The application of novel segmentation software to create left atrial geometry for atrial fibrillation ablation: The implication of spatial resolution

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Abstract

Background: The application of new imaging software for the reconstruction of left atrium (LA) geometry during atrial fibrillation (AF) ablation has not been well investigated.

Methods: A total of 27 patients undergoing AF ablation using a CARTO Segmentation Module system were studied (phase I). High-density LA mapping using PentaRay was merged with computed tomography-based geometry from the auto-segmentation module. The spatial distortion between the two LA geometries was analyzed and compared using Registration Match View. The associated contact force on the two LA shells was prospectively validated in 16 AF patients (phase II).

Results: Of the five LA regions, the roof area had the highest quality score between the two LA shells (1.7 ± 0.6). In addition, among the pulmonary veins (PVs), higher quality scores were observed in bilateral PV carinas (both 1.8 ± 0.1, p < 0.05) than in the anterior or posterior PV regions. Furthermore, surrounding the PV ostium, the on-surface points had a significantly higher contact force when targeting the high-density fast anatomical mapping shell than for the auto-segmentation module (right superior pulmonary vein, 20.7 ± 5.8 g vs 12.5 ± 4.4 g; right inferior pulmonary vein, 19.3 ± 6.8 g vs 11.8 ± 4.8 g; left superior pulmonary vein, 22.5 ± 7.3 g vs 11.2 ± 4.5 g; left inferior pulmonary vein, 15.7 ± 6.9 g vs 9.7 ± 4.4 g, p < 0.05 for each group).

Conclusion: The CARTO Segmentation Module and Registration Match View provide better anatomic accuracy and less regional distortion of the LA geometry, and this can prevent excessive contact and potential procedural complications.

Keywords: Atrial fibrillation; CARTO Segmentation Mapping; Fast anatomical mapping; Left atrium geometry

1. INTRODUCTION

Pulmonary vein (PV) isolation is the cornerstone procedure of atrial fibrillation (AF) ablation, especially for individuals with paroxysmal AF.1 The reconstruction of left atrium (LA) geometry three-dimensional (3D) geometry is important for effective and safe catheter ablation,2 and the incorporation of LA geometry and electroanatomic mapping can help to achieve a wide area circumferential ablation with better outcomes3 and reductions in radiation exposure4 and procedural duration.5 Clear visualization of the tissue interface is one of the keys to establish good catheter tip-tissue surface contact,6,7 and successful ablation and prevention of complications remain critically dependent on appropriate catheter tip-tissue contact. Several methods have been proposed to create the LA anatomic shell, including point-by-point electroanatomic mapping, intracardiac echocardiography, and fast anatomical mapping (FAM). Of these, FAM allows for the rapid recreation of 3D chamber geometries by moving sensor-based catheters placed in the LA. Furthermore, a recent study demonstrated that the use of a multi-electrode catheter could facilitate the detection of residual PV gaps and improve ablation outcomes.8 However, the creation of FAM using a multi-electrode catheter may overestimate the size of LA geometry and volume owing to distortion of the LA anatomy, which
may then result in the delivery of ablation lesions away from the intended anatomical targets.8,10 On the other hand, contact force ablation catheter-guided mapping has been reported to be better at preventing anatomical distortion than conventional FAM methods.11 However, the anatomic distortion can only be attenuated in regions with adequate contact points. Moreover, the completion of adequate mapping points using a contact force ablation catheter is time-consuming.12

To address these issues, new imaging software, CARTO Segmentation Module (Biosense Webster, Diamond Bar, CA, USA), has recently been developed to improve the resolution of LA geometry. However, the accuracy and applicability of this technology have not been fully studied in clinical practice. Therefore, the aims of this study were to: (1) clarify anatomic differences between computed tomography (CT) geometry created by the CARTO Segmentation Module and CT geometry created manually; (2) investigate anatomic differences in LA geometry derived from PentaRay-created FAM and CARTO Segmentation module CT geometry; and (3) assess differences in contact force based on surface contours generated by integrated FAM and CT geometry derived from the CARTO Segmentation Module in patients with AF.

