Incidence, location, and cause of recovery of electrical connections between the pulmonary veins and the left atrium after pulmonary vein isolation

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Aims The aim of this study was to reveal the incidence, location, and cause of recovery of the electrical connections (ECs) between the left atrium and the pulmonary veins (PVs) after the segmental ostial PV isolation (PVI).

Methods and results Pulmonary vein mapping and successful PVI were performed using a computerized three-dimensional mapping system (QMS2TM) with a basket catheter in 167 PVs in 53 consecutive patients with atrial fibrillation (AF). In 14 patients with recurrent AF after PVI, the same PV mapping and isolation as in the first procedure were performed, and the PV potential maps constructed by QMS2 in two different procedures were compared. Forty-nine recovered ECs were observed in 27 PVs, and all were eliminated by a few local radiofrequency (RF) applications. Thirty-four (69%) of those ECs recovered at the edge of original ECs, and another 15 (31%) recovered at the mid-portion of continuous broad original ECs.

Conclusion Electrical connection recovery occurred most commonly at the edges of original ECs and occasionally at the mid-portion of continuous broad original ECs after PVI probably due to tissue oedema neighbouring the segmental RF lesions. Further RF lesions at the edge of original ECs and linear ablation to the continuous broad ECs may help reduce AF recurrence.

KEYWORDS Atrial fibrillation; Pulmonary veins; Multielectrode basket catheter; Three-dimensional potential mapping; Radiofrequency catheter ablation

Introduction The pulmonary veins (PVs) have been demonstrated to be the major source of atrial premature beats triggering paroxysmal atrial fibrillation (AF).1,2 Segmental ostial catheter ablation (SOCA) to electrically isolate the PVs from the left atrium has been proposed as an effective technique to cure paroxysmal AF.3,4 However, in SOCA, frequent recovery of the electrical connections (ECs) between the left atrium and the PVs has become the main cause of AF recurrence.3–7 Therefore, if the cause of the EC recovery between the left atrium and the PVs is elucidated and the EC recovery can be prevented, SOCA may be the most effective strategy. The aim of this study is to reveal the incidence, location, and cause of the EC recovery after SOCA and to investigate whether the EC recovery could be prevented.

Methods Patient characteristics The study population consisted of 53 consecutive patients (46 men, 58 ± 12 years) with symptomatic paroxysmal AF refractory to 4 ± 1 class I or class III anti-arrhythmic drugs. The mean AF history was 4 ± 4 years (1–13). The mean left atrial dimension was 37 ± 5 mm (25–46), and mean left ventricular ejection fraction was 66 ± 9% (56–89). No patient had any structural heart disease and three had emboli. Each patient gave informed consent, and all anti-arrhythmic drugs were discontinued for at least five half-lives prior to the study.

Electrophysiological study A 7-French decapolar catheter with 1.5-1 mm interelectrode spacing between each electrode pair (St Jude Medical, Daig Division, Minnetonka, MN, USA) was introduced into the coronary sinus via the subclavian vein. The transseptal procedure was performed with intracardiac echocardiography guidance recorded.
with a 9-French transducer catheter (Boston Scientific, Natick, MA, USA) operating at 9 MHz. Catheterization into the left atrium was performed with a one-puncture and two-sheath technique (one sheath (8-French, St Jude Medical, Daig Division) for an ablation catheter and another (8.5-French, Soft Tip EP Sheath™, EP Technologies, Boston Scientific Corporation, San José, CA, USA) for a mapping catheter). Intravenous heparin was administered to maintain an activated clotting time of >250 s after the atrial transseptal procedure. The diameters of all four PVs were determined by biplane selective angiography in all cases.

