Initial Experience in the Use of Integrated Electroanatomic Mapping with Three-Dimensional MR/CT Images to Guide Catheter Ablation of Atrial Fibrillation

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Image Integration Guided Atrial Fibrillation Ablation. Introduction: No prior studies have reported the use of integrated electroanatomic mapping with preacquired magnetic resonance/computed tomographic (MR/CT) images to guide catheter ablation of atrial fibrillation (AF) in a series of patients. Methods and Results: Sixteen consecutive patients with drug-refractory AF underwent catheter ablation under the guidance of a three-dimensional (3D) electroanatomic mapping system (Carto, Biosense Webster, Inc., Diamond Bar, CA, USA). Gadolinium-enhanced MR (n = 8) or contrast-enhanced high-resolution CT (n = 8) imaging was performed within 1 day prior to the ablation procedures. Using a novel software package (CartoMerge, Biosense Webster, Inc.), the left atrium (LA) with pulmonary veins (PVs) was segmented and extracted for image registration. The segmented 3D MR/CT LA reconstruction was accurately registered to the real-time mapping space with a combination of landmark registration and surface registration. The registered 3D MR/CT LA reconstruction was successfully used to guide deployment of RF applications encircling the PVs. Upon completion of the circumferential lesions around the PVs, 32% of the PVs were electrically isolated. Guided by a circular mapping catheter, the remaining PVs were disconnected from the LA using a segmental approach. The distance between the surface of the registered 3D MR/CT LA reconstruction and multiple electroanatomic map points was 3.05 ± 0.41 mm. No complications were observed. Conclusions: Three-dimensional MR/CT images can be successfully extracted and registered to anatomically guided clinical AF ablations. The display of detailed and accurate anatomic information during the procedure enables tailored RF ablation to individual PV and LA anatomy. (J Cardiovasc Electrophysiol, Vol. 17, pp. 459-466, May 2006)
of AF for a median of 6 years, which were refractory or intolerant to a median of 1.5 antiarrhythmic drugs. Ten patients had paroxysmal AF, four had persistent AF, and two had permanent AF. Five patients also had documented atrial flutter. One patient had coronary artery disease and one had aortic valve disease. Seven patients had hypertension. No patient had left ventricular dilatation, and the left ventricular ejection fraction averaged 59%. Mild (40–45 mm), moderate (45–55 mm), and severe (>55 mm) dilatation of the LA was revealed by transesophageal echocardiography in seven, two, and two patients, respectively. All patients underwent contrast-enhanced MR (n = 8) or CT imaging (n = 8) within 24 hours prior to the ablation procedure to allow image integration for the AF ablation.

**MR Imaging**

Eight patients underwent Gadolinium-enhanced MR imaging of the LA and PVs using a 1.5-T MR imaging system (Signa Horizon LX; GE Medical Systems, Milwaukee, WI). MR angiograms were obtained with a breath-hold 3D fast spoiled gradient-echo imaging sequence in the coronal plane. The acquisition time was approximately 15 seconds. Source images were transferred to a workstation (Advantage Windows 4.0, GE Medical Systems) and were reformatted to axial images with the thickness of 1.6 mm for later image integration.

**CT Imaging**

Eight patients were imaged using a 64-slice CT scanner (Aquilion, Toshiba Medical Systems Corporation, Tochigi, Japan). Helical CT scanning (120 kV, 400 mA, 11–13 helical pitch, 400 ms/rotation gantry speed, 0.5 mm slice thickness) was performed after intravenous injection of 120–140 mL contrast media (Isovue, Bracco Diagnostics, Inc., Princeton, NJ, USA) at an infusion rate of 3 mL/sec. CT scanning was performed during one breath-hold at the end-expiratory phase. The scanning time was approximately 10 seconds. A simultaneous ECG was recorded to retrospectively assign the source images to the respective phases of cardiac cycle. Reconstruction of images was performed at 0.5 mm intervals at 10 time points at 10% intervals, with the center of the reconstruction window being between 0% and 90% of the cardiac cycle. A 70% or 80% phase location which corresponded to atrial end-diastole was selected for imaging registration in patients who were in sinus rhythm at the time of imaging. In patients in AF at the time of imaging, a 50% phase location was selected for imaging registration because it yielded the best image quality.

