Published in final edited form as:

Heart Rhythm. 2010 April ; 7(4): 489–496. doi:10.1016/j.hrthm.2009.12.007.

Relationship between Intended Sites of RF Ablation and Post- Procedural Scar in AF Patients, Using Late Gadolinium Enhancement Cardiovascular Magnetic Resonance

Jason E. Taclas, MS¹, Reza Nezafat, PhD^{1,2}, John V. Wylie, MD³, Mark E. Josephson, MD^{1,2}, Jeff Hsing, MD¹, Warren J. Manning, MD^{1,2,4}, and Dana C. Peters, PhD^{1,2}

¹ Beth Israel Deaconess Medical Center, Department of Medicine¹ (Cardiovascular Division), Boston, MA, USA

² Harvard Medical School, Boston, MA, USA

³ St. Elizabeth's Medical Center, Boston, MA and Tufts University School of Medicine, Boston, MA

⁴ Department of Radiology, Boston MA, USA

Abstract

Background—Radiofrequency (RF) ablation of the left atrium (LA) in patients with atrial fibrillation (AF) is guided by electroanatomic mapping systems. The cardiovascular magnetic resonance (CMR) late gadolinium enhancement (LGE) technique can detect scar after ablation. Direct comparisons between the locations of intended RF ablation sites and locations of scar formation in the LA have not been performed.

Objective—We sought to develop and employ a method for comparing the sites of RF application with the sites of post-procedural scar formation in the LA.

Methods—A method for rigid registration of CMR LGE images with electroanatomic mapping data (CARTO data), visualization of the registered data sets, and quantification of the correlations was developed and employed in 19 studies of patients with AF. The distance between the CARTO points and the CMR LA surface was measured as the mean integration error. The distance between each CARTO ablation and the nearest scar was measured. The gaps in sites of LGE and in CARTO ablation were also assessed qualitatively, in six sectors of each PV.

Results—The custom registration method provided a mean integration error between CARTO and CMR of 2.7 ± 0.7 mm. The average distance between CARTO and LGE scar was 3.6 ± 1.3 mm. Qualitatively, 20% of sectors with sites of CARTO ablation showed no evidence of LGE.

Conclusion—There was a visual and quantitative correspondence between CARTO ablation sites and LGE scar, but for twenty percent of CARTO ablation sites there was no visible corresponding LGE.

Corresponding address: Dana C. Peters, PhD, 330 Brookline Avenue, Boston, MA 02115, USA, Phone: 617 667 8037, Fax: 617 975 5480, dcpeters@bidmc.harvard.edu.

Other authors: None.

Conflicts of Interest: Dr. Manning receives research support from Philips Healthcare. Dr. Josephson receives consulting fees from Biosense Webster.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Keywords

CARTO; late gadolinium enhancement; left atrium; RF ablation; pulmonary vein isolation; delayed enhancement; MRI; contrast agent

Introduction

Radiofrequency (RF) ablation of the pulmonary veins (PV) is an invasive but increasingly popular therapy for atrial fibrillation (AF) patients (1) based on the principle of creating scar tissue to electrically isolate the pulmonary veins from the left atrium (LA) (2–4). At our institution, an electroanatomic mapping (EAM) system, CARTO (Biosense, Webster, Diamond Bar, CA, USA), is used in real time to create a map of the surface of the LA and PVs during the procedure, and to display the locations of ablations relative to the LA and PV ostia (5–8).

Magnetic resonance angiography (MRA) images acquired before and after PV isolation (PVI) are used clinically to visualize the anatomical structures, pre-procedurally (9) and intra-procedurally (6) to plan and perform the ablation, and after the procedure to monitor for PV stenosis (10). After PVI, the scar generated by RF ablation can be imaged using high spatial resolution late gadolinium enhancement (LGE) (11–14) cardiovascular MR (CMR). LGE CMR does not require additional gadolinium contrast, but makes use of the same dose of contrast used for the MRA, after a delay during which the gadolinium accumulates in the scar tissue and washes out of the blood pool.

Recently, methods for merging CMR or CT anatomical data with EP anatomic data have been introduced, motivated by the possibility that a more accurate depiction of anatomy might improve the speed and effectiveness of the ablation procedure (6,7) and reduce procedure time and radiation dose. Ablation points are recorded on the CARTO system, but the efficacy of each ablation (i.e. the creation of permanent tissue damage) is difficult to determine during the procedure.