**PV mapping and SOCA with a multielectrode basket catheter**

In all cases, PV mapping and SOCA were performed by the same technique, as previously reported.8 The left superior PV (LSPV), left inferior PV (LIPV), right superior PV (RSPV), and right inferior PV (RIPV) were all targeted for this PV isolation (PVI) technique, according to the evidence reported in the previous studies.2,4 However, when the RIPV was difficult to cannulate with a multielectrode basket catheter (MBC), it was isolated with a ring catheter as previously reported.3,4 A 31 mm MBC (Constellation™, EP Technologies), which consisted of eight splines (A–H) with eight 1 mm electrodes with 2 mm spacing, was deployed within the target PV coaxially to its long axis and with its most proximal electrodes positioned at the PV ostium. The location of the MBC splines was determined by the biplane fluoroscopy on the basis of the position of splines A and B, which could be identified by their radiopaque markers. QMS2™ is a computerized three-dimensional mapping system, which can construct a three-dimensional colour map from a total of 56 bipolar electrograms recorded by an MBC.10 The QMS2 was connected to an MBC via an amplifier. The electrical signals were filtered from 30 to 200 Hz. QMS recordings were obtained during sinus rhythm (right PVs) or distal coronary sinus pacing (left PVs). The time phase of interest was set as the time interval between the earliest atrial potentials and the latest PV potentials during one beat. The temporal resolution of the QMS analysis could be arranged from one-eighth to one-64th of the given time phase (one-32nd or one-64th was most commonly used). The electrical activity in the space between the splines was estimated by a bicubic spline interpolation to construct a continuous map. An animation of a three-dimensional potential map, which could reflect a series of electrical activations, was used to reveal the style of EC, distribution of the PV musculature, and activation pattern within the PV. A colour setup with a gradation which corresponded to the relative size of the potential amplitude could be arranged variously on the QMS map. In the present study, it was essential to minimize the low-amplitude left atrial potentials and to emphasize the high-amplitude PV potentials for constructing a clear three-dimensional map of the PV potentials. In principle, the colour setup was arranged to assign colours consisting of dark green, yellow, and red to the potentials with amplitudes larger than half of the largest amplitude of all the related potentials (colour threshold). When the small potentials needed to be emphasized, the colour threshold was decreased to 30% of the largest amplitude of all the related potentials.

The short stay of the activation wavefront near the outer frame of the three-dimensional PV potential map before the longitudinal propagation, which reflected a conduction delay, was defined as indicating the left atrial-PV junction where continuous fractionated potentials connecting the left atrial potentials and PV potentials were observed. The serial activation patterns moving around the outer frame of the three-dimensional PV potential map before the longitudinal propagation were defined as indicating the left atrial-PV junction. The onset of a centrifugal activation at the left atrial-PV junction was identified as a prior EC.

In the SOCA procedure, a radiofrequency (RF) application was delivered to the preferential EC identified by the three-dimensional PV potential map with the guidance of a navigation system (Astronomer™) associated with the MBC. Radiofrequency energy was delivered with a target temperature of 55°C and maximum power output of 30 W for 60 s (EPT-1000TC generator, EP Technologies), using an 8 mm tip catheter (Blazer II 5770T, EP Technologies). The QMS recording was performed after every RF application, and if the elimination of a target EC was confirmed, another EC was identified and ablated. Successful SOCA was defined as either the abolition or the dissociation of the distal PV potentials.

**Follow-up and re-ablation**

During the follow-up period, no anti-arrhythmic drugs were administered in any of the patients. Clinical follow-up was performed at 2 weeks, 1 month, and every month thereafter, using 24 h-Holter and cardiac recordings, and enhanced electron beam tomography for the detection of PV stenosis in all patients.

In the patients who underwent a second session because of AF recurrence after the first SOCA procedure, the same PV mapping and SOCA as in the first session were performed. All splines of the MBC were attempted to be deployed to the same sites within the target PVs as in the first session using biplane fluoroscopic guidance and contrast medium.

**Identification of the EC between the left atrium and the PVs, distribution of the PV musculature, and EC recovery**

The style of the EC and PV musculature was finally determined after the effect of the RF applications was evaluated by the QMS mapping. In the PVs with EC recoveries after SOCA, both three-dimensional PV potential maps obtained in two separate sessions were compared to identify the location of the EC.

**Analysis of the predictor of the EC recovery after SOCA**

In the patients who underwent a second session, the factor that could be the predictor of an EC recovery was investigated.

**Statistical analysis**

Continuous variables are expressed as the group mean ±1 SD. Comparisons of continuous variables were analysed with the use of the Student’s t-test or ANOVA. The χ² test was used to compare non-parametric data in different groups. The multivariate logistic regression analysis was performed to determine the independent predictors of the EC recovery. Statistical significance was selected at a value of P < 0.05.