**Image Segmentation and 3D Surface Image Extraction**

The MR/CT images were transferred to a novel version of an electroanatomic mapping system (Carto XP, Biosense Webster Inc.), which had been equipped with an image integration software (CartoMerge™ Image Integration Module).

Image segmentation refers to the separation of the 3D anatomy of individual cardiac structures from a 3D volume rendered from imported two-dimensional MR/CT slices. Segmentation was achieved in a three-step process. First, the volume of interest was defined by selecting a lower and upper threshold of intensity value, which differentiated the boundary between the blood pool and the endocardium. Using a software algorithm, the volume of interest was separated from the whole 3D volume by extracting all voxels within the pre-selected threshold intensities. (Fig. 1A,B) Second, “seeds” were placed on distinct cardiac and thoracic structures in the separated volume of interest. A second algorithm was implemented from each “seed” to its respective borders, resulting in separation of individual anatomic structures (Fig. 1B,C). Finally, by using a third algorithm, the segmented volumes for individual anatomic structures were extracted as 3D surface reconstructions for image registration (Fig. 1D).

**Electrophysiologic Study**

Prior to the electrophysiologic study, informed written consent was obtained from each patient, and transesophageal echocardiography was performed to exclude LA thrombus. Patients were studied with use of conscious sedation. One 6 French quadripolar catheter was placed at His-bundle position and one 7 French decapolar deflectable catheter was inserted into the coronary sinus. A double transseptal puncture was then performed under fluoroscopic guidance and two long vascular sheaths were introduced into the LA. Following the transseptal puncture an initial intravenous bolus of 5,000 IU heparin was given, and repeated doses of heparin were given to maintain the activated clotting time >300 seconds. Selective biplane PV angiograms were obtained using the technique we reported previously.5

**Electroanatomic Mapping and Image Registration**

In the current study, electroanatomic mapping of the LA was an integral part of the LA registration process. LA registration refers to superimposing the segmented 3D LA surface reconstruction on the real time LA electroanatomic map created by the Carto XP electroanatomic mapping system which enables detection of the real time location and orientation of the mapping and ablation catheter (NaviStar, Biosense Webster, Inc.). The timing reference of the electroanatomic mapping system was set to the bipolar electrogram recorded from the most proximal coronary sinus electrode pair. Thus, catheter tip location was sampled at atrial end-diastole, approximating the time point at which the CT datasets were selected for image registration.

The LA registration process consisted of three steps. First, the Navistar catheter was deployed 2 to 4 cm inside each PV and slowly pulled back to the LA. During this course, multiple PV points were sampled. Using a special feature of the Carto system, virtual tubes that surrounded the sampled PV points were created to represent the tubular part of the PVs. Under fluoroscopy four endocardial locations were sampled including the 6 o’clock mitral annulus position and the junctions of the LA and right superior PV, right inferior PV, and left inferior PV. The estimated corresponding locations of these four endocardial sites were annotated on the imported 3D MR/CT LA surface reconstruction. Thus, four “landmark pairs” were created by the system. Three to seven endocardial sites at each of the five LA areas including posterior LA, superior LA, anterior LA, lateral LA, and inferior LA were sampled under biplane fluoroscopy guidance. (Fig. 2A) Second, an algorithm called “landmark registration” was performed to approximate the catheter mapping space with the reconstructed 3D images by matching the landmark pairs. (Fig. 2B) Third, another software algorithm called “surface registration” was performed to fit the 3D MR/CT surface reconstruction with the electroanatomic map points by
Figure 1. Workflow of left atrial (LA) segmentation and extraction. A: The volume of interest (in orange) was defined by selecting a lower and upper threshold of signal intensity. B: “Seeds” (green dots) were placed on distinct cardiac structures within the volume of interest (in gray) which was separated from the whole 3D volume. C: The boundaries between cardiac chambers were defined by a software algorithm expanding from each “seeds” to its borders and resulted in separation and color coding of individual cardiac structures. D: The surface reconstruction of the LA with pulmonary veins shown as wireframe was extracted from the segmented LA volume, shown in posteroanterior view. Ao = aorta; LAA = left atrial appendage; LI = left inferior pulmonary vein; LS = left superior pulmonary vein; LV = left ventricle; PA = pulmonary artery; RA = right atrium; RI = right inferior pulmonary vein; RS = right superior pulmonary vein; RV = right ventricle.