We sought to evaluate the outcome of the ablation procedure by developing a custom method to register and visualize the LGE scar in the context of PV anatomy and electroanatomic mapping (i.e. CARTO) data, and to quantify the distances between LGE scar and RF ablation. We hypothesized that the scar observed on LGE CMR would correlate to the CARTO ablation points, and sought to characterize the percent of regions with intended ablations but without apparent LGE scarring (15).

Methods

From 59 consecutive patients with follow-up data for AF recurrence, 35 (59%) had diagnostic post PVI LGE images. Of these 35, the 19 patients who had accessible CARTO mapping data were studied. These subjects underwent PVI procedure, as described elsewhere (16,17). Briefly, an 8mm standard tip (n=15) or a 3.5mm (n=4) externally irrigated tip ablation catheter was advanced through a transseptal sheath into the LA. The catheter type was changed due to clinical changes in the PVI procedure during the study period. A circular catheter, advanced through a second transseptal sheath, was placed at each PV ostium to guide ablation and to confirm PV entrance and exit block (2–4). The RF ablations were placed 5–10 mm outside of each PV ostium until electrical PVI was achieved. For the 8mm catheter, the maximum temperature setting was 52° C, and maximum power output was 50 Watts; for the 3.5mm catheter, power was limited to 30 Watts. Ablation was performed for 30–120 seconds at each site, based on changes in local electrograms. All PVs were routinely isolated in all patients,

without routine addition of empiric ablation lines in the LA. Electroanatomic mapping was performed using CARTO XP. Clinical data regarding AF recurrence were obtained for each patient using a 7-day event monitor at multiple intervals during the first year. Recurrence included any symptomatic or asymptomatic AF lasting longer than 10 s and occurring >30 days after PVI. CARTO raw data, consisting of locations of mapped LA surface points and ablation points, along with points along each PV branch, were exported. 3D CARTO representations of the ablations were also obtained for comparison. For one patient with a repeat PVI procedure, the CARTO bipolar voltage map of the LA surface, obtained at the repeat PVI, was compared with the LGE scarring pattern obtained 2 years prior after the 1st PVI.

Subjects underwent LGE CMR >30 days after their 1st PVI. The MRA was performed during the first pass of a gadolinium contrast agent through the LA (9), using 0.2mmol/kg injection of Gd-DTPA (Magnevist, Berlex Laboratories, Wayne, New Jersey). Fifteen to 25 minutes after the injection, a 3D free-breathing, ECG-triggered LGE sequence was performed (11). The LGE sequence (14) used a gradient echo inversion recovery technique, with an inversion time set to null left ventricular (LV) myocardium. The spatial resolution was $1.3 \times 1.3 \times 4\text{--}5\text{ mm}^3$, interpolated to $0.7 \times 0.7 \times 2.5\text{ mm}^3$. All CMR imaging was performed using a Philips 1.5T CMR scanner (Achieva, Philips Healthcare, Best, NL), using a 5-element cardiac coil. LA systolic volume was measured using the biplane method with CMR 2-chamber and 4-chamber cine images (17), which were acquired as part of the clinical protocol. LV ejection fraction was measured using a stack of 2D short-axis cine images covering the LV.

Segmentation and registration

The images (both MRA and LGE) and CARTO data (Figure 1) were then processed to correlate scar formed by catheter ablation with intraprocedural sites of RF application. The processing provided visualization of the scar and sites of RF application. It also provided quantitative evaluation of the distances between LGE/scar and ablation sites.

