Integrated Electroanatomic Mapping With Three-Dimensional Computed Tomographic Images for Real-Time Guided Ablations

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Background—New ablation strategies for atrial fibrillation or nonidiopathic ventricular tachycardia are increasingly based on anatomic consideration and require the placement of ablation lesions at the correct anatomic locations. This study sought to evaluate the accuracy of the first clinically available image integration system for catheter ablation on 3-dimensional (3D) computed tomography (CT) images in real time.

Methods and Results—After midline sternotomy, 2.3-mm CT fiducial markers were attached to the epicardial surface of each cardiac chamber in 9 mongrel dogs. Detailed 3D cardiac anatomy was reconstructed from contrast-enhanced, high-resolution CT images and registered to the electroanatomic maps of each cardiac chamber. To assess accuracy, targeted ablations were performed at each of the fiducial markers guided only by the reconstructed 3D images. At autopsy, the position error was $1.9 \pm 0.9$ mm for the right atrium, $2.7 \pm 1.2$ mm for the right ventricle, $1.8 \pm 1.0$ mm for the left atrium, and $2.3 \pm 1.1$ mm for the left ventricle. To evaluate the system’s guidance of more complex clinical ablation strategies, ablations of the cavotricuspid isthmus (n=4), fossa ovalis (n=4), and pulmonary veins (n=6) were performed, which resulted in position errors of $1.8 \pm 1.5$, $2.2 \pm 1.3$, and $2.1 \pm 1.2$ mm, respectively. Retrospective analysis revealed that a combination of landmark registration and the target chamber surface registration resulted in $<3$ mm accuracy in all 4 cardiac chambers.

Conclusions—Image integration with high-resolution 3D CT allows accurate placement of anatomically guided ablation lesions and can facilitate complex ablation strategies. This may provide significant advantages for anatomically based procedures such as ablation of atrial fibrillation and nonidiopathic ventricular tachycardia. (Circulation. 2006;113:186-194.)

Key Words: catheter ablation ■ electrophysiology ■ imaging ■ mapping

Although catheter ablation procedures traditionally have been guided by electrophysiological mapping, novel ablation strategies have emerged over the last decade that are based mostly on anatomic considerations. For many of these procedures, as for atrial fibrillation, nonidiopathic ventricular tachycardia, and atrial flutter treatment, success depends on the ability to place ablation lesions at predefined anatomic targets like pulmonary vein (PV) ostia, myocardial scar, and the cavotricuspid isthmus.

Fluoroscopy, although frequently used in electrophysiology, has been of limited use because of its poor soft-tissue resolution and its relatively high radiation to patient and medical staff. Therefore, various 3-dimensional (3D) mapping systems have been developed that allow the real-time display of the ablation catheter in relation to the cardiac anatomy. However, these 3D systems can only approximate the cardiac anatomy because they are reconstructed from multiple endocardial catheter electrode recordings and cannot replicate the detailed cardiac morphology as displayed with computed tomography (CT) or magnetic resonance imaging (MRI).

Therefore, a clinical need exists for mapping systems that allow image integration to provide this anatomic information. The first of those systems (CartoMerge, Biosense Webster Inc) has now become clinically available and allows anatomic guidance of ablation procedures on preacquired CT or MR images. However, the accuracy and clinical applicability of this technology have not been evaluated.

Thus, this study sought to assess the true accuracy of this image integration technique for each cardiac chamber, to evaluate its ability to facilitate clinical ablation procedures, and to compare various methods of image registration.
Methods
Animal Preparation
The animal studies were performed in 9 mongrel dogs weighing 30 to 35 kg (Archer Farms, Belcamp, Md). The experimental protocol was approved by the institutional animal care and use committee. Before intubation, the animals received thiopental sodium (Pentothal, Abbott Laboratories) 260 to 300 mg IV and were maintained on isoflurane 1% to 2% (Narkomed GS, Draeger Medical, Inc). Vascular access was obtained by percutaneous puncture or cut down of the femoral vein and artery. The chest cavity was accessed via sternal thoracotomy, and the pericardium was incised. Then, 2.3-mm CT markers (Beekley Corporation) were attached to the epicardial surface of each of the cardiac chambers with a cyano-acryl based glue (Krazy Glue). After placement of the markers, the pericardium and chest were surgically closed.