2. METHODS

2.1. Study design and population

2.1.1. Phase I study

This retrospective study enrolled 27 patients who underwent ablation for drug-refractory and symptomatic paroxysmal or persistent AF using the CARTO 3.0 mapping system version 4.3 (Biosense Webster, Diamond Bar, CA, USA) at Taipei Veterans General Hospital. The patients underwent 12-lead electrocardiography, 24-hour Holter monitoring, echocardiography, and CT angiography of the PVs prior to the procedure. 3D chamber geometry was created by manual CT segmentation and the CARTO Segmentation Module software (Biosense Webster, Diamond Bar, CA, USA). LA parameters including longitudinal diameter and transverse diameter, and PV parameters including cross-sectional area and the diameter were compared between the two geometry shells. All parameters were measured as previously described.13,14

We also evaluated regional discrepancies between the geometry shells derived from FAM using a 1-mm electrode spacing multi-electrode mapping catheter (PentaRay, Biosense Webster; Diamond Bar, CA, USA) and the CARTO Segmentation Module.

2.1.2. Phase II study

In the phase II study, we prospectively enrolled 16 patients with symptomatic AF who underwent catheter ablation between August 2018 and November 2018. The image processing was performed in a manner similar to that in the phase I study. ThermoCool SmartTouch catheters (Biosense Webster) were used for ablation. To create ablation lesions on the FAM geometry, the ablation was guided by the FAM anatomical shells. We then graded the contact force of each ablation lesion on the area with a quality score of 1 or >1. This study was conducted at Taipei Veterans General Hospital in Taiwan and was approved by the Institutional Review Board of Taipei Veterans General Hospital (IRB: 2019-04-001CC) and the Department of Health, Taiwan. Written informed consent was obtained from all patients.

2.2. Cardiac computed tomography imaging

All patients underwent multi-detector computed tomography (MDCT) to reconstruct PV and LA anatomy. MDCT was performed on a Siemens Somatom Definition system with a 64-slice dual-source configuration (Siemens AG, Healthcare Sector, Erlangen, Germany) within 24 hours before the ablation procedure to avoid significant variations in LA anatomy and volume secondary to changes in preload and afterload conditions. Retrospective electrocardiogram-gated spiral scanning was performed with collimation of 1.2 mm during injection of 80 mL of contrast medium (Iomeron 400 mg I/mL, Bracco, Milan, Italy) at a flow rate of 4 mL/s. The cardiac telediastolic phase was automatically determined in patients with sinus rhythm, while manual determination was performed in patients with AF to minimize motion artifacts. The images were then acquired during the end-expiratory phase. Multi-planar reconstruction, maximum intensity projection, and volume rendering were used to define and describe the LA anatomy. LA volume was measured using dedicated volume analysis software (Syngo VE32B Volume, software version 1.0, 2008, Siemens AG). The LA was manually outlined on axial images using a 3-mm thickness sequence. MDCT images (slice thickness 1.5 mm, position increment 0.7 mm) were then stored on a CD and data were loaded into the image integration module of the mapping system (CARTOMERGE Module, Biosense Webster). Segmentation of the MDCT images was then performed as previously described,15,16 and the LA contours were semi-automatically reconstructed and the volume was calculated. Ostial PV diameters, LA anterior–posterior, lateral-septal, and superior–inferior diameters were also manually measured. Isolated LA and PVs after 3D reconstruction were then exported to the mapping system for subsequent mapping and integration processes.

2.3. Cardiac computed tomography imaging and sub-segmentation of LA geometry

The CARTO Segmentation Module software was also used to create another LA geometry. The segmentation reconstruction was a combination of the two main methods: the first was intensity, using the scan data of 4,096 possible values, and the second was model-based. The combination of these two methods could yield the best segmentation results for both sides of the heart with high required accuracy. The workflow using the module has been described in a previous study.16

The LA body was divided into five sub-segments including roof, posterior wall, septum, anterior wall, and left lateral wall.11 Fig. 1 illustrates an example of the LA sub-segments. The PVs were divided separately into three sub-segments per side, including anterior, posterior and carina.

2.4. Creation of Fast Anatomical Map (FAM)-based LA and PV Images

The creation of FAM-based LA and PV geometry has been described in previous studies.17,18 A high-density mapping catheter (PentaRay, Biosense-Webster) was used in all cases for the generation of FAM. The average mapping sites in the left atria included more than 1800 points for each patient.

