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Original Article

Pulmonary vein potential mapping in atrial fibrillation with high density and standard spiral (lasso) catheters: A comparative study

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ABSTRACT

Background: The dominant single-shot procedure for Pulmonary Vein Isolation (PVI) is the Cryoballoon Ablation (CBA) technique using a spiral catheter (Achieve™, AC) for mapping and monitoring purposes. We hypothesized that Basket Catheters, such as the High Density Mesh Mapper (HDMM), with its high-density mapping properties, could detect Pulmonary Vein Potentials (PVPs) that the octapolar AC would not be able to identify.

Methods: Twenty-four patients (average age 61.8 ± 10 years) with either paroxysmal or persistent atrial fibrillation (AF) (Paroxysmal AF or Persistent AF) were enrolled in the study. While the patients were in sinus rhythm, all pulmonary veins (PVs) were prospectively mapped both prior and subsequent to CBA with a 32-pole HDMM and an 8-pole AC. PVPs were recorded using both catheters, and their location was allocated to one of four PV quadrants. Then, the quadrant findings of the mapping catheters were compared.

Results: Mapping using the HDMM allowed for more precise identification of PVPs both before and after CBA compared to AC mapping. We identified an average of 83.6 ± 4.8 PVPs in all four PVs (this means 20.9 ± 10.5 PVPs /per single PV per patient [HDMM], 14.5 ± 1.3 PVPs/in all four PVs and 3.6 ± 2.7 PVPs /per single PV per patient [AC]) before ablation, thereby leading to a significant difference in the identification of PVPs per PV quadrant. Of 384 PV quadrants/24 patients analyzed, the HDMM identified PVPs in 279 and AC in only 192 quadrants ($P < 0.05$).

Conclusion: High-density mapping with a Basket Catheter, such as the HDMM, detects PVPs that remain undetected when using the standard AC catheter in CBA procedures.

1. Introduction

Atrial fibrillation (AF) is the most commonly sustained arrhythmia and has been treated for years by using conventional radiofrequency ablation in a point-by-point fashion [1,2]. However, due to emerging technology, several single-device techniques have been used as alternatives in the therapy of pulmonary vein isolation (PVI). Within the scope of single-device techniques, cryoballoon ablation (CBA) has played a prominent role; it is a well-established technique for the ablation of paroxysmal atrial fibrillation (PAF), but is less commonly used for the ablation of persistent atrial fibrillation (PersAF) [3–5].

The isolation of pulmonary veins (PVs) is effective as a form of treatment for both PAF and PersAF. The elimination of all pulmonary vein potentials (PVPs) is the main goal in overcoming the arrhythmia. Mapping catheters can rapidly and effectively identify the site of first activation of the exiting PVPs, thus guiding radiofrequency ablation for effective, clinically efficient, and safe AF ablation procedures. For mapping electrical conduction between the left atrium and PVs, the most common tool is a conventional spiral catheter. The distal end of the catheter is an open, circular loop (with a loop diameter range of 15–25 mm) equipped with either 10 or 20 electrodes. Standard spiral catheters are mainly used in conventional point-by-point radiofrequency ablation procedures.

For single-shot techniques, like the CBA, a modified spiral mapping catheter has been introduced for the identification of

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PVPs prior to ablation and also for monitoring purposes during the ablation process [6]. The Achieve™ Mapping Catheter (AC) is an intra-cardiac electrophysiological diagnostic catheter, which can be used for both first and second generation cryoballoon CB (Arctic Front Advance™). The distal part of the AC is a circular loop with 8 evenly spaced electrodes. Two-loop diameters are now available, one with a 15-mm and the other with a 20-mm outer diameter. The inter-electrode distance varies between 4 and 6 mm (for the 15- and 20-mm diameter loops, respectively). The more number of electrodes present, the more accurately PVPs can be identified [7]. Despite the emerging technical evolution of the last two decades, the primary success rate of PVI has not exceeded 70%. Even with multiple procedures, only a maximum of approximately 80% success rate can be achieved.

In this context, the development of the High Density Mesh Mapper™ (HDMM) was a rational step. The multi-electrode basket catheter fitted with a 32-pole circular mesh structure provides high-resolution recording in a closed space. The catheter can be spanned as an umbrella with a maximum diameter of 25 mm. For performing a successful PVI, the use of basket catheters, such as the HDMM, have been described in the past, especially because a basket catheter allows for the sophisticated analysis of myofibrils spread throughout the PVs parallel to the longitudinal axis of a PV [8–10].