CT Imaging
The animals were imaged during end expiration with a cardiac-gated, 32-slice multidetector CT scanner (Aquilion, Toshiba Medical Systems Corporation). Helical CT scanning (120 kV, 460 mA, 6.4 helical pitch, 400-ms/rotation gantry speed) with a thickness of 0.5 mm was performed from the aortic arch to the diaphragm every 90 seconds for 6 minutes after intravenous injection of 5 mL/kg contrast media (Visipaque, Amersham Health Inc) at an infusion rate of 3 mL/s.

Postprocessing of the axial CT images was performed with a Vitrea Workstation, version 2.7 (ViTAL Images, Inc) selecting an end-diastolic CT data set. Axial images were reconstructed with a slice thickness of 0.8 mm (Figure 1) and transferred to an electroanatomic mapping system.

Image Segmentation and Extraction
Image segmentation, the extraction of the 3D anatomy of individual structures from the cardiac CT images, was performed with a novel version of an electroanatomic mapping system (Carto XP, Biosense Webster Inc) that had been upgraded with an image segmentation and integration module (CartoMerge, Biosense Webster Inc). Segmentation was achieved in a 3-step process. First, by selecting lower and upper thresholds for the signal intensity of interest, the boundaries between the blood pool and the endocardium (endocardial surface) were defined within the data set (Figure 2A). Second, “seeds” were placed on the axial CT images identifying distinct cardiac (eg, left atrium [LA]) and thoracic structures (eg, ribs). Using a function called competitive region growth, a software algorithm extrapolated from the signal density of the “seed” sites and extended its ascribed region radially until encountering an area belonging to the region of another seed (Figure 2B). Third, by using a second software algorithm that enabled extraction of the individual intracardiac surface wall, multiple 3D models were generated and used for the further registration process (Figure 2C).

Electroanatomic Mapping
After CT imaging, the animals were brought back to the electrophysiological laboratory. Electroanatomic mapping was performed with the Carto XP platform, which determines the real-time location and orientation of the ablation catheter by determining the decaying field strengths (5 × 10⁻⁵ to 5 × 10⁻⁶ T) emitted by 3 electromagnetic coils embedded in a location pad beneath the table.
Anatomic Carto maps of the right atrium (RA), superior vena cava (SVC), inferior vena cava (IVC), right ventricle (RV), LA, left ventricle (LV) and aorta (Ao) were sequentially created by sampling of evenly distributed endocardial sites with a fill threshold of 15 mm using biplane fluoroscopy. The R wave in lead II was chosen as the timing reference of Carto points approximating the end-diastolic CT data set. Thirty to 50 endocardial points were acquired per cardiac chamber. The corresponding endocardial sites of the epicardial CT markers were defined with biplane fluoroscopy and annotated with the Carto system.

**Image Registration**

Image registration is the crucial part of the integration process and refers to superimposing the 3D reconstructed CT images onto the Carto maps derived from catheter mapping. This was performed by combining 2 independent registration methods. First, “landmark registration” was performed by navigating the catheter under fluoroscopic guidance to 3 anatomically defined intracardiac locations and matching the estimated catheter position with the corresponding cursor position on the 3D reconstructions. This step approximated the catheter mapping space with the reconstructed 3D images (Figure 3A and B). In all experiments, landmark registration was performed with 3 RA locations such as the coronary sinus ostium, SVC-RA junction, and IVC-RA junction. Second, “surface registration” was performed to further register the 3D CT reconstructions to the catheter-based Carto maps. This registration uses a software algorithm that results in the smallest average distance between the corresponding endocardial sites with a fill threshold of 15 mm using biplane fluoroscopy. The R wave in lead II was chosen as the timing reference of Carto points approximating the end-diastolic CT data set. Thirty to 50 endocardial points were acquired per cardiac chamber. The corresponding endocardial sites of the epicardial CT markers were defined with biplane fluoroscopy and annotated with the Carto system.