2.5. Comparison of FAM-based and CARTO Segmentation-derived 3D LA Geometries

The reconstructed CT data sets were merged with the geometries via three registration processes. Visual alignment was performed with the use of landmark pairs, that is, landmarks of the right PV carina, established on the FAM images, and corresponding sites on the reconstructed CT image.19 After surface registration,20,21 a manual iterative process was used to minimize differences in individual PV positions and overall LA geometry.22 The spatial distortion between the two LA geometries was analyzed and compared to Registration Match View. The quality score was used to define the concordance of the two geometries, and quality scores of 1, 2, and 3 were defined.
as distances between the two anatomical shells of <5 mm, 5–10 mm, and >10 mm, respectively (Fig. 2). The average quality score was calculated for each sub-segmentation of LA and PVs. We defined a quality score of 1 as regions having “perfect” matching and >1 for the remaining regions. To validate the quality score method, the inter-observer coefficient was calculated by two blinded operators.

2.6. Comparison of Contact Force between Regions with Different Quality Scores
Wide area circumferential ablation of the PVs was based on the FAM-derived geometry, and the ablation lesion was intended to target the FAM anatomic shell. During ablation, automatic ablation lesion tagging with simultaneous contact force recording was used. After ablation, the contact force of each ablation lesion was compared between perfectly matched (quality score = 1) and imperfectly matched (quality score > 1) regions.

2.7. Statistics and analysis
Data are expressed as mean ± standard deviation for normally distributed continuous variables and proportions for categorical variables. The parameters of geometries derived from different methods were compared using the Wilcoxon signed-rank test. The quality score between different sub-segmentations was analyzed using one-way ANOVA with post hoc paired comparisons. The contact force of the ablation lesions between different matched regions was analyzed using a two-tailed t-test. All statistical analyses were performed using SPSS version 22.0 (IBM Corporation, Armonk, NY, USA), and a p value <0.05 was considered to be statistically significant.

3. RESULTS
3.1. Phase I study

3.1.1. Patient characteristics
A total of 27 patients who underwent AF ablation (24 male, mean age 53.6 ± 8.0 years) were studied, including 22 (81.5%) with paroxysmal AF and five (18.5%) with persistent AF. With regards to the structural assessments, the mean left ventricular ejection fraction was 57.9 ± 8.2% and LA diameter was 39.7 ± 5.3 mm. Table 1 shows the baseline characteristics of the study population.

3.1.2. Comparison of LA derived from the CARTO Segmentation Module and manual segmentation of CT geometry
The longitudinal and transverse diameters of the LA calculated by manual segmentation were longer than those derived from the CARTO Segmentation Module (65.2 ± 5.6 mm vs. 62.0

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**Fig. 1** The LA body was divided into five sub-segments, including the roof, posterior wall, septum, anterior wall, and left lateral wall. (A–E) Examples of the LA sub-segments. (F,G) Examples of three sub-segments of the pulmonary veins, including anterior PV antrum, carina and posterior PV antrum.
± 14.0 mm, \( p < 0.01 \) and 58.1 ± 6.7 mm vs. 56.3 ± 7.0 mm, \( p < 0.001 \), respectively; Table 2). Furthermore, a larger cross-sectional area and longer diameters of each PV were observed in the LA calculated by manual segmentation (\( p < 0.01 \) for each PV, Table 2).

3.1.3. Comparison of geometries derived from the CARTO Segmentation Module and FAM

Among the five sub-segmentations of the LA body, the obtained quality score in the roof area (1.7 ± 0.6) after merging the two geometry shells was significantly higher than those in the other regions. LA anterior wall (1.1 ± 0.2) and posterior wall (1.0 ± 0.2) had the lowest quality score between the two geometries (Fig. 3A). Furthermore, among the sub-segmentation surrounding the PVs, the highest quality scores were observed surrounding the bilateral PV carinas (both 1.8 ± 0.1) (Fig. 3B).

3.2. Phase II study

3.2.1. Patient characteristics

Of the 16 patients who underwent AF ablation (10 males, mean age 58.6 ± 6.7 years), paroxysmal and persistent AF was identified in 15 (93.8%) and one (6.3%) of the patients, respectively. The left ventricular ejection fraction was 59.4 ± 4.6% and the LA diameter was 37.8 ± 4.5 mm. Table 1 shows the baseline characteristics of the study population.

