Extra-Cavity Image Registration via the Aortic Root During Left Ventricular Mapping and Ablation

ORIGINAL INVESTIGATION

ABSTRACT

Background: Computed tomography (CT) image integration is of limited use in left ventricular (LV) ablation due to inadequate accuracy of registration. The current study aimed to investigate the accuracy and feasibility of extra-cavity LV image registration via the coronary cusp.

Methods: Consecutive patients were enrolled as the validation group (n = 41) and feasibility group (n = 48). After extra-cavity registration via the aortic root, the LV anatomy derived from CT image was activated and moved into real space. Accuracy of LV anatomy via this registration method was verified by intracardiac echocardiography reconstruction in the validation group and tested further in the feasibility group via measuring the location differences (<3 mm) and volume difference (<8 mL).

Results: In validation group, the LV volume of CT image and ICE map were comparable (113.6 ± 15.5 mL vs. 109.0 ± 15.3 mL, P = .27), and the location difference was 3.1 ± 1.1 mm at LV summit, 1.8 ± 0.9 mm at the free wall, and 1.8 ± 0.7 mm at the LV apex. There was a mean of 2.9 ± 1.2 mm and 3.0 ± 1.0 mm length difference in anterior PM and posterior PM, the position difference of the PM's base was 2.8 ± 0.9 mm for anterior PM and 2.2 ± 0.9 mm for posterior PM. In feasibility group, the distance differences of LV summit, LV septum, LV apex, and LV free averaged 1.8 ± 0.8 mm, 1.5 ± 0.7 mm, 1.4 ± 0.6 mm, 1.3 ± 0.7 mm, respectively. Compared with validation group, acute success (100% vs. 96.5%, P = .51), complications rate (4.9% vs. 2.0%, P = 0.59) and fluoroscopic time (1.6 ± 1.1 vs. 1.9 ± 1.6 minutes, P = .30) exhibited no significant difference, but was significantly reduced with procedure time (74.5 ± 8.1 vs. 61.2 ± 9.5 minutes, P < .001) with CT image registration only.

Conclusion: LV mapping and ablation could be successfully achieved by extra-cavity registration via coronary cusp without needing positions within LV beforehand.

Keywords: Catheter ablation, computed tomography, image registration, left ventricular, mapping

INTRODUCTION

Transcatheter ablation of cardiac arrhythmias was initially performed under the guidance of fluoroscopic view. Later, the 3-dimensional (3D) mapping system was invented, exhibiting the ability to display catheter(s) in 3D space and create 3D maps of any heart chamber of interest.[1] Combined with conventional electrophysiology knowledge, using the 3D mapping system was proved to improve success, and reduce radiation exposure.[2-4]

To provide more detailed anatomic information, superimposing of 3D images derived from computed tomography (CT) or magnetic resonance (MR) on the acquired 3D map of cardiac chamber was introduced and called "registration," and its accuracy requires: 3D map created during procedure must be correct; the paired positions that chosen for registration should be the corresponding locations of 3D images and 3D maps. The paired positions are usually the featured landmarks that are defined by arbitrary selection. 3D map created during the procedure requires contact of mapping catheter with the endocardium, and its accuracy tends to be affected by contact force, and cardiac and respiratory motions. When it is incorrectly created, 3D map itself tends to give an erroneous interpretation.

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Currently, image registration is commonly used for AF ablation, but it is rarely reported for left ventricular (LV) ablation.[5,6] The main reason is the complexity of LV anatomy such as papillary muscles (PM), tendons, as well as trabecular muscles, and these structures hinder the roving of mapping catheters, rendering the mechanic bumping and distortion of LV reconstruction unavoidable. Meanwhile, in LV, featured landmark(s) that allow operator to choose for registration is lacking.[7]

Aortic root, on the other hand, is a centrally located, tube-like structure with a smooth endocardial surface,[8,9] when mapping catheter roves around, bumping-induced contraction and anatomic distortion would never happen. Meanwhile, the aortic root has featured landmarks—3 aortic sinuses, which can be used for paired positions, theoretically, it is very suitable for registration. However, although aortic root is the extension of LV, as an extra-cavity structure, whether it can be used for LV registration remains unknown.