**Targeted CT Marker Ablations**

Each of the 4 chambers was registered sequentially with a predefined combination of landmark and surface registrations, as shown in the Table. Fluoroscopic accuracy measurements using this registration method during preliminary experiments in 2 animals had found the position error to be within 3 mm for all 4 cardiac chambers, which had been arbitrarily chosen as an acceptable cutoff.

After registration of the specific target chamber, fluoroscopy and all annotations of the Carto maps were disabled. The reconstructed CT markers were displayed on the image integration system. Using exclusively the location information from reconstructed CT images, we navigated the ablation catheter to the endocardial sites corresponding to each of the CT markers. Stability of the catheter position was confirmed over several respiratory and cardiac cycles, and a single radiofrequency (RF) lesion was created (60 seconds, 50 W, 50°C). Impedance decrease was monitored to confirm RF ablation.

**Clinical Anatomically Based Ablations**

To assess the ability to facilitate clinical electrophysiological procedures, an RA flutter line (n=4) was created after RA and RV surface registration during a pullback across the cavotricuspid isthmus (40 W, 50°C, 30 seconds each) without the use of fluoroscopy. To evaluate the potential use for transseptal puncture, the ablation catheter was anatomically guided to the atrial septum after RA/SVC/IVC surface registration, and a single ablation lesion (40 W, 50°C, 60s) was placed in the membranous part of the fossa ovalis (n=4) guided only by the registered CT images. After transseptal puncture and RA/LA/Ao surface registration, circumferential PV ablation (left superior, right superior or inferior common PV) was attempted with an RF setting of 50 W and 50°C in the anterior LA and 35 W and 50°C in posterior LA (n=6). Placement of the circumferential lesions was guided only by the registered LA CT image. Ablation sites were annotated if RF energy was applied for at least 15 seconds at a site with the goal of diminishing impedance and >50% amplitude decrease of the local intracardiac electrogram.

**Accuracy Assessment of Targeted CT Marker Ablation**

After completion of the ablation protocols, the animals were euthanized by intravenous injection of potassium chloride solution. The chest was opened and inspected for evidence of cardiac and extracardiac complications. The heart was excised, and the CT marker position was documented and photographed. Each cardiac chamber was sequentially dissected, and the RF lesions were documented and recorded. Because the CT markers were placed epicardially, the position error was defined as the distance between the center of the CT marker and the epicardial projection point of the CT marker.

**Registration Methods for Target Ablation in Individual Cardiac Chambers**

<table>
<thead>
<tr>
<th>Cardiac Chamber</th>
<th>Registration Method</th>
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<tbody>
<tr>
<td>RA</td>
<td>LM plus RA/SVC/IVC surface</td>
</tr>
<tr>
<td>RV</td>
<td>LM plus RA/RV surface</td>
</tr>
<tr>
<td>LA</td>
<td>LM plus RA/Ao/LA surface</td>
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<tr>
<td>LV</td>
<td>LM plus RA/Ao/LV surface</td>
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LM indicates landmark; SVC, superior vena cava; and IVC, inferior vena cava.
center of the ablation lesion. The epicardial projection point was determined by the perpendicular placement of a straight surgical needle through the center of the endocardial ablation lesion by 2 independent observers. Accuracy was reported as the mean distance of 3 independent measurements of its epicardial exit point to the center of the CT marker.

