Anatomy-based characteristics of far-field SVC electrograms in right superior pulmonary veins after isolation

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ABSTRACT

Background. Far-field electrograms from superior vena cava (SVC) can be present in right superior pulmonary vein (RSPV) after pulmonary vein (PV) isolation. Objectives. To analyze the characteristics of far-field SVC potentials in RSPV after PV isolation and the local anatomy difference between patients with and without the potentials. Methods. Patients undergoing PV isolation were retrospectively reviewed, contrast-enhanced computed tomography (CT) was performed before procedure for observing the anatomical relationship between RSPV and SVC. The prevalence and characteristics of far-field SVC electrograms were described and compared to far-field left atrial potentials at the nearest point along the linear ablation lesion. The anatomical proximity of RSPV and SVC on a 2-dimensional horizontal CT view was compared between patients with and without far-field SVC potentials. Results. Far-field SVC electrograms were observed in 35/92 (38%) patients with an amplitude of 0.24 ± 0.11 mV and a major deflection slope of 0.051 ± 0.036 mV, both significantly higher than far-field left atrial electrograms (p < .001). In patients with far-field SVC electrograms, 83% had connected RSPV-SVC, defined as distance between RSPV and SVC endocardium less than 3 mm at the layer of RSPV ostium roof, while in patients without far-field SVC electrograms, 70% had disconnected RSPV-SVC. Conclusions. Far-field SVC electrograms appeared in RSPV with a prevalence higher than previously reported and a sharper major deflection compared to far-field left atrial electrograms. Connected RSPV-SVC on CT was associated with the presence of far-field SVC electrograms.

Introduction

It is universally agreed that complete pulmonary vein (PV) isolation is the cornerstone of catheter ablation in patients with atrial fibrillation (AF) [1,2]. Careful evaluation of PV isolation, including differentiating near-field from far-field electrograms originating from adjacent extra-PV structures by using mapping and pacing maneuvers, can help avoid futile ablation [3,4]. Superior vena cava (SVC) is one of the contributing sources of far-field signals appearing commonly in anterior aspects of right superior pulmonary veins (RSPVs) for their close anatomical relationship [5–7]. According to an early study, SVC potentials, recorded with circular mapping catheter with the help of venography, appeared in RSPVs in 23% patients during sinus rhythm right after successful PV isolation [8]. However, the anatomical difference accounted for the presence or absence of SVC potentials has not been clearly described. Currently, PV isolation is routinely performed with the assistance of a high-density 3-dimensional (3 D) mapping system, and computed tomography (CT) scan is widely used as pre-procedural guidance for understanding the procedural-related anatomy. In this study, we analyzed the detailed characteristics of far-field-SVC potentials in RSPV after PV isolation using 3D mapping system and studied the relationship between the CT-based local anatomy and the presence of far-field-SVC electrograms.

Methods

Study population

Consecutive patients with AF referred to our center undergoing PV isolation for initial catheter ablation of AF from January 2019 to September 2020 were retrospectively reviewed. Exclusion criteria included: (1) Patients with a history of previous ablation in the left atrium (LA); (2) Unsatisfactory image quality of preprocedural CT scan; (3) Lack of remapping after PV isolation, or insufficient points (<1.0/cm²) acquired in the region of RSPV [9]; (4) Unsuccessful PV isolation. All patients...
provided written informed consent. The study was approved by the institutional review board of Huashan Hospital Fudan University (Number of approval: KY2019-552).

Preprocedural data collection

Patients' clinical records involving basic information, diagnosis, co-morbidity, CHA2DS2-VASc score, laboratory tests results were retrieved from hospital information system. All patients underwent transthoracic echocardiography for evaluating cardiac function and atrial size. Transesophageal echocardiography was performed in patients without contraindication to exclude LA thrombi before procedures. Contrast-enhanced CT scan was performed for the assessment of local anatomical characteristics in the vicinity of RSPV-SVC. A 2-dimensional (2D) horizontal view was mainly used for observation. Based on the previous echocardiographic study on PV structure [10], subjects were defined as having "connected RSPV-SVC" if the shortest distance between RSPV antrum and SVC endocardium was less than 3 mm in the layer of RSPV ostium roof. When minimal distance was over 3 mm, subjects were classified as "disconnected RSPV-SVC."