Using Matlab 7.1 (Mathworks, Natick, MA, USA), as described previously (17,18), scar tissue (visibly hyper-intense regions) was segmented (Figure 2A,B) from the LGE images using a visually determined threshold and manually drawn regions of interest (ROIs) that included only the LA wall and PV ostia. The intra and inter-observer variability of this thresholding method have been reported (17). The MIPAV (version 4.0.0, NIH, USA) software package was used to manually segment the MRA images to isolate the LA (Figure 2C, D). A rigid registration was performed utilizing image coordinates, and landmarks such as the aorta were used to register the LGE CMR images to the segmented MRA images (Figure 2E). We developed a custom-built registration tool for fusing the EP and CMR data, using VTK v5.0.4 and ITK v3.4.0 C++ programming toolkits. Inputs to the software included the segmented MRA and LGE images (as DICOM files), the CARTO data (as two text files corresponding to ablation and surface mapping points), and two files containing the coordinates of PV ostia as observed the MRA and CARTO data sets. The MRA images were processed using the Marching Cubes algorithm to extract a 3D surface. The coarse rigid registration used the PV ostia locations (typically the left inferior, left superior, and right superior) as landmarks. After the coarse rigid registration, a fine registration between the LA surface points (mapped by CARTO, excluding ablation points) and the LA surface (obtained from the MRA) was performed, based on the iterative closest point (ICP) algorithm (6,19).

Quantitative evaluation

After registration of the three segmented data sets, distance metrics were recorded, including: distances between the CARTO surface points (excluding ablation sites) and the nearest LA surface pixel extracted from the MRA (the mean integration error); distance between each CARTO ablation site and the nearest pixel with LGE (CARTO-LGE distance), and distance

between every pixel with LGE/scar (i.e. every pixel on the LA wall which was hyperenhanced in the LGE images) and the nearest CARTO ablation site (LGE-CARTO distance). These last two metrics—the distance between the CARTO ablations and the scar by LGE, in the forward and backward directions—are illustrated in Figure 2H. The mean integration error describes the accuracy of the registration between CARTO and the MRA. A shorter CARTO-LGE distance implies the presence of an ablative lesion with each CARTO point, while a larger distance indicates the absence of ablative lesion nearby the CARTO point. The LGE-CARTO distance may be partially related to the lesion size due to one ablation site.

Qualitative evaluation

A 3D visualization module displayed the fused MRA, LGE scar, and CARTO ablation data sets in the same coordinate space, to allow for an interactive visual evaluation of the registration, and provide a method of comparing LGE scar and CARTO ablation points. The 3D fusion could be observed in a wire-mesh mode, to visualize ablations and scar lying below the MRA surface, with the capability of shrinking the MRA shell if it obstructed visualization. One reader (DP) with >3 years of experience in LGE imaging of RF ablations evaluated the registered data sets using the 3D visualization tool. For each study, each PV – right inferior PV (RIPV), right superior PV (RSPV), left inferior PV (LIPV), and left superior PV (LSPV) – was divided into 6 sectors; superior, superior-anterior, anterior-inferior, inferior, inferior-posterior, and superior-posterior. The observer noted for each sector around the PVs: i) absence of LGE ii) absence of CARTO ablation sites. From these data, the extent of gaps in CARTO and LGE and mismatch between LGE and CARTO could be estimated qualitatively. Because not all sectors of each PV were targeted with ablations, we also used this data to also determine the extent of LGE gaps only in sectors with CARTO ablation sites. This latter metric accounts for intentional gaps in the ablation pattern.

Statistics and analysis

Continuous data are presented as mean $\pm$ standard deviation. The clinical data, mean integration error, and ablation to scar distances, and quantitative metrics were compared using unpaired t-tests between groups. The Chi-squared test was used to compare proportions. A two-sided p-value <0.05 was considered significant. All statistics were performed in Microsoft Office Excel 2003 statistics package, or with or Stata IC 10, StataCorp (College Station, Texas USA). Correction for multiple comparisons was not performed in this exploratory study.

Results

Patient characteristics are summarized in Table 1, and include 79% men and mean age of 57 ± 11 years. With an average follow-up of 148 ± 89 days, nine (47%) of the 19 patients had AF recurrence, and an average time to recurrence of 104 ± 75 days. Recurrent AF was associated with non-paroxysmal AF. Examples of registered images are shown in Figure 3, compared with CARTO representations showing the intended ablation pattern from the first PVI. There was a similarity in the spatial relationship of the ablations to the PV ostia in both representations (Figure 3A–D). The LGE pattern strongly reflected the CARTO ablation pattern (black arrows, Figure 3A, C). In one patient with recurrent AF, who had a repeat PVI, the LGE pattern is compared to the resulting scar/low voltage (<0.5mV) pattern obtained during a repeat PVI. The LGE pattern appears to roughly reflect the pattern of scar/low voltage on a repeat procedure (Figure 3E–H).