rendering the smallest average distance of the two datasets. (Fig. 2C)

Registration Accuracy Assessment and Catheter Ablation

The accuracy of LA registration was assessed by three means. First, the quality of alignment between the Carto PV virtual tube and the 3D MR/CT PV anatomy was determined. A good alignment was considered when no PV points used for the creation of the Carto virtual tube representing a given PV was located >5mm outside the surface of the MR/CT reconstruction of the corresponding PV. The distance from the PV points to the MR/CT PV reconstruction surface was calculated by the system and color-coded with green indicating distance <5 mm, yellow between 5 and 10 mm, and red >10 mm. The assessment of PV alignment was performed by two authors independently and differences were resolved by consensus. Second, the ability of registered reconstructions-guided catheter navigation into the PVs and the left atrial appendage (LAA) was tested. Third, the mean distance of the 3D MR/CT surface reconstruction to the real time electroanatomic map points (surface-to-point distance) was calculated by a software feature of the mapping system. The registration of the 3D MR/CT surface reconstruction was considered accurate enough to guide RF energy delivery only when the following criteria were fulfilled: (1) no more than one PV without a good alignment; (2) successful catheter navigation into all the PVs and the LAA under the guidance of the registered 3D MR/CT reconstructions only; and (3) ≤3 mm mean surface-to-point distance.
Figure 2. Left atrium (LA) registration. A: Landmark pairs (highlighted with colored circles) at the 6 o’clock mitral annulus (MA) position and the junctions of the LA and right superior pulmonary vein (RS), right inferior pulmonary vein (RI), left inferior pulmonary vein (LI) were annotated on the 3D CT LA surface reconstruction (upper image, shown as wireframe) and the LA electroanatomic map (lower image, shown as solid shell) with colored tubes representing pulmonary veins (PVs). B: After landmark registration, the 3D LA surface reconstruction was superimposed on the electroanatomic map (shown as mesh). Note, the misalignment of the LS, LI, and RS between the two image datasets, indicated by the yellow or red color of the PV points (arrows) sampled in those PVs. C: After surface registration was executed, the PV alignment between the two image datasets was significantly improved, indicated by the green color of the PV points. The green, yellow, and red colors of the electroanatomic map points indicate their distance of <5 mm, 5–10 mm, and >10 mm, respectively, from the registered CT reconstruction surface.

After image registration, the Carto PV tubes were disabled and the threshold of the electroanatomic map was set to zero. Thus, the catheter tip location in relation to the registered 3D MR/CT LA reconstruction could easily be visualized. The software module enables the visualization of the catheter tip projection either on the complete 3D MR/CT reconstruction or in a virtual cardioscopic view. (Fig. 3A and B)

The ablation strategy was to create circumferential RF lesions around each pair of the ipsilateral PVs under the guidance of the registered 3D MR/CT reconstruction. RF current was delivered to the 8 mm-tip of the Navistar catheter immediately outside PV ostium. Continuous intracardiac electrogram monitoring and occasional fluoroscopy was used to assure stable catheter tip-tissue contact. The RF energy was applied continuously with repositioning of the catheter tip every 10–20 seconds at a target temperature of 55°C and a maximum power of 70 W in a temperature control mode. The target was either to reduce local bipolar voltage by 80% or...
The RF ablation location was annotated when at least 10 seconds of RF energy was delivered. A circular catheter (LassoTM, Biosense Webster or Orbiter PVTM, Bard, Lowell, MA, USA) was placed at the PV ostium for PV potential mapping. If PVs were not disconnected from the LA upon completion of the circumferential lesions, segmental ostial ablation targeting the electrical breakthroughs was performed under the guidance of fluoroscopy and circular mapping with the goal of PV isolation, using a method similar to that proposed by other authors.2 The locations of segmental ablations were recorded by the electroanatomic mapping system and the distance from these ablations to the PV ostium was measured on the registered 3D MR/CT reconstruction.