Accuracy Assessment of Clinical Anatomically Based Ablations
At autopsy, the location of the cavotricuspid ablation lesions was documented. Their relative position to the tricuspid valve (as measurement of the position error in the anteroposterior axis) and the distance to the atrial septum (position error in the lateral-septal orientation) were measured and compared with the recorded distances on the registered 3D CartoMerge images. The location of the targeted ablation of the fossa ovalis was documented, and the distance of ablation lesion center to the center of the membranous fossa ovalis was measured. To assess the PV ablations, the distance of the ablation lesions to the ostium of the corresponding PV was measured and compared with the 3D CartoMerge image. If the Carto map indicated continuous ablation lines, inspection for gaps was performed on the pathological specimen.

Assessment of Registration Strategies
A predefined comparison of various registration methods was performed retrospectively to evaluate the influence of different registration strategies on the ablation accuracy. Right-sided landmark registration was combined for each cardiac chamber with different combinations of surface registrations of cardiac structures. With each registration method, the distances between the 3D reconstructed CT markers and their corresponding points on the Carto maps were measured to the nearest 0.1 mm and analyzed separately for each cardiac chamber.

Statistical Analysis
The data are presented as mean ± SD, range, counts, or percentages. Because repeated measurements in the animals may be correlated with each other, a generalized estimating equation model was used to investigate correlation among different registration methods (ie, groups) for a given chamber. A pairwise t test with Sidak-adjusted probability values was used for between-group comparison. The adjusted probability value is equal to 1−(1−unadjusted probability value)^k, where k is the number of comparisons. Values of P < 0.05 were considered significant. All statistical analyses were performed using the SAS statistical package (SAS Institute).

Results
Animal Model and CT Imaging
Animal preparation and contrast-enhanced CT imaging was successfully performed in all 9 animals. All CT markers were easily identified on the axial CT images. Best image quality with least artifact was consistently achieved 180 seconds after contrast injection. After appropriate threshold selection, segmentation and 3D reconstruction were successfully performed for all individual cardiac chambers (n = 36) and vascular structures (n = 27).

Electroanatomic Mapping and Image Registration
Carto maps were reconstructed for the RA, RV, LA, and LV from an average of 44±14, 55±14, 54±14, and 39±15 endocardial position recordings, respectively. Carto maps of SVC and IVC contained 24±4 and 21±6 points, respectively, and the Ao contained 88±21 position recordings. Total mapping time averaged 57±17 minutes. A total of 37 endocardial corresponding points of the CT markers were annotated on the Carto maps (n = 14 for RA, n = 10 for RV, n = 11 for LA, n = 10 for LV); they were used to analyze different registration strategies.

Position Error of Targeted CT Marker Ablation
Figure 4 shows the typical result of targeted atrial and ventricular RF ablations. A straight surgical needle (with silk thread) was placed perpendicularly through the center of the LA ablation lesion (Figure 4A). Shown in Figure 4B are the epicardial exit points and their distance to the white 2.3-mm
CT marker (arrow), which allowed determination of the position error. Accuracy was determined analogously for the ventricular ablations, as shown in Figure 4C and 4D. Of a total of 50 attempted RF ablations, 45 RF lesions were identified at autopsy: 11 RA lesions, 10 RV lesions, 12 LA lesions, and 12 LV lesions. The overall position error was 2.2 ± 1.1 mm (range, 0 to 4.9 mm), with an average ablation size of 6.1 ± 1.4 mm. When analyzed for the individual cardiac chambers, accuracy for the RA, RV, LA, and LV was 1.9 ± 0.9 mm (range, 0.5 to 3.5 mm), 2.7 ± 1.2 mm (range, 1.3 to 4.9 mm), 1.8 ± 1.0 mm (range, 0 to 4.0 mm), and 2.3 ± 1.1 mm (range, 0.2 to 4.1 mm), respectively. There was a trend toward greater position error in ventricular targeted ablation than atrial targeted ablation (2.5 ± 1.2 versus 1.9 ± 0.9 mm; P = 0.06). No difference was seen for ablations in the right compared with the left sides of the heart.