It is possible that, with the rather "rough" AC, PVPs may remain undetected. In our study, we aimed to analyze the signal detection quality when using the AC in comparison to that when using the HDMM.

2. Material and methods

2.1. Patients selected

This study included 24 consecutive patients with symptomatic AF, who were scheduled for CBA treatment. Detailed information concerning LA anatomy was obtained by two-dimensional transesophageal and computed tomography scan prior to the procedure. Anti-arrhythmic drug therapy was not discontinued prior to ablation. The endpoint of the successful acute ablation procedure was the confirmation of entry and exit conduction block after CBA, both with the AC, as well as with the HDMM.

2.2. The High Density Mesh Mapper™

The HDMM (BARD Electrophysiology, Lowell, MA, USA) is a non-deflectable, octapolar, expandable, mesh-configured electrode catheter, consisting of two opposing 16 electrode pairs. The interwoven electrodes enable complete circumferential mapping of the PV by their staggered, overlapping recording configuration of the bipolar pairs (1–3; 2–4; 3–5 etc. up to 31–1; 32–2). In total, 32 bipolar electrograms (EGMs) can be simultaneously recorded (Fig. 1). When fully spanned at the transition zone between the LA and PV, the catheter allows for high-density mapping within a PV.

2.3. The 20 mm loop Achieve catheter

The AC is an inner lumen mapping catheter specifically designed to be used in combination with a CB to obtain PV-electrograms during cryoenergy application. The AC is inserted