METHODS

Study Population
From January 2016 to January 2018, patients requiring LV mapping and ablation were recruited for this study. Initially, the patients were enrolled to assess the accuracy of this registration method as verified by intracardiac echocardiography (ICE) (Verification group). Later, LV mapping and ablation were performed after registration with CT image only (Feasibility group). The patients with prior cardiac surgery or significant congenital heart disease were excluded. The study complied with the Declaration of Helsinki, and the protocol was approved by the Institutional Review Boards. Each participant provided their written informed consent.

Computed Tomography Imaging Acquisition and Reconstruction
The CT imaging was acquired with contrast-enhanced dual-source CT (SOMATOM Definition Flash, Siemens Healthineers, Forchheim, Germany) 1 day before the procedure. The default parameters were shown as followings: slice thickness, 0.75 mm; gantry rotation speed, 330 ms per rotation; tube voltage, 120 kV; effective charge, 320 mAs/rot; pitch, 0.2. Scanning was performed after injection of 120-140 mL nonionic contrast media at a flow rate of 3 mL/s during 1 breath-hold at the end-expiratory phase during sinus rhythm. The scanning duration was approximately 10 seconds. A simultaneous electrocardiogram (ECG) was recorded

HIGHLIGHTS
- Left ventricular registration could be achieved using extra-cavity structures.
- This registration method could be accomplished before the catheter reaches left ventricle.
- The accuracy of extra-cavity registration is reliable in different complex structures with minimal error.
- Various left ventricular mapping and ablation could be successfully performed using extra-cavity registration without intracardiac echocardiography.

to retrospectively assign the source images to the 75% phase location with the center of the reconstruction window being between 0% and 90% of the R-R interval.

The raw CT data was imported to an electroanatomical mapping system using custom-designed software (Carto-Merge, Biosense Webster, Inc., Diamond Bar, CA, USA). Segmentation of the cardiac chamber was performed to separate the LV, aortic root from the surrounding cardiac structures. Of note, during segmentation, LV PMs were featured as devoid of blood pool and indirectly exhibited as cavern or dentation-like structures (Figure 1).

Extra-Cavity Left Ventricular Registration via Aortic Root
Under local anesthesia, a 3.5 mm, deflectable quadripolar saline-irrigated catheter (NaviStar Thermal-Cool, Smart-Touch, Biosense Webster, USA) was retrogradely introduced into the aortic root from the right femoral artery. Catheter-based reconstruction of the aortic root was performed by using a fast anatomic mapping (FAM) module in the Carto 3 system. The contact force was controlled between 5 g and 10 g. Three aortic sinuses were specially reconstructed. If the catheter dropped into LV, the tracing was erased, and only the model of aortic root was retained.

After that, the CT images of the LV and the aortic root were exported into the real-time mapping system for registration. Three crucial landmarks were manually tagged in the FAM maps and CT images, including the left coronary cusp, the right coronary cusp, and non-coronary cusp. Landmark registration was then performed between the 2 maps. Surface registration was applied to further accommodate the 2 maps. The process of image registration was completed after the 2 maps was matched (Figure 2). The anatomy of LV chamber was obtained via extra-cavity registration.

Assessing the Accuracy of Extra-Cavity Left Ventricular Registration by Intracardiac Echocardiography
In the verification group, ICE-guided LV reconstruction was used to assess the registration accuracy. After completing registration, a new map was opened for ICE reconstruction. A 10-French phased-array ICE catheter (SOUNDSTAR, Biosense Webster, Diamond Bar, California, USA) was introduced via the left femoral vein. The respiratory- and ECG-gated contours of LV as well as PMs were sequentially acquired by rotating the ICE probe inside the right ventricle. The ICE planes were equally acquired for each structure to fully elucidate the contours of LV. Full short- and long-axis of LV and PM were defined by an experienced clinical specialist and an on-site electrophysiologist.

Upon the completing LV reconstruction by ICE, LV chamber segmented from CT scan was activated and moved into the window of ICE-reconstructed map. The consistency of 2 maps was examined by volume difference and location differences:

Volume difference: The volume of LV chamber segmented from CT was measured and compared with the LV volume reconstructed by ICE.
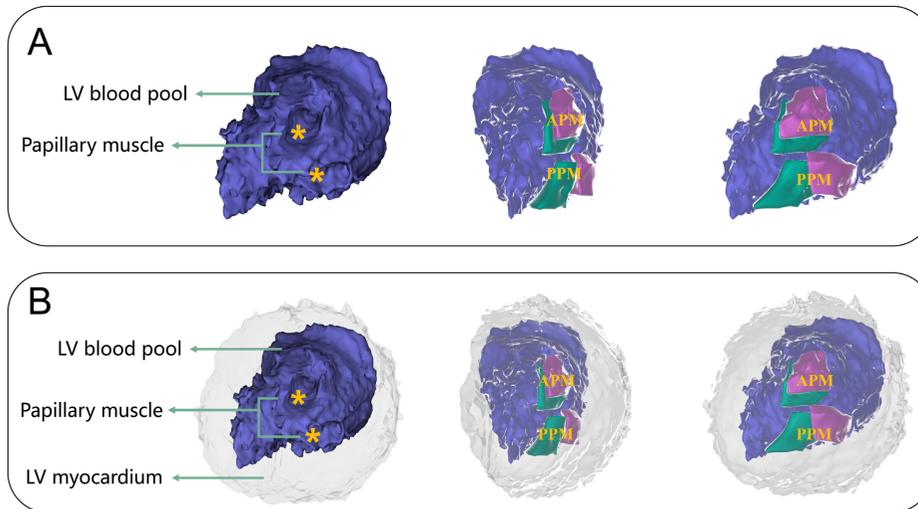
Figure 1. Well-aligned PM anatomies between CT images and ICE maps after extra-cavity registration. The anterior and posterior PM were indirectly visualized as the cavern or dentation-like structures (yellow asterisks) on CT image. The ICE reconstructed PMs were indicated as green or purple color structures. After extra-cavity registration, the CT images were found to be well-aligned with ICE maps. APM, anterior papillary muscle; LV, left ventricle; PPM, posterior papillary muscle.

Location differences were assessed by measuring the distances of corresponding positions on the CT geometry and ICE-created map, those positions including LV summit, LV apex, and LV free wall. The distance would be zero if they are totally matched. The assessment was achieved by acquiring the corresponding positions through the ICE view. A built-in distance measurement tool was used to calculate the absolute location difference. This process was achieved by 2 independent experienced electrophysiologists and an ultrasonologist. The same site was repeatedly calculated 3 times and averaged the results as the final measurement.

Well-matched registration was defined as volume difference <8 mL, and location difference <3 mm of all the 3 measured positions.

Feasibility of Left Ventricular Mapping and Ablation via Extra-Cavity Left Ventricular Registration Only

In this feasibility group, after extra-cavity registration, the CT image was brought into a real-time mapping window. LV mapping and ablation were conducted under the guidance of this CT image without using ICE. The contact of mapping catheter with the LV summit, septum, apex, and free wall was tested by experienced operators with contact force controlled between 5 g and 10 g. Further, the real-time positions were collected, and the corresponding positions on the CT image were defined as landmarks. Then the distance between the real-time positions and the corresponding positions on the CT image could be automatically calculated via registration error measurement. The distance difference <3
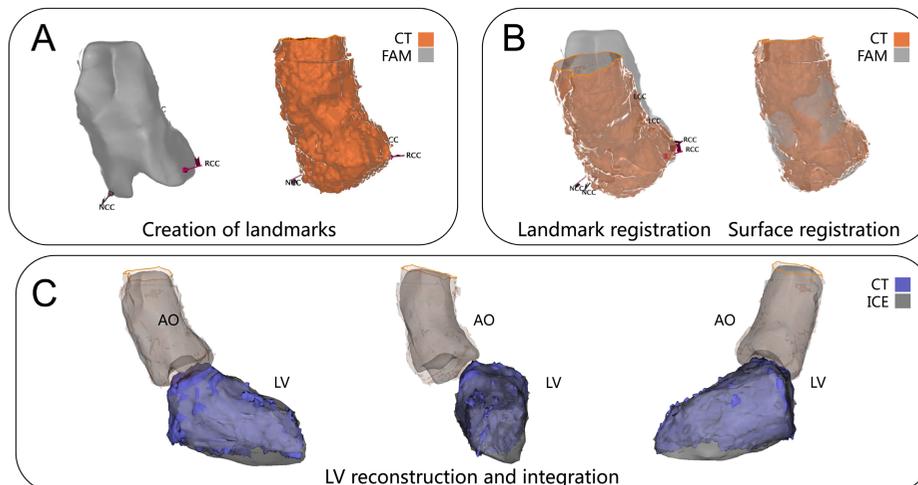

Figure 2. Imaging registration and verification. A. The paired landmarks (shown as flags) were respectively tagged on the aortic root in the FAM map (left, gray) and CT map (right, orange). B. The aortic CT map was superimposed on the FAM map after landmark and surface registration. C. After registration, the LV CT image (purple) was moved into real space without positions within LV and compared with the LV chamber reconstructed by ICE (gray), and the 2 anatomies were well accommodated. AO, aortic root; CT, computed tomography; FAM; fast anatomical mapping; ICE, intracardiac echocardiography; LV left ventricle.