3.2.2. Validation of contact force between regions with different quality scores

A total of 926 ablation lesions were acquired for validation of the contact force between regions with different quality scores, including 801 at regions with a quality score of 1 and 125 at regions with a quality score of >1. The contact force at areas with a quality score > 1 was significantly higher than that at areas with a quality score of 1 (19.9 ± 7.0 g vs 11.3 ± 4.7 g, \( p <0.05 \); Fig. 4A). The higher contact force at the areas with a quality score >1 was consistent in each PV (RSPV: 20.7 ± 5.8 g vs. 12.5 ± 4.4 g; RIPV: 19.3 ± 6.8 g vs. 11.8 ± 4.8 g; LSPV: 22.5 ± 7.3 g vs. 11.2 ± 4.5 g; LIPV 15.7 ± 6.9 g vs. 9.7 ± 4.4 g, \( p < 0.05 \) for each group; Fig. 4B). Regions with a quality score of >1 had more ablation lesions with a contact force >20 g comparing to those with a quality score of 1 (32.0% vs. 5.0%, \( p < 0.05 \); Fig. 4C).

3.2.3. Reproducibility

The inter-observer agreement in measurement of anatomic parameters and quality score yielded intra-class correlation coefficients of 0.79 and 0.98, respectively (95% confidence
The baseline characteristics of patients in Phase I and Phase II

|                      | Phase I (N = 27) | Phase II (N = 16) |
|----------------------|-----------------|------------------|
| Age, years           | 53.6 ± 8.0      | 58.6 ± 6.7       |
| Male                 | 24.0 (88.9%)    | 10.0 (62.5%)     |
| SBP, mmHg            | 126.0 ± 15.6    | 128.9 ± 13.7     |
| HR, bpm              | 79.7 ± 19.6     | 71.6 ± 10.5      |
| BMI                  | 25.7 ± 2.9      | 24.0 ± 2.9       |
| eGFR, ml/min/1.73 m² | 74.3 ± 15.0     | 73.6 ± 14.6      |
| AF characteristics   |                 |                  |
| Paroxysmal AF        | 22.0 (81.5%)    | 15.0 (93.8%)     |
| Persistent AF        | 5.0 (18.5%)     | 1.0 (6.3%)       |
| Comorbidity          |                 |                  |
| Hypertension         | 11.0 (40.7%)    | 5.0 (31.3%)      |
| Diabetes mellitus    | 1.0 (3.7%)      | 0.0%             |
| Coronary artery disease | 4.0 (14.8%)  | 2.0 (12.5%)      |
| Congestive heart failure | 3.0 (11.1%) | 1.0 (6.3%)       |
| Stroke               | 2.0 (7.4%)      | 0.0%             |
| CHA2DS2_VAS score    | 0.9 ± 0.8       | 1.4 ± 1.1        |
| Echocardiography     |                 |                  |
| LA diameter, mm      | 39.7 ± 5.3      | 37.8 ± 4.5       |
| LA volume index, ml/mL² | 27.3 ± 4.0    | 27.0 ± 4.0       |
| LV, %                | 57.9 ± 8.2      | 59.4 ± 4.6       |

Table 2: The parameters of PV and LA between the 3D geometry shells created by manual CT segmentation and CARTO Segmentation Module software

|                      | LA shell by manual CT segmentation (n = 27) | LA shell by CARTO Segmentation Module (n = 27) | p   |
|----------------------|-----------------------------------------|------------------------------------------|-----|
| RSPV diameter (mm)   | 19.9 ± 2.9                              | 18.5 ± 2.9                               | <0.01|
| RSPV CSA (mm²)       | 310.9 ± 6.7                             | 268.6 ± 6.5                              | <0.01|
| LSPV diameter (mm)   | 21.1 ± 3.5                              | 20.1 ± 3.5                               | <0.01|
| LSPV CSA (mm²)       | 349.8 ± 9.5                             | 317.9 ± 9.6                              | <0.01|
| RIPV diameter (mm)   | 18.4 ± 3.1                              | 16.9 ± 3.0                               | <0.01|
| RIPV CSA (mm²)       | 265.9 ± 7.6                             | 225.2 ± 6.9                              | <0.01|
| LIPV diameter (mm)   | 17.0 ± 3.5                              | 15.4 ± 3.0                               | <0.01|
| LIPV CSA (mm²)       | 226.9 ± 9.8                             | 187.2 ± 6.9                              | <0.01|
| LA longitudinal diameter (mm) | 65.2 ± 5.6 | 62.0 ± 14.0 | <0.01|
| LA transverse diameter (mm) | 58.1 ± 6.7 | 56.3 ± 7.0 | <0.01|

CSA = cross-sectional area; LA = left atrium; LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein.