Position Error of Clinical Anatomically Based Ablations

Figure 5A and 5B shows the typical result of a targeted ablation of the fossa ovalis, which was achieved in all 4 experiments with exclusive guidance of the cardiac 3D reconstructions. The average distance of the center of the ablation lesion to the center of the fossa ovalis was 2.2 ± 1.3 mm. All ablation lesions were located within the central membranous part of the fossa. The anatomic target site and catheter navigation were identified with an endocardial view of the right-sided septum at right anterior oblique projection (Figure 5A) and required 34 ± 7 seconds.

Shown in Figure 5A and 5C is a representative example of a cavotricuspid isthmus ablation. At autopsy, the recorded ablation location on the 3D reconstruction correlated well with pathologic results in all 4 experiments. The position error measured in the anteroposterior axis from the ablation lesions to the tricuspid valve ring was 1.8 ± 1.5 mm; the position error in the lateral-septal direction from the ablation lesions to the atrial septum was 2.8 ± 1.8 mm.

Figure 6 shows an example of a PV ablation. Circumferential ablation lesions were created around the PV ostium. No fluoroscopy was used during these ablations. Six PVs (2 left superior PVs, 3 right superior PVs, 1 inferior common PV) were successfully targeted. Distances of the ablation lesions from the PV ostia were measured on the 3D reconstructions and compared with the pathologic results at autopsy, which showed a position error of 2.1 ± 1.2 mm. No erroneously placed ablation lesions were found inside the PV, as predicted by the 3D map. Although ablation lines were continuous on the mapping system, 2- to 4-mm gaps were observed in the ablation lines surrounding the PVs (Figure 6B, arrow).

Assessment of Registration Strategies

Figure 7A shows the relative accuracy of catheter ablation based on the results of 4 different RA registration methods (landmark registration, landmark plus RA surface registration, landmark plus RA/SVC surface registration, landmark

Figure 6. Example of a PV ablation. A, Posteroanterior view of the registered left atrium CT image on which RF lesions (red tags) encircling the right superior PV (RSPV) were superimposed. B, Circumferential ablation lesions at the ostium of the RSPV at autopsy with 1 gap (arrow) in the ablation line. LSPV indicates left superior PV; LMPV, left middle PV; and ICPV, inferior common PV.
plus RA/SVC/IVC surface registration). The accuracy was similar with each of these registration methods.

Shown in Figure 7B is the analysis of the position error with 4 different RV registration methods. Landmark plus RV surface registration yielded the best registration results, which were significantly better than landmark registration and landmark plus RA surface registration. Landmark plus RA/SVC/IVC surface registration was superior to landmark registration. No significant differences were found between landmark plus RV surface registration and landmark plus RA/SVC/IVC surface registration.

The differences among the 4 LA registration methods are shown in Figure 7C. Registration strategies, including any of the left-sided structures (LA or Ao), yielded registration results that were comparable to an extensive right-sided registration (landmark plus RA/SVC/IVC surface registration) but were superior to a limited right-sided registration (landmark plus RA surface registration).

Figure 7D displays the differences found among the 4 LV registration methods. Landmark plus LV surface registration yielded the best registration results, which were significantly better than a limited right-sided registration (landmark plus RA surface registration). No significant differences were found between landmark plus LV surface registration, landmark plus Ao surface registration, and an extensive right-sided registration (landmark plus RA/SVC/IVC surface registration).

Of note, the distances between the endocardial Carto points and the epicardial CT markers displayed in Figure 7 include the atrial or ventricular wall thickness, which was 1.9±0.9, 6.3±1.7, 3.2±0.7, and 10.6±2.1 mm for the RA, RV, LA, and LV, respectively, at the ablation sites.

**Discussion**

**Main Findings**

This is the first study to evaluate the sole image integration system that has now become clinically available. Our findings indicate that (1) the position error allows accurate placement of anatomically targeted ablations in each cardiac chamber;
(2) this image integration system can be successfully used for the anatomically correct placement of RF lesions analogous to the strategies of complex clinical ablation procedures; and (3) the combination of landmark registration with surface registration of the target chamber results in an acceptable position error for each cardiac chamber.