**Results**

**QMS mapping and SOCA**

QMS mapping with an MBC was performed in 53 LSPVs, 53 RSPVs, 46 LIPVs, and 30 RIPVs in the 53 patients. Seven left PVs with a common trunk in which an MBC could be positioned appropriately were included in the group of LSPVs. The deployment of the MBC was impossible in 23 RIPVs, because of their small ostia or complex branching patterns. The mean ostial diameter was 21 ± 2, 20 ± 2, 19 ± 3, and 18 ± 4 mm in the LSPVs, RSPVs, LIPVs, and RIPVs, respectively. The mean ostial diameter of the LSPVs was significantly larger than that of the RSPVs (P < 0.05), LIPVs (P < 0.005), or RIPVs (P < 0.0001), and that of the RSPVs (P < 0.0001) and LIPVs (P < 0.0005) was significantly larger than that of the RIPVs.

In all the PVs in which the QMS mapping was available, successful SOCA could be achieved. The incidence of a
continuous broad (>50% circumference) EC was significantly higher in the LSPVs (51%, \(P < 0.005\)) and RSPVs (42%, \(P < 0.05\)) than in the LIPVs (22%). No significant differences for those were observed between the RIPVs (40%) and the three other PVs. In 23 RIPVs in which QMS mapping was not available, successful SOCA was achieved with a ring catheter. The averages of the total procedure time and fluoro time were 201 ± 82 and 94 ± 36 min, respectively. The RF delivery duration needed to complete the PVI was 4 min in the LIPVs, 4 min in the RIPVs, and 4 ± 3 min in the RSPVs. The total RF energy was 12 610 ± 11 510 J in the LSPVs, 10 660 ± 9690 J in the RSPVs, 6670 ± 3830 J in the LIPVs, and 5570 ± 3640 J in the RIPVs.

**Follow-up and repeat procedures**

During the follow-up period (263 ± 108 days), 26 (49%) patients were free of asymptomatic AF without any anti-arrhythmic drugs after the first procedure. Five (9%) of the 27 (51%) patients were free of symptomatic AF with one anti-arrhythmic drug that failed to control the AF before the procedures. Three of the former patients and two of the latter patients had asymptomatic AF recurrence probably because the AF was limited to a short duration of <5 s.

Another 22 (42%) patients still had symptomatic recurrent AF with the administration of anti-arrhythmic drugs, although both the frequency and the duration of the AF attacks had decreased. Fourteen patients with recurrent AF, 11 of whom still had drug-refractory symptomatic AF, gave informed consent and underwent a repeat electrophysiological study and catheter ablation.

**QMS mapping and SOCA in the repeat procedures**

Repeat procedures were performed at a mean of 155 ± 98 days after the first session. In the repeat procedure, QMS mapping with an MBC was performed in all of 46 PVs (14 LSPVs, 14 RSPVs, 10 LIPVs, and 8 RIPVs), in which successful SOCA with the guidance of QMS mapping was achieved in the first session. In each of the 14 patients who underwent repeat procedures, an EC recovery was observed in at least one PV. In 27 (60%) of those 46 PVs [9 (64%) LSPVs, 9 (64%) RSPVs, 5 (50%) LIPVs, and 4 (50%) RIPVs] and 3 (50%) of 6 RIPVs, in which successful SOCA with the guidance of a ring catheter was achieved in the first session, an EC recovery was observed. In those 30 PVs, a total of 54 (20 in the LSPVs, 15 in the RSPVs, 7 in the LIPVs, and 12 in the RIPVs) with successful SOCA with a ring catheter] localized EC recoveries were observed. The EC recoveries were located in the superior wall of four (20%) LSPVs, two (13%) RSPVs, one (4%) LIPV, and three (25%) RIPVs, in the inferior wall of seven (35%) LSPVs, seven (47%) RSPVs, two (29%) LIPVs, and four (33%) RIPVs, in the anterior wall of five (25%) LSPVs, three (20%) RSPVs, one (4%) LIPV, and one (8%) RIPV, and in the posterior wall of four (20%) LSPVs, three (20%) RSPVs, three (43%) LIPVs, and four (33%) RIPVs. Although the EC recoveries in the superior PVs tended to occur more frequently in the inferior wall, there were no significant differences in the occurrence of EC recoveries among the locations.