Concomitant Ablations

Patients with the history of atrial flutter (n = 5) also underwent conventional cavotricuspid isthmus ablation with the endpoint of bidirectional isthmus block. Superior vena cava isolation was performed in patients with permanent AF (n = 2) using the technique we reported elsewhere.5

Data Analysis

Upon completion of the RF lesions encircling the right and left PVs, the mean distance between all points (points for registration plus points for ablations) on the electroanatomic map and the registered 3D MR/CT surface reconstruction at the stage of landmark registration and surface registration was obtained from the system.

Data are presented as mean ± SD, percentage, counts or range, as appropriate. Paired-samples t-test was used to compare the point-to-surface distance at two registration stages. Chi-square test with Fisher’s exact test was used to compare categorical variables. All the tests were two tailed. A P value < 0.05 was considered statistically significant.

Results

MR/CT Imaging and Image Segmentation Data

Preprocedural MR/CT imaging was successfully performed in all patients. Among the 16 patients studied, 14 patients were in sinus rhythm while two were in AF during MR (n = 1) or CT (n = 1) imaging. The LA with PVs was segmented and extracted successfully from the reconstructed 3D images in all patients. This process took 9.0 ± 2.8 minutes for the MR images and 8.6 ± 3.0 minutes for the CT images. Due to the higher spatial resolution, segmented 3D LA reconstructions from CT scans showed an improved endocardial surface and PV anatomic detail when compared to MR imaging. (Fig. 4)

PV and LA Anatomic Patterns

The segmented 3D MR/CT LA reconstructions revealed different PV anatomic patterns. A typical 4-PV pattern was present in 10 patients (63%). The presence of a short and long left common trunk was observed in three patients (19%) and two patients (13%), respectively. A right middle PV was observed in one patient (6.3%). The anatomic patterns from the 3D MR/CT reconstructions correlated well with the results of selective PV angiography.

The segmented 3D MR/CT LA reconstructions depicted well the complex anatomic relationship between the left-sided PVs and the LAA. Among the five patients with a left common trunk, a narrow ridge (<4 mm in width) separating the LAA orifice from the ostium of the left common trunk was found in two patients. Among the 11 patients without a left common trunk, eight patients had a narrow ridge separating the LAA orifice from the LSPV ostium (n = 5), LIPV ostium (n = 1), or both left PV ostia (n = 2).

Image Registration Data

All patients underwent image registration while in the same rhythm as they were in during MR/CT imaging. The integrated electroanatomic mapping and LA registration process required 16 ± 5.2 minutes and 24 ± 6.7 LA endocardial locations were sampled for the surface registration.

After landmark registration, a good alignment between the Carto PV virtual tube and the reconstructed 3D PV image was achieved in 26/60 PVs (43%). A combination of landmark registration and surface registration significantly improved the percentage of PVs with a good alignment to 95% (57/60PVs), P < 0.001. Figure 2 shows a representative case with the improvement of PV alignment after surface registration. After the image registration process, successful catheter navigation into the PVs and LA appendage was achieved in all patients with the sole use of the registered 3D MR/CT reconstructions.

Upon completion of surface registration, the average surface-to-point distance ranged from 0.89 ± 0.79 mm to 2.71 ± 1.81 mm. This results in a mean of 2.13 ± 0.51 mm for the patient group as a whole.

PV Ablation

The registered 3D MR/CT reconstruction was used to guide the deployment of RF applications encircling the PVs in all patients. The catheter tip was dynamically displayed on the registered 3D MR/CT LA reconstruction, which provided anatomic details of the LA and the PVs. The relative location of the catheter tip to important LA structures including PV ostia and LAA correlated well with the intracardiac electrograms and fluoroscopic monitoring. The placement of the circumferential lesions was tailored to the individual anatomy provided by the 3D MR/CT reconstruction (Fig. 5A,B). In patients with a narrow ridge between the left-sided PVs and the LAA, it was very difficult to stabilize the ablation catheter on the ridge shown on the 3D MR/CT reconstruction. It was often observed that catheter tip abruptly dropped into the displayed LAA orifice, which correlated with the electrographic demonstration of large amplitude signals and fluoroscopic LAA position. In this situation, RF lesions had to be placed at the anterior portion of the left-sided PV ostium (Fig. 5C). In patients with a wider rim between the left-sided PV and the LAA, RF lesions were successfully placed along the corridor between the two structures guided by the registered 3D MR/CT reconstruction (Fig. 5D).