**Accuracy of Targeted CT Marker Ablation**

Several previous studies have evaluated the possibility of image integration with anatomically guided electrophysiological procedures. Our laboratory has shown the feasibility of integrating CT images to guide electrophysiological catheter navigation with an accuracy and precision of 4.7±1.7 and 2.2±0.7 mm, respectively.10 Two subsequent studies have documented the ability to use MR images to guide point ablations in the RA with an in vivo accuracy of 3.9±2.1 mm and a precision of 3.9±0.5 mm.11,12 Septal 3-point lines could be created with a position error of 1.7 to 2.3 mm.12 In these experiments, however, registration was performed with skin surface markers, which is more prone to error if applied to wide clinical practice.

Recently, 2 animal studies have investigated targeted ablation on the registered MR or CT images. One study used a customized program to integrate 3D LV MR images with real-time electroanatomic maps in a dog model.13 The researchers reported a difference between the expected and actual distances of the ablation lesions from the LV targets (iron oxide injections) of 1.8±0.5 mm. In combination with a real-time, noncontact mapping system, Sra et al.14 reported a position error of 2.0±3.6 mm for the ablation of LA targets (pacemaker lead screws) in a chronic dog model.

The present study is the first evaluation of the only image integration system approved for patient care. The accuracy found in our study is well in line with the results of the prior investigational devices. When evaluating these results, we should note that the position error of 2.2±1.1 mm reported in this study reflects the actual distance of the lesion center to the target center, which is the most clinically relevant parameter. Position error results in this animal study were highly consistent with no ablation lesion measuring >4.9 mm from the marker, which compares favorably to other studies in which errors up to 15 mm were noted.14 Additionally, accuracy results were comparable for each of the cardiac chambers when both registration methods were combined.

The overall accuracy determined in this study is the incremental result of multiple, individual errors. First, the position error of the Carto electromagnetic location system has been reported to be <0.8 mm.15 Second, the 3D image segmentation and extraction is dependent on CT quality and individual threshold determination, which can be an additional source of error. Third, the selected registration method significantly affects the resulting accuracy, as indicated by our retrospective analysis. Fourth, interval changes in cardiac anatomy or contractility, as well as respiratory, cardiac, and body motion, are only partially compensated for and will further increase the position error.

Given the increased use of anatomically based ablation procedures and the favorable ratio of lesion size to position error, image integration might be able to supply sufficient morphological guidance for most ablation procedures.

**Accuracy of Clinical Anatomically Guided Ablations**

The advantage of image integration appears to be most evident in guiding complex anatomically based ablation procedures like PV ablation. However, very limited information is available on whether the RF lesions displayed on 3D maps provided by the current mapping systems4–7 correspond well with the pathological results. This is especially critical for atrial fibrillation ablations in which placement of RF lesions in the PV has been associated with creation of PV stenosis.16

To the best of our knowledge, this study presents for the first time a pathological evaluation of the presumed ability to create PV ablations with 3D mapping technology. At autopsy, the targeted RF ablations of the PV ostia were confirmed in all experiments with an acceptable position error. However, despite the display of continuous, linear ablation lesions around the PV ostia, several gaps were found within the ablation lines, ranging from 2 to 4 mm. The most likely explanation for this observation is “stretching” of the atrial wall because of catheter manipulation. During the creation of a continuous ablation line, the tip of a deflected catheter can get “hung up” on, for example, atrial trabeculi along its course on the atrial wall. Further deflection of the catheter will stretch and pull down the atrial wall and therefore move the indicated tip position on the 3D mapping system to the “next spot,” while the tip is still in contact with the same atrial tissue. When the catheter tip is finally freed, the elasticity moves the atrial wall back up, resulting in a gap between the last ablation site and the current “next spot” indicated by the 3D system.

In this study, the overall notion of reliable anatomic location could also be confirmed with anatomically guided flutter ablation along the cavotricuspid isthmus and with targeted ablation of the fossa ovalis as a surrogate of a transseptal puncture. Accuracy was consistently <3 mm.