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mm was deemed as well-matched registration. Meanwhile, the procedural time, fluoroscopic time, complication rate, and success rate were collected and compared with the verification group.

Statistical Analysis

Continuous variables are expressed as mean ± SD or median (interquartile range).

Comparisons are performed using the *t*-test or Mann–Whitney *U*-test according to the normality with K-S test. Categorical variables were expressed as number (percentage) and compared using Fisher's exact test or chi-square test. All tests were performed using SPSS software (Version 22).

RESULTS

Patients' Characteristics

During the study period, a total of 89 patients were enrolled in the current study. The verification group included 41 cases; the feasibility group included 48 patients. The clinical characteristics were presented in Table 1. In the feasibility group, the ventricular arrhythmia was originated from the outflow tract in 6 patients (14.6%), LV PMs in 19 patients (46.3%), and LV fascicles in 16 (39.1%). In the verification group, the ventricular arrhythmia was presented in LV PMs in 25 patients (52.2%) and LV fascicles in 13 (27.0%). Ten patients in the verification group manifested pathological ventricular tachycardia, among which 7 patients had ischemic cardiomyopathy, 2 had arrhythmogenic cardiomyopathy and 1 had dilated cardiomyopathy. No significant differences in clinical parameters were found between the groups.

Accuracy of Extra-Cavity Registration

After extra-cavity registration, the CT image was moved into real-time window and compared with the LV geometry reconstructed by ICE. The location differences between the CT and ICE maps were presented in Table 2. The LV volume of CT image and ICE map averaged 113.6 ± 15.5 mL and 109.0 ± 15.3 mL (*P* = .269), respectively. The registration error was highest in the LV summit and reached a difference of 3.1 ± 1.1 mm. It had better performance in the LV free wall with a difference of 1.8 ± 0.9 mm and LV apex with a difference of 1.8 ± 0 .7 mm. The PMs were indirectly visualized as the carven

Table 1. Clinical Characteristics

Characteristics	Group A (n = 41)	Group B (n = 48)	P
Age, years	41.1 ± 9.4	42.9 ± 10.0	.508
Male, n (%)	16 (57.1)	18 (62.1)	.705
Types of arrhythmias			
Outflow tract VA	6 (14.6)	0 (0.0)	<.001
Papillary VA, n (%)	19 (46.3)	25 (52.2)	
Fascicular ILVT, n (%)	16 (39.1)	13 (27.0)	
VT in structural heart disease, n (%)	—	10 (20.8)	

ILVT, idiopathic left ventricular tachycardia; VA, ventricular arrhythmia; VT, ventricular tachycardia.

Table 2. Mean Distance to the ICE Map in Group A

Parameters	Difference
LV alignment	
LVA distance, mm	1.8 ± 0.7
Summit distance, mm	3.1 ± 1.1
Free wall distance, mm	1.8 ± 0.9
APM alignment	
Length difference, mm	2.9 ± 1.2
Base distance, mm	2.8 ± 0.9
PPM alignment	
Length difference, mm	3.0 ± 1.0
Base distance, mm	2.2 ± 0.9

APM, anterior papillary muscle; EAS, earliest activation site; LV, left ventricle; LVA, left ventricular apex; PPM, posterior papillary muscle.

structure in the CT map. There was a mean of 2.9 ± 1.2 mm and 3.0 ± 1.0 mm length difference in anterior PM and posterior PM. The position difference of the PM's base was 2.8 ± 0.9 mm for anterior PM and 2.2 ± 0.9 mm for posterior PM.

Acute success was achieved in all patients with 2 patients having local hematoma. No other complication occurred. The CT image and ICE reconstruction time were presented in Table 3. The total procedural time and fluoroscopic time were 74.5 ± 8.1 minutes and 1.6 ± 1.1 minutes, respectively.