The LGE pattern was obscured by artifacts due to un-suppressed blood flowing into the LA, resulting from our respiratory compensation method (11) in 3/19 studies for the RSPV.

Therefore, 3/76 PVs were not included in the qualitative study, but remained in the quantitative study due to the challenge of separating the contributions of each PV in these measurements.

Quantitative results

The mean integration error and other distance metrics are summarized in Table 1, demonstrating the good registration (low mean integration error; 2.7 ± 0.7) between the CARTO surface points (excluding ablations) and the MRA surface. The average distance between CARTO ablations points and LGE scar (CARTO-LGE) was 3.6 ± 1.3 mm and the average distance between LGE pixels and CARTO ablations (LGE-CARTO) was 6.9 ± 1.6 mm. There was no association between recurrence and the mean CARTO-LGE distance, but there was non-significant ($p=0.11$) association between recurrence and higher mean integration error.

Table 2 compares patient characteristics for patients stratified by high vs. low mean integration error, and high CARTO-LGE distances, vs. lower distances. The median values were used as cutoffs. Non-paroxysmal AF was associated with greater mean integration error and greater CARTO-LGE distances ($p<0.05$). Other factors associated with lower mean integration error included being in sinus rhythm during the PVI ($p=0.07$), and having a large LA ($p=0.07$).

Comparing the irrigated 3.5 mm vs. the non-irrigated 8 mm catheter, there was no difference in the LGE-CARTO ablation distance (6.2 ± 1.0 vs. 7.1 ± 1.7 mm, respectively, $p=0.32$) or in CARTO-LGE distance (2.7 ± 0.7 mm vs 3.7 ± 1.4 mm, $p=0.16$).

Qualitative results

Qualitative evaluation was performed employing 3D visualization capabilities which permit viewing at any angle, use of a wire mesh to represent the surface, and visualizing the LGE and ablations endoscopically (Figure 4). Through qualitative visual assessment of all 6 sectors in each of 4 PVs (24 sectors total), gaps in LGE were found after registration in all subjects, with an average of 5.9 ± 4.3 sectors (25% of all sectors) showing gaps. Gaps in CARTO ablation sites were found in 1.4 ± 1.4 (6%) sectors per patient; notably CARTO ablations were most frequently absent from the anterior-superior sector of the LSPV (26% and 44% of all non-recurrent and recurrent patients respectively). LGE was present in the absence of CARTO ablation sites in 0.2 ± 0.4 (1%) sectors.

Gaps in LGE in the presence of CARTO ablation sites occurred in 4.7 ± 4.3 (20%) sectors. Figure 5 plots, for each PV and for each sector, the results of the qualitative study, recording the percent of patients who had gaps in LGE in the presence of CARTO points (i.e. CARTO but no LGE), for each sector (a radar plot). For the left superior PV, for all patients, the gaps were mainly in the superior-anterior region (53% compared to 16% for other sectors), adjacent to the left atrial appendage. For the LIPV, gaps in the superior portion of the LIPV were more prevalent in patients with recurrence (44% with vs. 0% without recurrent AF, $p=0.013$). For the RSPV, non-recurrent patients had more gaps in superior sector ($p=0.13$), and fewer gaps in the inferior-anterior sector ($p=0.11$), compared to non-recurrent patients.

Figure 6 presents data on both the circumferential distribution of gaps in LGE/scar for each PV, and gaps in LGE in the presence CARTO ablation sites. Larger numbers of gaps in LGE/scar were found in patients with recurrence than without recurrence for each PV ($p=NS$). Patients with recurrent AF had significantly more gaps, averaged over all patients and all PVs ($p=0.01$). Numbers of gaps were smaller when measured as gaps in LGE in the presence of CARTO ablation sites ($p=NS$).

Discussion

Our main finding is a good qualitative and quantitative relationship between CARTO representations of ablation locations and scar by LGE. The mean distance between the CARTO ablation points and the LGE surface (3.6 ± 1.3 mm) is close to the mean integration error of 2.7 ± 0.7 mm, indicating that most ablations were associated with scar. However, CARTO ablations in locations without evidence of scarring were found in 20% of the PV sectors analyzed, while 5% of regions were without scar because they were without CARTO ablations (e.g. Figure 3C, arrow). Although some scar may not be visible on the LGE images due to image quality and spatial resolution, this still provides 20% as an upper limit on the percent of ineffective ablations, in the absence of possible pre-existing scar.