Upon completion of the circumferential lesions around the PVs, electrical PV isolation was achieved in 19/60 PVs (32%). The remaining 41 PVs (68%) were eventually isolated from the LA by a mean of 4.5 ± 2.5 RF applications guided by the circular mapping catheter and fluoroscopy. These ablations were located 12 ± 3.9 mm distal to the PV ostia as defined by the 3D MR/CT reconstruction.
Concomitant Ablations, Procedural Data, and Clinical Outcomes

Cavotricuspid isthmus ablation and superior vena cava isolation were successfully performed in all attempted patients. The total procedure time and fluoroscopy time were 237 ± 35 minutes and 75 ± 13 minutes, respectively. No complications were observed.

At the 6-month follow-up, 8/10 patients (80%) with paroxysmal AF, 2/4 patients (50%) with persistent AF, and 0/2 patients with permanent AF were free of AF recurrence without the use of antiarrhythmic drugs.

Surface-to-Point Distance

Upon completion of the circumferential ablations, 151 ± 47 RF application locations were annotated on the electroanatomic map, including 79 ± 26 encircling the left-sided PVs and 72 ± 26 encircling the right-sided PVs. There was a trend towards reduction of distance between all electroanatomic map points and the surface of the 3D MR/CT LA...
reconstruction using a combination of surface registration and landmark registration as compared to landmark registration alone (3.05 ± 0.41 mm vs 3.57 ± 0.98 mm, P = 0.08).

No significant differences in surface-to-point distance were found between patients with CT imaging and those with MR imaging at each stage of registration (3.85 ± 1.15 mm vs 3.28 ± 0.75 mm after landmark registration; 2.96 ± 0.39 mm vs 3.14 ± 0.45 mm after surface registration; P = NS, for both comparisons).

Discussion

To our knowledge, this is the first report on the use of integrated electroanatomic mapping with 3D MR/CT images to guide clinical catheter ablation of AF in a series of patients. Our findings suggest that: (1) CT and MR images can be successfully used for the anatomically correct extraction and reconstruction of the LA and PV anatomies; (2) 3D MR/CT reconstructions can be accurately registered with a real-time mapping system using a combination of two registration strategies; (3) 3D image integration allows tailored RF ablation to individual PV and LA anatomy during AF ablation procedure.

The preacquired MR or CT images have been successfully used as a roadmap for neurosurgery and bronchoscopy. In a series of studies, our laboratory had shown the ability of integrating MR or CT images to guide catheter navigation and anatomically targeted ablation. Using skin markers as fiducial points for image registration, we demonstrated the feasibility of using registered CT image to guide catheter navigation in the heart with an accuracy and precision of 4.7 ± 1.7 mm and 2.2 ± 0.7 mm. Two subsequent studies showed that registered MR images can be used to anatomically targeted atrial and ventricular ablations with an accuracy of 3.9 ± 2.1 mm and a precision of 3.9 ± 0.5 mm. Several recent studies demonstrated the accuracy of targeted ablation guided by integrated 3D mapping system with MR or CT images. In a dog model, one group reported a position error of 1.8 ± 0.5 mm in ablating left ventricle targets using a customized program to integrate 3D left ventricle MR images with real-time electroanatomic maps. In combination with a real-time, noncontact mapping system Sra et al. reported a position error of 2.0 ± 3.6 mm for the ablation of LA targets in dogs guided by the registered LA CT image. The only commercially available image integration system used in this study was recently evaluated by our laboratory in a dog model and was found to have an overall position error of 2.2 mm in targeted ablation guided by the registered CT images in all cardiac chambers.