Feasibility of Mapping and Ablation Under Extra-Cavity Image Registration

The CT image reconstruction time and registration time were 4.1 ± 1.2 minutes and 3.0 ± 1.0 minutes, respectively. After extra-cavity registration with CT image only, the distance between the real-time positions and corresponding positions on CT images was measured. The distance differences of LV summit, LV septum, LV apex, and LV free averaged 1.8 ± 0.8 mm, 1.5 ± 0.7 mm, 1.4 ± 0.6 mm, 1.3 ± 0.7 mm respectively (Figure 3, 4). Three patients with pathological ventricular tachycardia required epicardial mapping and

Table 3. Procedural Parameters

Duration	Group A (n = 41)	Group B (n = 48)	P
Acute success (%)	100.0	96.5	.322
Complications rate (%)	4.9	2.0	.305
Fluoroscopic time, minutes	1.5 (1.0-2.0)	1.5 (1.0-2.8)	.492
CT image reconstruction, minutes	4.0 (4.0-5.0)	5.0 (4.0-5.0)	.434
Image registration, minutes	3.0 (2.3-4.0)	2.0 (2.0-3.0)	.081
ICE reconstruction, minutes	21.4±3.2	—	—
Mapping duration, minutes	17.9±3.6	11.2±2.8	<.001
Procedural time, minutes	74.5±8.1	61.2±9.5	<.001

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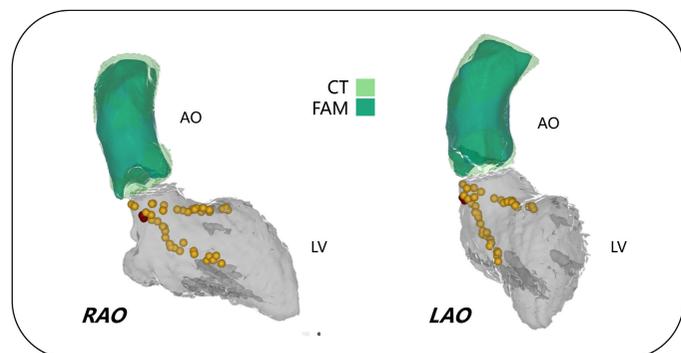Li et al. Left Ventricular Registration via Aortic Root

Figure 3. Ablation of fascicular ventricular tachycardia after extra-cavity registration only. This was a case of idiopathic left ventricular tachycardia arising from the left-sided His. After extra-cavity registration via the aortic root, the LV anatomy segmented from CT image was activated and moved into real space. All subsequent mapping and ablation were carried out guided by this CT image only, the left anterior and posterior fascicles were mapped out and found well aligned with the LV septum. The tachycardia was successfully treated by ablation at the origin (indicated by red point). AO, aortic root; CT, computed tomography; FAM; fast anatomical mapping; LAO, left anterior oblique; LV, left ventricle; RAO, right anterior oblique.

ablation in which the myocardium was specifically reconstructed and integrated. The epicardial side was also well correlated with electro-anatomical mappings (Figure 5). One patient developed a local hematoma after the procedure. No other complication was observed.

Compared with the validation group assisted by ICE, acute success (100% vs. 96.5%, $P = .322$), complications rate (4.9% vs. 2.0%, $P = .305$), and fluoroscopic time [1.5 (1.0-2.0) vs. 1.5 (1.0-2.8) minutes, $P = .492$] exhibited no significant difference. However, the procedural time was significantly reduced in the validation group (74.5 ± 8.1 vs. 61.2 ± 9.5 minutes, $P < .001$, Table 3).

DISCUSSION

Major Findings
LV registration could be achieved via extra-cavity structure, i.e., aortic sinus. And this image registration method does not require positions within LV and yields the same accuracy as ICE-guided reconstruction, supporting its clinical use for LV mapping and ablation.