The previous RF lesions were recognized in the re-map of the repeat session as low-voltage areas around the left atrial-PV junction, along which the activation from the recurrent EC propagated throughout the PVs. The comparison of the original three-dimensional PV potential map from the first session with the re-map of the repeat session demonstrated that the distribution of the PV muscle-lature in all the re-maps was identical to that in the original maps and that the combination of the recurrent ECs and the previous RF lesions on the re-map corresponded to the original EC on the original map. From those findings in the PV potential maps and fluoroscopic images, the anatomical orientation of the original map could be completely correlated with the re-map. The comparison of the original map with the re-map revealed that out of 49 EC recoveries, 34 (69%) were at the edges of the segmental or continuous broad ECs (Figures 1A, B, and C and 2) and another 15 (31%) at the mid-portion of the continuous broad ECs (Figures 2 and 3). Electrical connection recoveries were observed only around the sites where the RF applications were delivered in the first session, and no EC recoveries of any PVs were observed in any other site away from the previous RF lesions.

**Re-ablation and follow-up**

In all 30 PVs with EC recoveries, the SOCA method was repeated again using the same technique as in the first session. Low-amplitude-delayed PV potentials were observed at the EC recovery sites identified by the QMS mapping (Figure 4). All of those EC recoveries could be eliminated by a local RF application (1 ± 1 min, 1820 ± 1330 J) without any catheter instability and resulted in successful SOCA of all PVs. All of the 14 patients, who underwent the re-ablation, were free of symptomatic AF without any anti-arrhythmic drugs during the follow-up period (235 ± 49 days) after the repeat session.

**PVs with and without an EC recovery**

The characteristics of the PVs with and without EC recoveries are shown in Table 1. Pulmonary veins with an EC recovery had a greater ostial diameter (\(P = 0.03\)) and needed more RF energy for the completion of the SOCA (\(P = 0.04\)).

**Predictors of an EC recovery**

The multivariate analysis between the 27 PVs with EC recoveries and the 19 PVs without EC recoveries after SOCA using QMS mapping revealed that an increase in the RF energy needed to complete the SOCA was the only predictor of EC recovery (Table 2). The left atrial dimension and left ventricular ejection fraction were excluded in this analysis, because some patients had both PVs with EC recoveries and those without EC recoveries.

**Complications**

Follow-up enhanced electron beam tomography revealed PV narrowing of between 25 and 50% in three PVs in three cases and ≤25% in seven PVs in five cases. No PV stenosis of ≥50% was found in any PV. The patients with PV narrowing were asymptomatic.

One patient developed a unilateral quadrantopsia after the procedure. No pericardial effusions occurred in any of the cases.
Discussion

In the SOCA, the fairly high occurrence of EC recoveries between the left atrium and the PVs has been recognized as the main cause of AF recurrence. The occurrence of EC recoveries after SOCA with an MBC in the present study was as high as that with a ring catheter. The cause of the EC recovery between the left atrium and the PVs

It is essential that formation of transmural RF lesions is needed to complete the PV electrical disconnection. The possibility of an EC recovery will be high where the musculature is thick, because it is difficult to achieve transmural RF lesions. This study showed that EC recoveries in the superior PVs tended to occur more frequently in the inferior wall. This might be because the PV musculature of the superior PVs was the thickest at the inferior walls, as shown by an anatomical study. Another possible explanation for that finding may be catheter instability. As the superior and inferior PVs often have a common antrum, negotiating the ridge between those PVs may make achieving catheter stability more challenging.

The present study revealed that by using a three-dimensional QMS potential map, the ECs were more likely to recover at the edge of the original ECs. It is known that tissue oedema is produced around the coagulation necrosis site in the myocardium where the RF energy was delivered. It has been shown that RF applications around the PVs produce local oedema. Therefore, the EC recovery at the edge of the original ECs may have been caused by

Figure 1: A three-dimensional potential map of the RSPV with the recovery of an EC at both edges of the continuous original EC after PVI. A bull's eye image was used for the style of the map, because the image could enable us to recognize the tubular structure of the PV. The grey round outer frame corresponds to the PV ostium and the centre of the image corresponds to the distal PV. The alphabetical letters from A to H indicate the splines of the basket catheter. The numbers indicate the time order. The schema shows the distribution of the PV musculature (pink area), which was identified by the three-dimensional potential map. The black arrow indicates the activation sequence within the PV. The blue area indicates the previous RF lesion. The time intervals between the map 1 and the four other maps are indicated on the right side of the map numbers. (A) A three-dimensional potential map before the first ablation. A continuous EC was identified from the inferior wall (spline A) to the superior wall (spline E). (B) A three-dimensional potential map before the re-ablation. The two activations entered into the RSPV through two recovered ECs at the superior wall (spline E) and antero-inferior wall (spline H), respectively. The activation from spline E seemed to propagate centrifugally throughout the PV along the previous RF lesions because another activation through the EC at spline H with very slow conduction could not collide with the activation from spline E. (C) A three-dimensional potential map after the elimination of the EC at the superior wall (spline E). After the elimination of the conduction through the EC at the superior wall (spline E), the activation through the EC at the antero-inferior wall (spline H) came in sight and propagated centrifugally throughout the PV along the previous RF lesions. A final local RF application at the antero-inferior wall (spline H) achieved a successful PVI.
this tissue oedema, which would mask the non-transmural RF lesions and enable the endpoint of the SOCA \(^1,4,8\) to be satisfied. If there are any segmentally separated ECs, this type of EC recovery between the left atrium and the PVs can occur more frequently.