With the above-mentioned limitations recognized, these results highlight the feasibility and accuracy of guiding complex, anatomically based, clinical ablations with image integration.

**Image Registration Strategies**

Our retrospective analysis suggests that the combination of landmark registration with surface registration results in an expeditious way to achieve sufficient accuracy for each cardiac chamber. This combination of registration methods has not been evaluated previously. Our initial image integration studies relied on external surface markers, which would be challenging in clinical practice.13,12,17 The other 2 reports rely on either a process similar to our surface registration (plus calculation of an initial coordinate transformation matrix)10 or landmark registration alone.14 In our study, using landmark registration alone resulted in an acceptable accuracy only in the RA, the chamber in which the landmark registration was performed. The observation that a careful landmark registration close to the target chamber can potentially be accurate is supported by the study of Sra et al.14 After
creating point-pair files at the PV-LA junction, they reported an accuracy of 2.0±3.6 mm for LA ablations. However, we found that even a small error in acquisition of 1 of the 3 points led to a “tilting” of the defined 3D plane, which could introduce a significant error, especially with increasing distance from the registration points. Such an error is shown in Figure 3B with a larger registration error for SVC or IVC compared with the RA, in which the landmark registration was performed. In these cases, it is possible to improve registration by including a fourth juxtapositioned point at, for example, the tricuspid valve ring. Our data further suggest that the integration of left-sided structures is preferable for any left-sided procedures. Interestingly, an extensive right-sided registration (landmark plus RA/SVC/IVC surface registration) resulted in an acceptable accuracy for the RV, LA, and LV registration.

The accuracy of the surface registration is also influenced by the number of endocardial mapping points. In our experiments, an average of 48 endocardial points per cardiac chamber was sampled with a threshold of 15 mm, which is smaller than that used in the clinical electroanatomic mapping studies.18,19 Whether sampling more endocardial points will significantly improve the registration accuracy needs further investigation. One study combining Ao and LV endocardial points for LV registration did not find an incremental improvement of the registration accuracy beyond 20 LV points.13

Given the small time requirements for landmark point and surface shell registration, we currently favor the combination of both registration methods to minimize the registration error.

Study Limitations

This study has several limitations. First, the concept of an animal study allowed idealized experimental conditions with controlled body motion, decreased respiratory artifacts, and few limits on procedure times. Human studies will have to take these issues into considerations. The second limitation of this study is that the ablation targets were placed epicardially, whereas the RF lesions were created on the endocardium. This may potentially introduce measurement errors because the epicardial projection point is used to evaluate position error. Great care was taken for correct assessment by 2 independent observers, and distance measurements were confirmed with perpendicular dissection if indicated. Although the consistency between the atrial and ventricular results, in which the small atrial wall thickness makes measurement errors less likely, argues for the validity of the measurements, we cannot rule out that the observed trend toward larger position error in the ventricle may reflect the effect of a larger wall thickness. Prior evaluation of various potential markers for atrial and ventricular measurements demonstrated artifacts for intramyocardial markers (eg, pacemaker lead screws, gold seeds) that negatively affected accurate segmentation. Intramyocardial injections were associated with a high complication rate in the atria. Finally, the main purpose of this study was to investigate whether the registered 3D images allowed the correct anatomic placement of ablation lesion at the targeted endocardial site. As such, an electrical evaluation of complex anatomic ablation such as isthmus block and PV isolation was not a pivotal part of the experiments because it would also depend on nonimaging factors such as tissue thickness, catheter handling, and power delivery. Similarly, some of the clinical ablation procedures like the circumferential PV ablation do not require PV isolation as an end point.1

Any kind of image integration technology faces the limitation that the CT/MR images had to be acquired before the procedure and may not accurately reflect interval changes. This fact is important because the image registration, ie, the correct superimposition of the reconstructed 3D anatomy onto the catheter mapping space, will determine its accuracy and clinical utility. In this study, optimization of the registration error was attempted in several ways. First, CT image acquisition, endocardial point recording, and catheter icon display were linked to the same phase in the cardiac cycle. Second, image registration was performed by combining 2 separate, internal registration methods (landmark and surface registrations) to potentially compensate for each other’s intrinsic error. Third, both registration strategies used anatomic points acquired at the time of the actual procedure, which may partially adjust interval changes in axis or rotation.