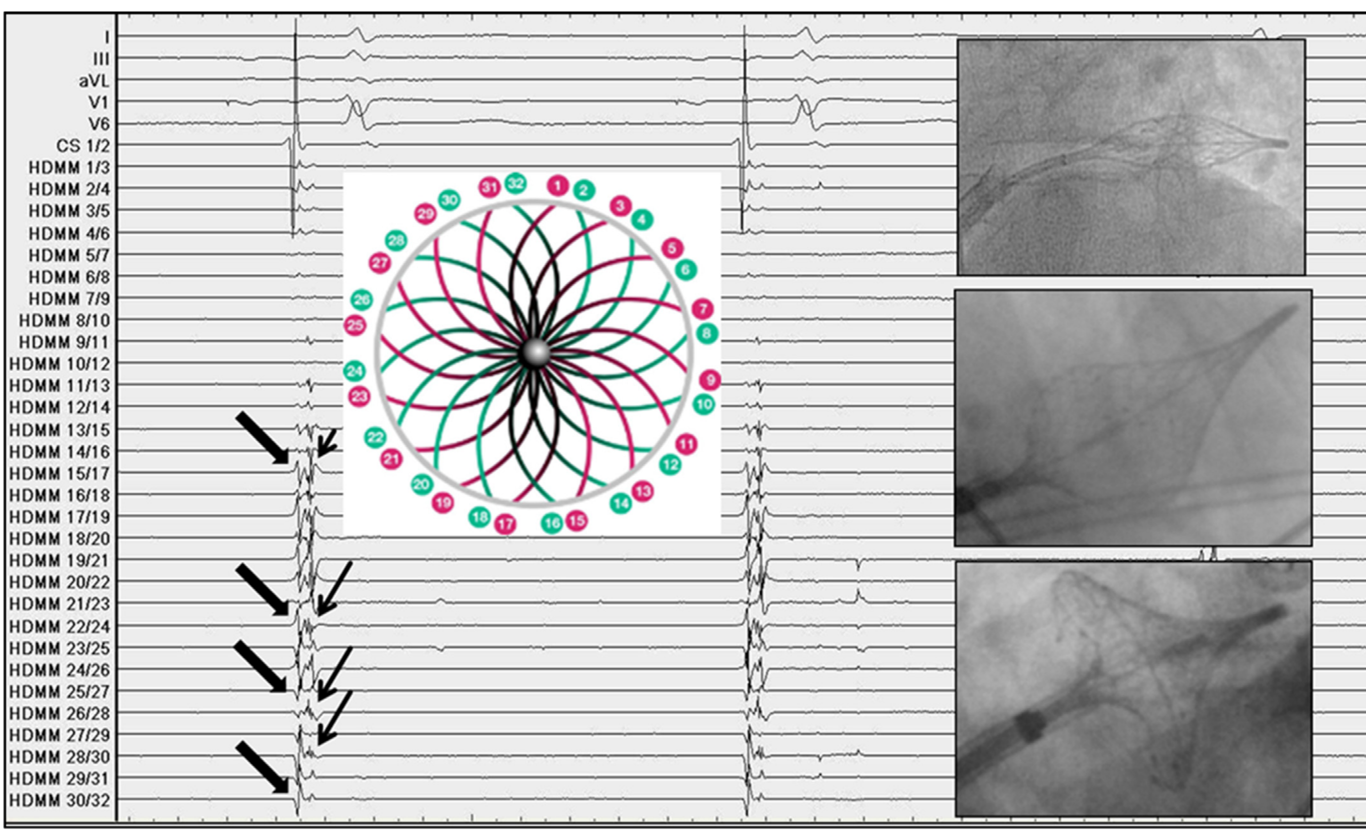

Fig. 1. Endocardial signals and fluoroscopic view of the High Density Mesh Mapper (HDMM) in ablation position. The HDMM is a non-deflectable, 8F expandable mesh-configured electrode catheter, consisting of two opposing 16 electrode pairs. The interwoven electrodes allow for complete circumferential mapping of the Pulmonary vein by staggered recording configuration between the electrodes 1–3; 2–4; 3–5 etc. up to 31–1; 32–2. In total, 32 unipolar or bipolar electrograms can be simultaneously recorded. From the top to the bottom: Surface ECG leads: I, II, aVF, V1, V6. Endo-cardiac signals: Coronary sinus CS 1/2, HDMM circumference 1/3, 2/4 until 31/1, 32/2. Example of typical endocardial signals prior to ablation located at the ostium of the Right superior Pulmonary Vein. Of the two components recorded, the first one is the atrial signal, indicated by the thick arrows, the second component of the fragmented signal is the Pulmonary Vein Potential, here indicated by the thin arrows.

into the inner lumen of the CB and placed distally to the catheter within the vein with the dual advantage of acting as a mapping catheter and supporting guidewire for the CB. The distal part of the 20 mm loop catheter consists of 8 evenly spaced electrodes with an interelectrode distance of 6 mm. As with the HDMM, we recorded electrograms from the PV with overlapping bipolar recording configuration of the bipolar pairs (1–3; 2–4; 3–5 etc., upto 8–2; here pictured as 1–2; 3–4 etc.).

2.4. Procedure management

The general procedure were performed as described previously [4–7]. The HDMM was inserted into the PV after extensive irrigation in a water bath to fully free the HDMM of oxygen bubbles. Due to its relatively stiff and protruding distal end, the sheath had to be securely positioned in the PV to avoid dislocation of the HDMM. The HDMM was then expanded in the distal part of each PV to observe the anatomy and electrophysiological properties. If no electrical activity could be recorded, the catheter was slowly withdrawn until atrial signals were observed. To obtain a complete circumferential electrical signal and to be able to positively confirm atrial localization of the HDMM, a slight withdrawal was necessary before the fully expanded catheter was pressed against the ostium of the PV.

After mapping and registering the PVPs in all PV, we exchanged the HDMM with the CB catheter. The 28 mm CB was maneuvered to all PV ostia via the circular mapping catheter. Before starting ablation, the AC was positioned in the venous ostium in order to record baseline electrical activity (Figs. 2–4A). Then, the AC was distally advanced, similar to when using a guidewire. The CB was subsequently wedged in the ostium, and occlusion was verified using a dye. The freezing cycle (generally two freezes lasting 240 s each) was started after the above-mentioned dye injection. Subsequent to ablation, we checked all PVs for re-connection or incomplete isolation, first with the AC and then by the withdrawal of the CB once again with the HDMM.

2.5. Assessment of electrical isolation with the Achieve Catheter (AC)

PV activity in each vein was recorded with the AC in a proximal position within the ostium prior toablation. Pacing from the distal and/or proximal CS was performed in order to distinguish different recorded endocardial signals on the mapping catheter. In this way, far-field atrial signals could be distinguished from true PV-Potentials. This approach, as well as exit block stimulation from inside the PV in a final step, was applied to all PVs, left- and right-sided PVs, respectively.