The mean distance between the LGE pixels and the nearest CARTO ablation point was found to be 6.9 ± 1.6 mm. This metric reflects that each ablation creates a larger lesion that surrounds it. The average LGE-CARTO distance was not correlated with recurrent AF, or with the type of catheter used. Previous animal studies (20) found that a single RF ablation at 50W caused a lesion of about 11 mm in diameter in the right ventricle. It might be possible to relate the average LGE-CARTO distance to lesion size, using assumptions about the geometry of the lesion. However, CARTO ablation points are collected at regular intervals during ablation, and only represent catheter location at a specific point in time. Catheter movement during RF application may influence the lesion size. Furthermore, this distance is also increased by the integration error between the MRI and CARTO data sets.

The qualitative study demonstrated the locations of gaps in LGE and CARTO. An LGE gap in the superior sector LIPV was significantly associated with recurrent AF. The superior PVs were most commonly without CARTO ablations (Figure 6). Only 1% of sectors demonstrated LGE without CARTO. We did not find an association between gaps in LGE in the RIPV and AF recurrence, as previously reported (18), but did find a trend towards more gaps in the inferior sector of the RIPV.

Using our custom registration we were able to document accuracy similar to the CARTO-Merge system (5,21–23), which reports mean integration errors of about 2 to 3 mm, compared with an average registration error of 2.7 ± 0.7 mm measured in this study. There was a non significant ($p=0.11$) trend towards better registration in patients without recurrence (2.5 ± 0.4 vs. 3.0 ± 0.8). Larger LA volume trended towards association with a higher mean integration error ($p=0.07$), as previously reported (21).

Non-paroxysmal AF was a strong predictor of both higher than median mean integration error ($p=0.04$), and higher than median CARTO-LGE distance ($p=0.009$). The reason may be that the MRA and LGE images were acquired soon after pulmonary vein isolation, when the patient was almost always in sinus rhythm, while CARTO data was acquired either in sinus rhythm (more likely for paroxysmal AF patients) or in non-sinus rhythm. The difference in rhythm may cause a difference in LA shape. Therefore, the mean integration error between the CARTO data and the post procedural MRA may be affected by any difference in rhythm, and this may explain the significant and non significant associations between mean integration error, and type of AF, LA volume, and recurrence.

A recent case report of a patient with recurrent AF demonstrated the LGE CMR can predict which PVs, and which sector, require re-isolation (24). Our method of comparing scar to intended ablation sites may be useful in guiding repeat procedures for such patients, as shown in Figure 3E–H.

Limitations

This study is limited by the small number of subjects. The LGE CMR method has not been validated or demonstrated to detect all RF ablation scar tissue in the LA. Additionally, the LGE scar representation is imperfect, relying on semi-automated segmentation and good image quality. Potential pre-existing scar may act to falsely enhance the correlation between LGE and CARTO, especially for recurrent patients for whom pre-existing scar is more prevalent (25,26). While the CARTO data is acquired at mid-diastole, during free-breathing, the LGE data are acquired in mid-diastole, at end-expiration, and the MRA data is acquired without ECG-gating, at end-expiration. Therefore, some mis-registration between CARTO and MR is inherent due to the differing respiratory and cardiac states. A non-rigid registration (27) might be able to overcome these differences and improve the registration accuracy. The software tool also had limitations, and could not compute the global or PV specific overlap between LGE and CARTO, or the number of ablations in each LGE gap. Therefore, the qualitative sector-based evaluation was used to describe the presence of LGE and CARTO for each sector.

Conclusion

There was a visual and quantitative correspondence between CARTO ablation sites and LGE scar, but for twenty percent of CARTO ablation sites there was no visible corresponding LGE.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Grant Support: This work was supported by a grant from the American Heart Association (AHA SDG 0530061N) and the NIH (NIBIB K01 EB004434-01A1).