Clinical Implications

Image integration fulfills an important clinical demand for detailed anatomic guidance. Abnormal anatomy like accessory PVs20 or common PV trunk21 can increase the risk of PV stenosis if not realized. Direct visualization could facilitate safer PV ablation through identification of the LA appendage and assist in selecting the correctly sized PV mapping catheters. For ablation of scar-mediated ventricular tachycardia, integration of delayed enhanced images could visualize the detailed scar anatomy and therefore facilitate the correct placement of continuous ablation lines and supplement or even replace voltage mapping. In cases of complex congenital heart disease, image integration may allow an individualized approach to the variety of anatomic abnormalities. The accuracy of this tested image integration system supports its clinical use in catheter ablation procedures in either the atria or ventricles. Our study suggests that it can facilitate even complex clinical ablation procedures in which anatomic guidance is the most helpful. While realizing its inherent limitations such as never-perfect registration and the inability to visualize the true catheter-myocardial contact (leading to potential gaps), we believe it presents a significant advantage over the previous, less-detailed reconstructed 3D maps and may prove especially helpful for the ablation of atrial fibrillation or nonidiopathic ventricular tachycardia. Further studies will have to determine whether this translates into improved procedural success and fewer clinical complications. Additionally, it sets the stage for further integration of other available technologies such as MRI and ultrasound to provide an additional real-time component and to allow visualization of the ablation lesions.

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Disclosures

Drs Dong and Calkins received research funds and equipment from Biosense Webster, Inc. Dr Solomon owns stock in Johnson & Johnson. E. Brehm and A. Preiss are employees of Biosense Webster, Inc. Dr Dickfeld received speakers bureau from Biosense Webster, Inc. The other authors report no conflicts.

References


**CLINICAL PERSPECTIVE**

New ablation strategies are based increasingly on anatomic consideration and require the placement of ablation lesions at the correct anatomic locations. We assessed the accuracy of a novel 3-dimensional (3D) electroanatomic system with image integration capability in a dog model. Computed tomography (CT) fiducial markers were surgically attached to the epicardial surface of each cardiac chamber. Detailed 3D anatomy of cardiovascular structures was reconstructed from contrast-enhanced CT images and registered to the real-time mapping space. Guided only by the reconstructed 3D images, targeted ablations were performed at each CT marker and resulted in an overall position error of 2.2 mm. Under the guidance of the system, RF lesions were placed at the fossa ovalis, cavitricuspid isthmus, and PV ostium with a position error of ≈2 mm. The results of this study demonstrated that image integration with 3D CT allows accurate placement of anatomically guided ablation lesions. The use of registered CT images to guide catheter ablation presents a significant advantage over the less-detailed surrogate geometry created by previously available 3D mapping systems. Because it provides detailed anatomic information on the catheter tip location in relation to the true cardiac anatomy, the image integration technique has the potential to facilitate many ablation procedures, especially those anatomically based ablation strategies such as atrial fibrillation ablation and nonidiopathic ventricular tachycardia ablation. It also sets the stage for further integration of other available technologies such as MRI and ultrasound to provide an additional real-time component and to allow visualization of ablation lesions.
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In the article by Dong et al titled, “Integrated Electroanatomic Mapping With Three-Dimensional Computed Tomographic Images for Real-Time Guided Ablations,” which was published in the January 17, 2006, issue of the journal (*Circulation*. 2006;113:186–194), the name of one of the authors was incompletely stated. “Al Lardo, PhD” should have read “Albert C. Lardo, PhD.” The authors regret this error.

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