various Shark LGE images. Sensitivity to atrial scar decreases exponentially as more k-space is shared while specificity remains above 80% for all Shark LGE images.

Figure 8.

Sample pulmonary vein bullseye for a patient 1–3 months post cryoballoon ablation. Blue represents regions with no scar while all other colors represent the pixel intensity. The left pulmonary veins show more complete encirclement while the right pulmonary veins show incomplete encirclement.

Figure 9.
Total encirclement for all four pulmonary veins across 11 patients. Colors note the number of patients that had a particular degree encircled.

Figure 10.

(a) Differences in percent encirclement for various epicardial pixel dilations. Encirclement decreases slightly as the number of pixels used for the epicardial dilation increases. (b) Differences in percent encirclement for various radial encirclement thresholds. Encirclement decreases as the number of standard deviations used in the scar intensity threshold increases. (c) Differences in percent encirclement for various radial encirclement thresholds when compared to a 2mm encirclement threshold. Encirclement decreases as radial encirclement

increases by approximately 5% for each millimeter increase in the radial encirclement threshold.

Table 1

Default values used for the epicardial dilation distance, scar intensity threshold, and radial encirclement threshold as well as the ranges tested to evaluate sensitivity to encirclement

	Default Value	Sensitivity Range
Epicardial dilation distance	3 pixels	1 – 5 pixels
Scar intensity threshold ($\mu \pm X\sigma$)	6 standard deviations	1 – 10 standard deviations
Radial encirclement threshold	2 mm	1 – 4 mm (1 mm increments)