We gratefully acknowledge the contributions of Dr. Yuri Ishihara, Dr. Luis Gutierrez of Philips Research North America, Drs. Steven Peiper and Ron Kikinis of NA-MIC for advice on image processing and visualization, Dr. Jeff Hsing for his expertise in EP, and past and present non-invasive CMR fellows at BIDMC, including Drs. Jason Ryan, Greg Piazza, Jonathan Chan, Joyce Meng, and Michael Chuang.

Bibliography

1. Cappato R, Calkins H, Chen S-A, et al. Worldwide Survey on the Methods, Efficacy, and Safety of Catheter Ablation for Human Atrial Fibrillation. *Circulation* 2005;111:1100–1105. [PubMed: 15723973]
2. Oral H, Pappone C, Chugh A, et al. Circumferential Pulmonary-Vein Ablation for Chronic Atrial Fibrillation. *New England Journal of Medicine* 2006;354:934–941. [PubMed: 16510747]
3. Pappone C, Rosanio S, Oreto G, et al. Circumferential Radiofrequency Ablation of Pulmonary Vein Ostia: A New Anatomic Approach for Curing Atrial Fibrillation. *Circulation* 2000;102:2619–2628. [PubMed: 11085966]
4. Oral H, Knight BP, Ozaydin M, et al. Segmental Ostial Ablation to Isolate the Pulmonary Veins During Atrial Fibrillation: Feasibility and Mechanistic Insights. *Circulation* 2002;106:1256–1262. [PubMed: 12208802]
5. Dong J, Dickfeld T, Dalal D, et al. Initial Experience in the Use of Integrated Electroanatomic Mapping with Three-Dimensional MR/CT Images to Guide Catheter Ablation of Atrial Fibrillation. *Journal of Cardiovascular Electrophysiology* 2006;17:459–466. [PubMed: 16684014]
6. Malchano ZJ, Neuzil P, Cury RC, et al. Integration of Cardiac CT/MR Imaging with Three-Dimensional Electroanatomical Mapping to Guide Catheter Manipulation in the Left Atrium: Implications for Catheter Ablation of Atrial Fibrillation. *Journal of Cardiovascular Electrophysiology* 2006;17:1221–1229. [PubMed: 17074008]