Mapping and PV isolation

Patients were anticoagulated with either novel oral anticoagulant or vitamin K antagonist for at least 3 weeks. Intracardiac electrograms were recorded (filtered 30–500 Hz for bipolar signals) using LabSystem Pro electrophysiology system (Boston Scientific, Boston, MA, USA) or Lead electrophysiology system (Jinjiang Electronic, Chengdu, Sichuan province, China). PV isolation was performed in all patients by using CARTO3 mapping system (Biosense Webster Inc, Irvine, CA, USA). The procedures were performed under conscious sedation, with either fentanyl or morphine for analgesia. A 5-French decapolar catheter (Biosense Webster Inc, Irvine, CA, USA) was introduced into the coronary sinus via the right internal jugular vein. When intracardiac echocardiography (ICE) was used, a 10-French ICE catheter (CARTOSOUND, Biosense Webster Inc, Irvine, CA, USA) was advanced into right atrium through left femoral vein. Two 8.5-French long sheaths (SL1, St. Jude Medical, Inc., St. Paul, MN) were advanced to the LA after double transseptal puncture guided by fluoroscopy or ICE. Intravenous heparin was given for achieving the target activated clotting time between 300 and 400 s. Thereafter, 3D map of the LA was constructed using a multi-spline duodecapolar mapping catheter (PentaRay™ with 2–6–2 mm electrode spacing, Biosense Webster Inc., Irvine, CA, USA).

An 8-French irrigated-tip radiofrequency (RF) ablation catheter (SmartTouchSF™, Biosense Webster Inc, Irvine, CA, USA) was used for circumferential PV isolation. The ablation line was designed for antral PV isolation approximately 1 centimeter (5–15 mm) away from the PV ostium based on 3D shell. RF energy was delivered for 20–30 s at each point, with power of 30–40 watts, an upper-limit temperature of 43 °C, and a saline irrigation rate of 8 mL/min. VisiTag™ module was able to automatically display ablation tags with different color according to force-over-time and catheter stability. The endpoint of PV isolation was the absence of PV potentials during sinus rhythm and CS pacing, plus failure to activate the LA during PV pacing.

Remapping and analysis of far-field potentials

When both ablation lines were completed, a voltage map including LA and PVs was created with PentaRay catheter if patients were in sinus rhythm (voltage color bar range: 0.1–0.5 mV). If patients were in AF rhythm after PV isolation (e.g. persistent AF), linear ablation was performed at the discretion of operators, and electrical cardioversion was thereafter given if patients remained in AF, followed by remapping. When residual potentials were present within the ablation circuit, it was necessary to differentiate incomplete PV isolation from far-field sensing of extra-PV origin. The origins of SVC were confirmed by (1) Potential recorded at anterior RSPV had a timing identical to that recorded at posterior SVC; (2) When pacing inside SVC using the ablation catheter adjacent to RSPV electrode, electrograms on PentaRay catheter was obscured in the pacing artifact (Figure 1). Far-field capture of RSPV was excluded by progressively decreasing stimulation amplitude to threshold and documenting simultaneous loss of capture on both the SVC and the RSPV catheters.

In anterior aspects of RSPV, at least 5 mm distal to ablation line, the points showing maximal bipolar far-field-SVC electrograms with amplitude ≥0.1 mV were recorded and taken into analysis. Patients with and without far-field-SVC electrograms matching the above criteria were divided into group 1 and group 2, respectively. Baseline clinical data were compared between two groups.

EGMs were measured by two electrophysiologists (N.X and W.G) using the CARTO3 mapping system. For each EGM, two measurements of timing and amplitude were performed by the two electrophysiologists, respectively. The average values were used as the results for analysis. In group 1, the amplitude, slope of major deflection, local activation time (LAT) in comparison to P wave onset of every patient were measured. Meanwhile, far-field LA potentials presenting along the circular lesion line at the nearest location to each corresponding far-field-SVC potential were also recorded as control potentials (Figure 2). Their above-mentioned characteristics were also analyzed and compared to the far-field-SVC electrograms.

Follow-up

Patients were discharged on anticoagulation ≥8 weeks after ablation observed in outpatient clinical at the 4th, 8th and 12th week after discharge and every 3 months thereafter. Extra visits were required in symptomatic patients. Holter recording was performed in all patients on the 3rd and the 6th month. Recurrence was defined as any documented
episode of AF persisting >30 s after a blanking period of 3 months.

Statistics
Clinical variables were expressed as a percentage (%) for categorical variables, mean with standard deviation (SD) for continuous variables and median with interquartile rate (IQR) for discontinuous variables. Characteristics between group 1 and group 2 were tested using the unpaired Student \( t \)-test for continuous variables and chi-square test or Fisher’s exact for categorical variables. In group 1, characteristics between far-field-SVC and far-field-LA electrograms were compared using paired Student \( t \)-test. Then the relationship between the presence of far-field-SVC electrograms and the RSPV-SVC anatomy were analyzed using chi-square test. A two-tailed \( p \)-value of < .05 indicated statistical significance. Statistical analysis was performed using SPSS 19.0 statistical software.