The formation of continuous RF lesions would also be needed to complete the PV electrical disconnection. The present study revealed that by using a three-dimensional QMS potential map, EC recovery was also seen at the mid-portion of the continuous broad original ECs especially in the superior PVs, which had a larger PV diameter and higher incidence of continuous broad original ECs than the inferior PVs.

This type of EC recovery could be caused by the tissue oedema, which masked discontinuous RF lesions and enabled the endpoint of the SOCA \(^1,4,8\) to be satisfied. It is the greatest merit of SOCA that only segmental ostial ablation targeting preferential ECs can achieve PV electrical disconnection. However, consequently, it can be a limitation that SOCA may not always allow the completion of continuous RF lesions, which is unlike linear ablation.

In the SOCA, the only predictor of EC recovery was an increase in the RF energy needed to complete the SOCA. The reasons why more RF energy was needed to complete the SOCA could be due to the myocardial wall thickness, large extent of the EC, bad manipulation because of anatomical limitations, and some of those were combined in many cases. However, further investigation into those factors was impossible because they (other than the extent of the EC) could not be quantitatively evaluated.

**Clinical implication**

It has been reported that the completion of PV electrical disconnections by repeated SOCA can eliminate paroxysmal AF in spite of a high occurrence of EC recovery after the SOCA.\(^7\) Therefore, if a technique to prevent the EC recovery can be designed, the efficacy of the SOCA in paroxysmal AF will be expected to increase.

The EC recoveries due to tissue oedema may not be eliminated completely as long as the SOCA is based on an electrophysiological approach. However, EC recoveries may be prevented because EC recoveries are more likely to occur at certain particular sites, as shown by the present study. The suggestion of the present study is that additional RF deliveries at the edge of original ECs or between the ablation sites in continuous broad original ECs after successful SOCA may reduce the occurrence of EC recoveries. Further, if a continuous broad EC is identified in advance by QMS mapping, a linear ablation may have to be performed there. A prospective study will be needed to confirm this.

**Study limitations**

The spatial resolution of the QMS mapping system might be an inherent limitation in determining the style of EC. The resolution of circumferential mapping with an MBC with eight bipolar electrodes on each of the eight splines is one-eighth of the circumference. Two or more separate fascicles between splines may have been recognized as a continuous fascicle. We reported the clinical efficacy of QMS mapping in identifying the ECs occurring between the splines, although that ability might depend on the interpretation of the QMS map. Because RF energy was delivered using an 8 mm tip catheter, the higher spatial resolution of the mapping may not be practically important. We believe that the identification of the sites of EC recoveries in this study makes clinical sense, because the same resolution of the mapping technique as in the first session was used in the repeat procedure.

Electrical connection recoveries might not have been the sole cause of the AF recurrence after the SOCA in this study because provocative manoeuvres to identify any non-PV triggers were not routinely performed. The analysis performed in this study might not have been adequate for investigating the EC recoveries after SOCA because it was limited to AF recurrence cases alone (most of which might have been a random minority who still had drug-refractory symptomatic AF). However, the
EC recovery was the main cause of the AF recurrence after the SOCA in this study because at least in the cases with a repeat procedure, AF was eliminated only by a repeat SOCA. We believe that a complete PV electrical disconnection is the most important concern for suppressing AF recurrence after SOCA and thus this study is of clinical significance.

Conclusions

The present study revealed that EC recovery occurred most commonly at the edges of original ECs and occasionally at the mid-portions of continuous broad original ECs after PVI probably due to tissue oedema neighbouring the segmental RF lesions. Therefore, further RF lesions at the edge of the original ECs and linear ablation of the continuous broad ECs may help increase the efficacy of SOCA in paroxysmal AF.

References