Table 2: The parameters of PV and LA between the 3D geometry shells created by manual CT segmentation and CARTO Segmentation Module software

4. DISCUSSION
4.1. Major findings
To the best of our knowledge, this is the first study to evaluate the impact of local LA distortion based on 3D-CARTO segmentation-derived geometries during AF ablation. There are several important findings in this study. First, there were longer LA diameters and larger cross-sectional areas of each PV created by manual segmentation than those derived from the CARTO Segmentation Module. Second, the CARTO Segmentation Module and Registration Match View provided better anatomic accuracy and less regional distortion of LA geometry. Third, the roof area and bilateral PV carinas had the highest spatial distortion. Therefore, avoiding excessive contact force when manipulating the catheter or performing ablation surrounding these regions is mandatory.

Radiofrequency lesions cause fibrosis with subsequent thinning of the atrial myocardium. Therefore, a high contact force, particularly during ablation, might increase the risk of cardiac tamponade. Recent studies have shown that contact force-guided...
Circumferential PV isolation is safe during PV isolation procedures. However, a contact force catheter is expensive and not affordable for every patient. Therefore, without the assistance of contact force information during AF ablation, clinicians need to avoid excessive force, particularly when manipulating catheters or ablating at the LA roof or carina region.

There are several limitations to this study. First, because CT imaging was performed prior to the ablation procedures, dynamic changes in rhythm, heart rate, contractility, or fluid state could have contributed to changes in heart size and potential registration errors. To limit these changes, we performed image registration and ablation procedures within 24 hours.

![Fig. 3](A,B) demonstrate the regional quality scores of the LA body and PV antrum between the FAM and CARTO segmentation-merged 3D CT geometries, respectively. The quality scores of the roof and PV antrum were significantly higher than those within the other regions.

![Fig. 4](A) Comparisons of the contact force of overall ablation points between a quality score of 1 and >1. (B) Comparisons of the contact force of ablation points at each PV antrum between a quality score of 1 and >1. A higher contact force was observed for the ablation points in the FAM with a quality score >1. (C) The distribution of contact force of the ablation points with a quality score of 1 and >1.
after the CT scan. Second, this study was conducted at a single center, which may limit the generalizability of the results to the other centers. The results may also have been confounded by the operators' experience and skill. Third, despite the “perfectly” merged LA geometries, the absolute distances between the FAM and CARTO segmentation-merged 3D CT geometries could not be directly measured. Fourth, given the limited study population, future investigations are warranted to validate the present findings in large-scale studies.

In conclusion, the CARTO Segmentation Module can help to define the exact anatomic location of the LA and PVs more accurately in AF patients, allowing for safer ablation. When the AF ablation is guided by FAM, clinicians should avoid ablation points located outside the LA surface derived from the CARTO Segmentation Module, especially for the roof and PV carina region. Our data revealed anatomic distortion of the LA shells created by different methods, and shed light on improving the safety and effectiveness of AF ablation.

ACKNOWLEDGMENTS

This work was supported by the Center for Dynamical Biomarkers and Translational Medicine, Ministry of Science and Technology (grant nos. 107-2314-B-010-061-MY2, MOST 106-2314-B-075-006-MY3, MOST 106-2314-B-010-046-MY3, and MOST 106-2314-B-075-073-MY3), Research Foundation of Cardiovascular Medicine, Szu-Yuan Research Foundation of Internal Medicine (107-02-036), Taipei Veterans General Hospital [grant numbers. V108C-032, V108C-107, V109C-113, V109D-048-001-MY2-1, C17-095, V106C-158, V106C-104, V107B-014, V107C-060, and V107C-054] and Taipei Medical University – Wan Fang Hospital (109-wf-eva-18).

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