Results
Baseline and procedure data
From January 2019 to September 2020, 92 patients undergoing PV isolation matching the above criteria were analyzed, 59 of which had paroxysmal AF and 33 had persistent AF. The median age of the whole cohort was 58.1 years old, and 23 (25%) patients were female. TEE was performed in 74/92 patients.
The connected RSPV-SVC was associated with the presence of far-field-SVC electrograms ($p < .001$)

**Follow-up**

The overall success rate was 76.1% at a 6-month follow-up. Statistical difference was not shown between group 1 and group 2 ($p = 0.804$).

**Discussion**

**Major findings**

The major findings of this retrospective study on far-field-SVC potential in RSPV based on 3D mapping system include:

1. Far-field potentials >0.1 mV originating from SVC could be demonstrated in 38% patients, which shows a higher prevalence than previously reported.
2. Those far-field-SVC potentials had steeper slope of major deflection than control far-field potentials along linear lesion, with similar timing and duration.
3. Connected RSPV-SVC was associated with the presence of far-field-SVC electrograms in RSPV.

**The value of discriminating far-field from near-field electrograms**

The posterior aspect of SVC lies adjacent to RSPV along the interatrial groove [7]. It is thus possible to record the electrical activities of myocardial sleeves of SVC when a catheter is placed at the anterior wall of RSPV, which masquerades incomplete PV isolation. To electrophysiologists, it is of great value to discriminate far-field from near-field signals in order to avoid excessive ablation. Measuring LAT and pacing SVC is the golden standard for confirming its origin [8,11,12]. But pacing SVC requires placing an extra catheter or retracting a catheter to right atrium, which potentially costs extra procedural time.

**The prevalence, characteristics and prediction of far-field-SVC electrograms**

Previous study showed only a minority of patients (23%) to have far-field-SVC potentials in RSPV [8]. The prevalence in our study was higher, even after exclusion of those patients presenting low voltage (<0.1 mV) electrograms. This was presumably caused by the difference of mapping approach. A multi-spline catheter was more flexible than a circular catheter and can be easily advanced and withdrawn on a 3D map to different positions in RSPV, while circular catheters were almost invariably placed within 5 mm from venography-confirmed PV ostium in the previous study. The contact site of two structures can vary among individuals, which indicates the possibilities to find far-field-SVC electrograms all along from ostium to distal RSPV [13]. Thus, the application of PentaRay catheter with 3D

| Table 1. Baseline characteristics in group 1 and group 2. |
|-----------------------------------------------------------|
| Group 1 (n = 35) | Group 2 (n = 57) | Value |
| Gender (female, %) | 20 | 28.1 | .462 |
| Age (years) | 56.7 ± 11.5 | 59.0 ± 11.6 | .671 |
| Height (cm) | 168.6 ± 7.2 | 168.1 ± 8.6 | .355 |
| Body weight (kg) | 72.1 ± 14.9 | 71.1 ± 10.0 | .512 |
| Paroxysmal AF (%) | 71.4 | 59.6 | .273 |
| DM (%) | 11.4 | 7.0 | .474 |
| HTN (%) | 34.3 | 17.5 | .555 |
| Stroke (%) | 8.6 | 7.0 | .999 |
| CKD (%) | 8.6 | 1.8 | .152 |
| CHA2DS2VASc score | 1.6 ± 1.3 | 1.3 ± 1.1 | .315 |
| RSPV-SVC (mm) | 38.7 ± 3.7 | 39.7 ± 5.5 | .384 |
| LVEF (%) | 66.5 ± 4.4 | 65.8 ± 5.3 | .531 |

AF: Atrial fibrillation; CKD: chronic kidney diseases; DM: diabetes mellitus; HTN: hypertension; LAD: left atrial diameter; LVEF: left ventricular ejection fraction; NT-proBNP: N-terminal prohormone of brain natriuretic peptide.

All PVs were proven successfully isolated at the end of procedures. First pass isolation after circular ablation of RPVs was completed in 78/92 (85%) patients. Nine patients had residual PV potential due to confirmed epicardial connection requiring RF directly at the insertion sites. The remaining five patients had incomplete PVI due to gap on the circle (including during a waiting period of 30 min).

In the whole population, far-field-SVC electrograms in RSPV were present in 35 (38%) patients (group 1), of which 25 patients had paroxysmal AF. In the remaining 57 patients without far-field-SVC potential (group 2), of which 34 patients had paroxysmal AF. The baseline characteristics including AF type, gender, CHA2DS2VASc score, etc. did not show a difference between the two groups (Table 1).