7. Reddy VY, Malchano ZJ, Holmvang G, et al. Integration of cardiac magnetic resonance imaging with three-dimensional electroanatomic mapping to guide left ventricular catheter manipulation: Feasibility in a porcine model of healed myocardial infarction. *Journal of the American College of Cardiology* 2004;44:2202–2213. [PubMed: 15582319]
8. Young-Hoon Kim H-ELH-NP. Use of Three-Dimensional Mapping Systems in the Catheter Ablation of Atrial Fibrillation. *Journal of Cardiovascular Electrophysiology* 2006;17:S16–S22.
9. Hauser TH, Yeon SB, McClennen S, et al. A method for the determination of proximal pulmonary vein size using contrast-enhanced magnetic resonance angiography. *J Cardiovasc Magn Reson* 2004;6:927–936. [PubMed: 15646896]
10. Hauser TH, Yeon SB, McClennen S, et al. Subclinical pulmonary vein narrowing after ablation for atrial fibrillation. *Heart* 2005;91:672–673. [PubMed: 15831661]
11. Peters DC, Wylie JV, Hauser TH, et al. Detection of Pulmonary Vein and Left Atrial Scar after Catheter Ablation with Three-dimensional Navigator-gated Delayed Enhancement MR Imaging: Initial Experience. *Radiology* 2007;243:690–695. [PubMed: 17517928]
12. Kim RJ, Fieno DS, Parrish TB, et al. Relationship of MRI Delayed Contrast Enhancement to Irreversible Injury, Infarct Age, and Contractile Function. *Circulation* 1999;100:1992–2002. [PubMed: 10556226]
13. Kim RJ, Wu E, Rafael A, et al. The Use of Contrast-Enhanced Magnetic Resonance Imaging to Identify Reversible Myocardial Dysfunction. *New England Journal of Medicine* 2000;343:1445–1453. [PubMed: 11078769]
14. Simonetti OP, Kim RJ, Fieno DS, et al. An Improved MR Imaging Technique for the Visualization of Myocardial Infarction. *Radiology* 2001;218:215–223. [PubMed: 11152805]
15. Halperin HR, Nazarian S. Damage assessment after ablation role of cardiovascular magnetic resonance. *J Am Coll Cardiol* 2008;52:1272–1273. [PubMed: 18926332]
16. Essebag V, Baldessin F, Reynolds MR, et al. Non-inducibility post-pulmonary vein isolation achieving exit block predicts freedom from atrial fibrillation. *Eur Heart J* 2005;26:2550–2555. [PubMed: 16183686]
17. Wylie JV Jr, Peters DC, Essebag V, et al. Left atrial function and scar after catheter ablation of atrial fibrillation. *Heart Rhythm* 2008;5:656–662. [PubMed: 18452866]
18. Peters DC, Wylie JV, Hauser TH, et al. Recurrence of Atrial Fibrillation Correlates With the Extent of Post-Procedural Late Gadolinium Enhancement: A Pilot Study. *J Am Coll Cardiol Img* 2009;2:308–316.
19. Besl PJ, McKay ND. A Method for Registration of 3-D Shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 1992;14:239–256.
20. Dickfeld T, Ritsushi K, Menekem Z, et al. Characterization of acute and subacute radiofrequency ablation lesions with nonenhanced magnetic resonance imaging. *Heart Rhythm* 2007;4:208–214. [PubMed: 17275759]
21. Heist E, Chevalier J, Holmvang G, et al. Factors affecting error in integration of electroanatomic mapping with CT and MR imaging during catheter ablation of atrial fibrillation. *Journal of Interventional Cardiac Electrophysiology* 2006;17:21–27. [PubMed: 17252200]
22. Patel AM, Heist EK, Chevalier J, et al. Effect of presenting rhythm on image integration to direct catheter ablation of atrial fibrillation. *J Interv Card Electrophysiol* 2008;22:205–210. [PubMed: 18506606]
23. Kuklik P, Szumowski L, Zebrowski JJ, Sanders P. Integration of the data from electroanatomical mapping system and CT imaging modality. *Int J Cardiovasc Imaging* 2009;25:425–432. [PubMed: 19039678]
24. Reddy VY, Schmidt EJ, Holmvang G, Fung M. Arrhythmia recurrence after atrial fibrillation ablation: can magnetic resonance imaging identify gaps in atrial ablation lines? *J Cardiovasc Electrophysiol* 2008;19:434–437. [PubMed: 18179530]
25. Oakes RS, Badger TJ, Kholmovski EG, et al. Detection and quantification of left atrial structural remodeling with delayed-enhancement magnetic resonance imaging in patients with atrial fibrillation. *Circulation* 2009;119:1758–1767. [PubMed: 19307477]

26. Verma A, Wazni OM, Marrouche NF, et al. Pre-existent left atrial scarring in patients undergoing pulmonary vein antrum isolation: an independent predictor of procedural failure. *J Am Coll Cardiol* 2005;45:285–292. [PubMed: 15653029]
27. Shen D, Davatzikos C. HAMMER: hierarchical attribute matching mechanism for elastic registration. *IEEE Trans Med Imaging* 2002;21:1421–1439. [PubMed: 12575879]

Figure 1. Representative examples of the raw data sets that were registered and correlated, shown for two patients. A,D) MR angiogram (MRA) of the left atrium. B,E) 3D LGE image after RF ablation, with scar visualized as hyperenhanced signal in the LA wall. C,F) CARTO data shows the surface and ablation points, as a point cloud.

Figure 2.

Registration technique. The CMR data (A,B) was segmented to isolate the left atrial scar and anatomy (C, D), coregistered (E), and then registered with CARTO data (F) using PV ostia landmarks, and ICP. The final registered data (G) can be visualized in 3D. Using the registered data sets, measurements were made of the nearest LGE pixel from a given CARTO ablation point (H, white arrow), and the nearest CARTO ablation point from a given LGE pixel (H, black arrow).

Figure 3.