Image Registration
CT/MR integration consists of 3 major steps: 2-dimensional raw data acquired prior to EP procedure; segmentation of 3D chamber(s) of interest from the 2-dimensional data; and finally image registration. The first 2 steps are well established, aiming to obtain CT/MR images before patients are transferred to the catheter lab. Registration refers to superimposing a 3D CT/MR image onto a real-time electro-anatomical map, which requires catheter-based reconstruction and landmark(s) definition. The former requires contact of mapping catheter with the endocardium and overcoming cardiac or respiratory motions. And the latter requires
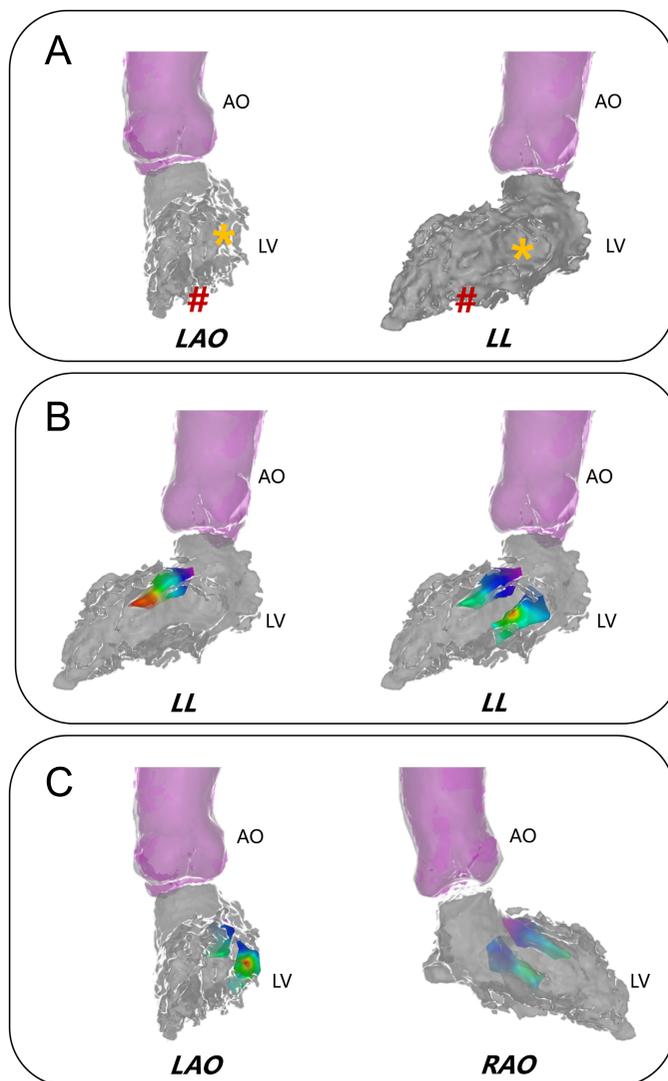

Figure 4. Ablation of papillary muscle ventricular arrhythmia after extra-cavity registration only. This was a case of premature ventricular contraction originating from lateral head of anterior PM. After extra-cavity registration via the aortic root, the LV anatomy of CT image was activated and moved into real space, and the PMs were exhibited as cavern structure in Figure 4A (asterisk, anterior PM; pound, posterior PM). Further mapping was performed on the medial and lateral bundles of anterior PM. The origin of premature ventricular contraction was localized at the middle part of lateral head (Figure 4B and 4C). AO, aortic root; LAO, left anterior oblique; LL, left lateral; LV, left ventricle; RAO, right anterior oblique.

adequately defining the landmarks, which is relatively objective, lacking golden standards. Prior studies indicated that reconstructed maps and landmark definitions are important impactors on the accuracy of image integration.

So far, image integration has mainly been used for atrial fibrillation ablation and showed a tendency to improve success and reduce ionizing radiation.[5,7,10] However, it is seldom reported for LV mapping and ablation.[11,12] Unlike the left atrium, LV exhibits more complex anatomy such as tendons,

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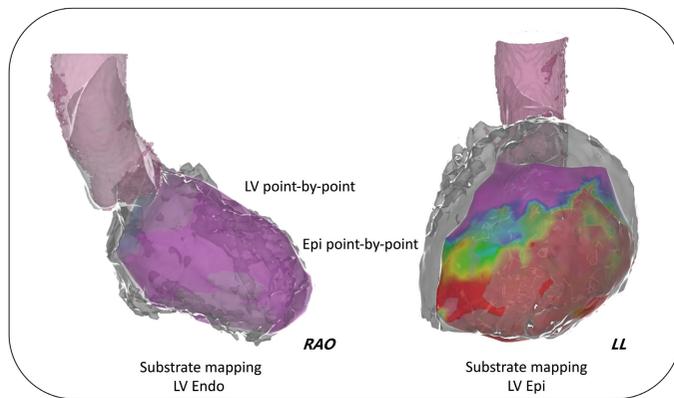
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Figure 5. Ablation of pathological ventricular tachycardia after extra-cavity registration only. This was a case of arrhythmogenic cardiomyopathy. After extra-cavity registration via the aortic root, the LV anatomy of CT image was activated and moved into real space. The voltage point-by-point mapping was initially performed at the LV endocardial side (left panel). No significant low voltage area was observed. Epicardial voltage mapping showed there was a large low-voltage area (right panel). Substrate modification ablation was targeted to the border zone. Of note, the 2 epicardial and endocardial LV CT map were derived from CT imaging separately, and both were well aligned with manually created maps. Endo, endocardial; Epi, epicardial; LL, left lateral; RAO, right anterior oblique.