**Characteristics of far-field electrograms**

In each patient in group 1, the site where maximal far-field-SVC potential presented was tagged on the 3D map (Figure 2). Potential characteristics between far-field-SVC and far-field-LA were compared. The points showing maximal far-field-SVC electrograms were located 10.6 ± 3.2 mm distal from ablation line. Compared with their corresponding far-field-LA potentials along the circuit at the same area, they have distinctly higher amplitude [0.24 ± 0.11 mV (range 0.1–0.28 mV)] and the LAT [23.3 ± 13.6 ms] and steeper slope of major deflection than control far-field potentials along linear lesion, with similar timing and duration.

**Different CT anatomy in patients with and without far-field-SVC electrograms**

Different RSPV-SVC anatomical relationship were shown by image from CT, including connected and disconnected RSPV-SVC (Figure 3). Connected RSPV-SVC could be observed from horizontal views of CT images in 83% (29/35) patients in group 1 but only 30% (17/57) in group 2.
mapping system can increase the probabilities of finding these potentials.

The far-field-SVC electrograms had a steeper mean slope in comparison to far-field-LA potentials. This could be explained by that far-field-LA electrogram was present at a site ablated by RF, which usually created a transmural necrotic lesion of approximately 4 mm in diameter [14,15]. The far-field-LA electrogram actually reflected the activation of relatively distant myocardium when the electrode pair was placed at the PV side of linear lesion. In contrast, there is only thin pericardial tissue in the interatrial groove between epicardium of SVC and RSPV [7]. This could also be validated by the real-time ICE image which directly combined the anatomy and electrograms (Figure 4; Supplementary material 1). Far-field-SVC electrograms also had a higher mean amplitude than far-field-LA, but selection bias existed as low voltage far-field-SVC potentials were excluded.

The previous study provided a method of identifying far-field-SVC electrograms by measuring LAT, with high predictive value [8]. This can sometimes be limited if an electrogram is found close to the ablation line, which can be either far-field-LA, far-field-SVC, or incomplete PV isolation. In our study, far-field-LA potentials were not significantly later than far-field-SVC, presumably due to the rapid conduction of Bachmann bundle [16–18], indicating that one cannot distinguish between different sources of far-field potentials solely by LAT if they are close to the RSPV ostium. Moreover, P waves can be very small in amplitude in diseased atria [19]. And in persistent AF, LAT measurement is unavailable before cardioversion, which is often performed after linear ablation in LA. CT image regarding local anatomy can be another consideration for speculating the presence and absence of the electrograms.

Different anatomy in the region of RSPV-SVC influencing far-field potentials

The close distance between RSPV and SVC is the major reason for the presence of far-field-SVC electrograms [5,20]. Myocardial electrical activation continuously conducted by the muscle sleeves extended up into SVC may generate enough high amplitude to be recorded within RSPV [21]. However, subtle variation in their anatomical relationship could exist among different individuals, from tightly connected to dissociated RSPV-SVC, which potentially influenced the presence and characteristics of far-field-SVC potentials. We used the standard of <3 mm from SVC to RSPV endocardium as the criteria for connected structures based on a recent ICE study showing that the mean thickness of anterior RSPV wall was 2.7 mm [10].

Relationship between the presence of far-field-electrograms and RSPV-SVC anatomy

In our study, connected RSPV-SVC was associated with the presence of far-field-SVC electrograms. When a tightly connected RSPV-SVC was observed on CT view before procedure, it would not be surprising to see a prominent far-field potential inside RSPV even after successful isolation. If far-field-SVC electrograms were highly suspected, pacing maneuver was encouraged for avoiding unnecessary mapping and ablation. However, the local anatomical proximity of

Figure 3. The relationship between different RSPV-SVC anatomy and presence of far-field-SVC electrograms. (A,B) A case presenting far-field-SVC electrogram (amplitude 0.24 mV, slope 0.12 mV/ms) at the yellow tag on 3D map (A) showed connected RSPV-SVC on CT at the layer of RSPV ostium (B). (C,D) A patient without far-field-SVC electrograms, RSPV was more distant from SVC at the layer of PV ostial level (D). AO: Aorta; electrogram: electrogram; RA: right atrium; RSPV: right superior pulmonary vein; SVC: superior vena cava.
the structures was not decisive, and there may be other factors influencing far-field electrograms, including the mapping catheter contact, overall atrial voltage, and the height of the SVC myocardial sleeve end [12,22,23].

Limitations

This was a retrospective study. 3-D reconstruction of atria was not routinely performed in CT scan. And right atrium shell was not routinely created in every patient. The settings of minimal electrogram amplitude and criteria for connected RSPV-SVC were partly arbitrary.

Conclusions

Far-field-SVC electrograms were observed in RSPV in 38% patients after successful PV isolation, which had sharper major deflection than far-field LA potentials. The presence of far-field-SVC electrograms was associated with connected RSPV-SVC on CT scan.

Disclosure statement

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