(A–D) CARTO representations of ablations (red), in their context of LA anatomy and PV branches, are compared to our custom registration method, which includes the MRA shell (tan), the ablations (red spheres), and the LGE scar (purple). A very good relationship between the CARTO map and the custom registration can be found visually. The relationship between LGE scar, and the CARTO ablations can be appreciated (black arrows). In C and D, a gap in LGE scar in the presence of a CARTO ablation gap is observed (arrow). E–H, A patient imaged after an initial PVI underwent a repeat procedure 2 years later. The post PVI images of scar (E, G) are compared with the bipolar voltage maps showing electrical scar patterns (F,H),

displayed using CARTO-Merge. A correlation is observed, showing corresponding LGE and low voltage of the right PVs.

Figure 4.

The 3D visualization is an excellent tool for qualitative evaluation of the extent of scarring around each PV, and its relationship to the PV ostia at any viewing angle (A,B), and providing endoscopic views (C). Sometimes CARTO ablations or LGE lie below the surface of the MRA shell. The MRA shell could be presented as a mesh to permit easier visualization of scar and ablations underneath the shell.

Figure 5.

(A–D) Qualitative assessment of gaps in LGE in locations where CARTO ablations were recorded. Radar plots show the percent of patients who had CARTO ablations but no LGE scar, for each of 6 sectors in each PV. S=superior, A=anterior, I=inferior, P=posterior. LSPV=left superior PV, LIPV=left inferior PV, RSPV=right superior PV, RIPV=right inferior PV.

Figure 6.

Qualitative assessment of 1) gaps in LGE and 2) gaps in LGE where CARTO ablations were recorded, for each PV. Average extent of LGE gaps in percent is shown for each PV, for patients with and without AF recurrence. Note that gaps are greater in patients with recurrent AF compared to those without.

Table 1

Patient characteristics, including CARTO to CMR metrics.

	All (N = 19)	Recurrent AF (N = 9)	Non-recurrent AF (N = 10)
Age (years)	57±11	57±9	58±12
Male sex	79% (15/19)	89% (8/9)	70% 7/10)
Left Ventricular Ejection Fraction (%)	56.1±10.4	57.4±9.2	54.9±11.8
RF ablation time (min.)	55±13	57±14	53±13
CARTO ablations (#)	148±37	163±55	133±24
Paroxysmal AF (%)	42% (8/19)	22% (2/9)*	60% (6/10)*
LA volume (systole)(ml)	134±42	145±53	121±19
Hypertension	47% (9/19)	67% (6/9)	30% (3/10)
Days post imaged	43±31	48±46	39±7
Body Mass Index (kg/m2)	28.1±4.0	29.4±2.7	26.8±4.6
Additional Ablation lines	32% (6/19)	22% (2/9)	40% (4/10)
MIE (mm)	2.7±0.7	2.5±0.4 [‡]	3.0±0.80 [‡]
CARTO-LGE (mm)	3.6±1.3	3.5±1.3	3.7±1.40
LGE-MRA (mm)	2.9±0.8	2.9±0.6	3.0±1.0
LGE-CARTO (mm)	6.9±1.6	6.8±1.7	7.00±1.7

*
p<0.05,

p=NS for all others,

[‡]
p=0.11.

MIE=Mean integration error, LGE =late gadolinium enhancement. RF=Radiofrequency. LA=Left Atrium.

Table 2

Correlation between CARTO to CMR metrics and clinical parameters

	MIE > 2.44 mm	MIE ≤2.44mm	CARTO-LGE >3.1mm	CARTO-LGE LGE ≤3.1mm
Recurrent AF	5/10 (50%)	5/9 (56%)	5/9 (56%)	5/10 (50%)
Paroxysmal AF	2/10 (20%) [‡]	6/9 (67%) [‡]	1/9 (11%) ^{**}	7/10 (70%) ^{**}
BMI (kg/m ²)	27.6±4.1	28.4±3.8	28±4.6	27±3.2
SR during PVI	5/10(50%) ^{***}	8/9 (89%) ^{***}	5/10 (50%) ^{***}	8/9 (89%) ^{***}
LA volume (mls)	152±43 [‡]	118±30 [‡]	147±32	146±40
CARTO-LGE (mm)	4.2±1.38 [*]	2.9±0.87 [*]	---	---

MIE=Mean integration error, LGE =late gadolinium enhancement. SR=sinus rhythm. PVI=pulmonary vein isolation.

^{*}
p=0.03,[‡]
p=0.07,[‡]
p=0.04,^{**}
p=0.009.

All else p>0.05.

^{***}
p=0.07.