PMs or muscular pectinate. When mapping catheter roving around, bumping-induced contraction tends to create a false space. Meanwhile, LV itself lacks the featured landmarks such as pulmonary vein ostia like the left atrium has, making it hard to select the corresponding positions for registration.

Extra-Cavity Left Ventricular Registration by Aortic Root

Usually, registration was performed via the paired positions of 3D map and 3D image of interest, and seldom performed via extra-cavity structures.[7,13,14] One study has used the descending aorta as one of the internal fiducial structures to guide left atrium image integration and yielded good accuracy.[15] Another study reported MR integration by using the left coronary artery as anatomical landmark for LV registration, but it showed a location error of 6.58 ± 1.63 mm.[16] However, the descending aorta is far from the heart and inconsistency exists in terms of pulsation and respiratory motions. And placing the mapping catheter within left coronary artery is not always safe. Meanwhile, both studies used the maps created manually by mapping catheters to evaluate the registration accuracy, which itself has inherent limitations.

On the other hand, the aortic root is a centrally located structure fixed in cardiac fibrous skeleton with featured landmarks and moves consistently with the heart motions. Its smooth endocardial surface seldom causes unintentional bumping and contraction when the catheter roves around. Thus, reconstruction of the aortic root is relatively easy to perform. Although aortic root is the extension of LV, as an extra-cavity structure, whether it can be used for LV registration has never been investigated.

In the current study, the aortic root was used for extra-cavity registration, LV anatomy was obtained and set in the real-time 3D space without positioning the catheter within LV chamber. Meanwhile, 3D map created by ICE was used for accuracy verification. Compared with catheter-based LV reconstruction, ICE provides non-contact, real-time LV reconstruction, and it provides a better caliber for verifying the location errors. The current study found that imported CT images by the extra-cavity registration method were consistent with the ICE-created map, and the anatomic deviation was minimal. Location error was more significant regarding LV summit (3.1±1.1 mm) than other regions (LV apex: 1.8±0.7; LV free wall: 1.8±0.9 mm) possibly due to inherent limitation of ICE catheter for inadequate tracing LV summit region. The accuracy of this registration was further verified by well alignment of PMs created by ICE with the anatomy of CT blood pool. Although the movement of PM is significant during each cardiac cycle and tends to distort the accuracy of the raw CT image. However, those location errors pose a minimal impact on the whole anatomy. This is corroborated by successfully mapping and ablation in the feasibility group, in which LV mapping and ablation were successfully carried out without needing additional reconstructions.

Clinical Implications

Though ICE catheter has been widely used in the ablation of idiopathic and non-idiopathic LV arrhythmia, they cost more resources. It is time-intensive to adjust the axial direction of ICE catheter to appropriately display the region of interest. It might take a longer time to reconstruct intracavity structures, like LV PMs, by ICE. Compared with ICE, obtaining an LV map via this extra-cavity registration is simple and time-saving. Based on our observation, the CT imaging reconstruction plus registration duration was less than 10 minutes. Our results also indicated this registration method was suitable for various types of arrhythmias in different sites of LV chamber, including the septum, PMs, and even epicardium. More importantly, extra-cavity registration shows a possibility of importing cardiac images into real-time 3D space via the landmarks outside of the chamber of interest, and this opens a new way for 3D reconstruction non-invasively. Theoretically, the extra-cavity landmarks could be anywhere only if they exhibit a fixed anatomic relationship with heart, compatible with respiratory movements. The assumption merits further study for related software and hardware development.

Study Limitations

This study has several limitations. First, anatomic deviation due to cardiac pulsation and respiratory motions cannot be completely avoided during obtaining CT image and 3D maps. However, this is the inherent limitation of 3D cardiac reconstruction, was minimized by same respiratory and ECG-gated image acquisition. Secondly, this registration method was suitable for mapping during sinus rhythm or premature ventricular contractions because the CT images were obtained during sinus rhythm, while mapping during VT is still a challenge.

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CONCLUSION

LV image registration could be achieved by using extra-cavity structures such as aortic with acceptable location errors.

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