The current study for the first time evaluated the image integration system in clinical AF ablation procedures and extended the previous work to complex RF ablations in patients. Using a combined registration strategy, the preacquired LA MR/CT images were accurately registered to the 3D mapping space. The position error of approximately 3 mm found in this study is in the range of previously reported accuracy of 2–3 mm in animal studies. This slight increase of position error might be attributable to several factors. First, longer durations between MR/CT scan and ablation may produce more interval changes between image acquisition and clinical ablation. Second, animal studies used intubation, pharmacological paralysis, and restraints, which likely decreased the position error. Additionally, the smaller canine heart size may have contributed to an overall improved accuracy.

Registration strategy is a crucial part of the image integration process. In the current study, we use a combination of two registration strategies. Our data indicated that the two registration strategies are complementary. Landmark registration enables to approximate the 3D MR/CT reconstructions to the real-time mapping space. We used three PV–LA junction sites as fiducial points since they are well defined and relatively “anchors” in the vicinity of prospective ablation sites. One site at the inferior mitral annulus was selected as an additional fiducial point in order to have the landmark pairs widely dispersed, which resulted in an additional decrease in the position error. As it is difficult to determine precisely the corresponding sites of real-time endocardial location on the 3D MR/CT reconstructions, the registration error after landmark registration only was significant as evidenced by about 60% PV misalignment between the two image datasets. Surface registration was able to adjust the registration error as evidenced by a significant improvement of the PV alignment and a trend to reduce the distance between 3D MR/CT reconstruction surface and multiple real-time endocardial locations.

The use of registered MR/CT images to guide catheter ablation presents a significant advantage over the less-detailed surrogate geometry created by previously available 3D mapping systems. As observed in the current study, the registered MR/CT LA reconstructions can provide accurate information on the catheter tip location in relation to the true anatomy of the PVs and the LA. Hence, the deployment of RF applications could be tailored to individual PV and LA anatomy which was shown highly variable in previous studies as well as in the current study. Whether the improvement of catheter navigation by the image integration technique can translate into better outcomes of AF ablation and avoid procedure-related major complications such as PV stenosis and tamponade needs to be determined by larger randomized studies.

Two observations from the current study give important insights into catheter ablation of AF. First, only about one third of the PVs were electrically isolated upon completion of circumferential ablations. Two groups reported a PV isolation rate of 59.6% and 55%, respectively, using an anatomic PV ablation approach in which an irrigated ablation catheter (currently not available in the United States) was used to create RF lesion. These observations suggest that the criterion of amplitude reduction of local electrogram by 80% or to <0.1 mV can not assure PV isolation which has been shown crucial to successful outcomes. Second, we found that the segmental RF applications guided by the circular mapping catheter were located over 10 mm distal to the PV ostium. This may explain the occurrence of PV stenosis following segmental PV isolation even when RF energy was delivered at or outside the angiogram-defined PV ostium. This may also partially contribute to the limited success achieved by the segmental PV isolation approach in patients with paroxysmal/persistent AF as over 10 mm of the proximal part of the PVs was left intact. This notion is supported by the excellent outcomes reported from groups who either created circumferential lesions over 10 mm outside the angiogram-defined PV ostia guided by electroanatomic mapping to reach the endpoint of electrical PV disconnection or perform PV isolation at the level of PV antrum guided by intracardial echocardiography.
We believe that image integration guided circumferential PV ablation using irrigated ablation technology will further facilitate complete isolation of the highly variable PVs.

The image integration technique has several limitations. As the MR/CT imaging is performed prior to the ablation procedures, registration error can arise from interval changes in the heart size because of differences in rhythm, rate, contractility, or fluid status. In addition, the static images of the registered MR/CT reconstructions give little information on true catheter-tissue contact. To limit interval changes, in the current study, image registration and ablation procedures were performed within 24 hours after MR/CT scans. And all patients underwent MR/CT image acquisition and image registration during the same rhythm. Investigations are under way to integrate real-time imaging techniques such as MR and ultrasound with electroanatomic mapping which provides real-time information on catheter-tissue contact and lesion formation.

Conclusions

Three-dimensional MR/CT images can be successfully extracted and registered to anatomically guided clinical AF ablations. The display of detailed and accurate anatomic information during the procedure enables tailored RF ablation to individual PV and LA anatomy.

References