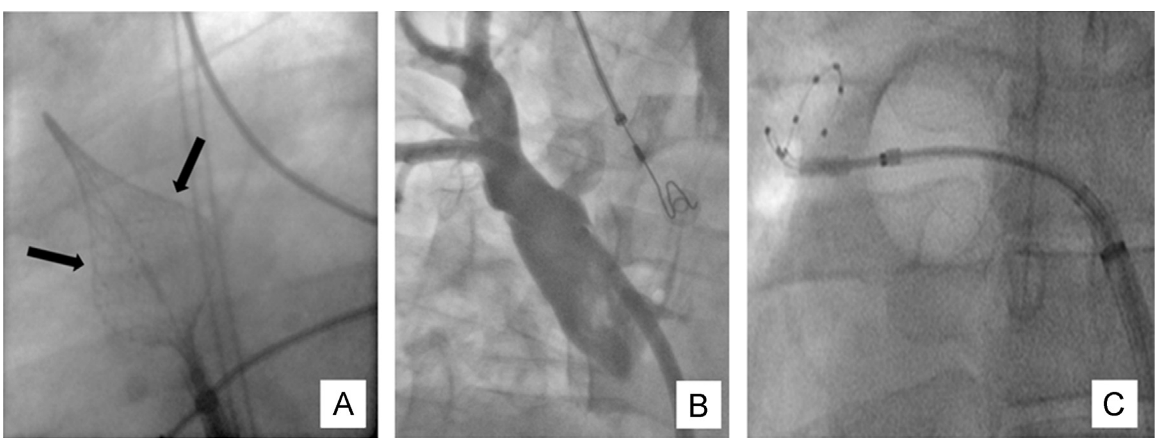

Fig. 2. The High Density Mesh Mapper (HDMM) in place at the left atrium–pulmonary vein junction closed to the right superior pulmonary vein (RSPV). (A) The catheter is not fully expanded like an umbrella, in this situation the catheter is half streched with the tip deep in the pulmonary vein and the shaft outside the vein. The de-isolated zone of the HDMM-catheter where the recording of the endocardial signals is performed is marked with an arrow. (B) The RSPV in which the catheter is located. (C) The same PV, now the Cryoballon with the mapping catheter (Achive) behind the balloon.

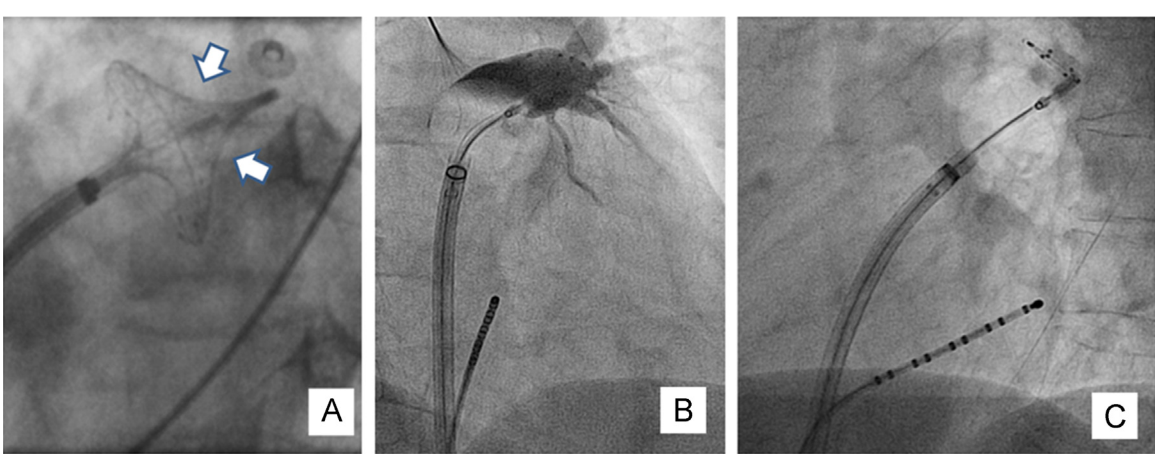

Fig. 3. (A) The High Density Mesh Mapper (HDMM) in place at the Left Atrium-Pulmonary Vein junction closed to the Left Superior Pulmonary Vein (LSPV). The catheter is fully expanded like an umbrella, in this situation the catheter is fully stretched with the tip deep in the Pulmonary Vein (PV) and the shaft outside the PV. The de-isolated zone of the HDMM, where the recording of the endocardial signals is performed is marked with arrows. (B) The same PV, now the Cryoballoon with mapping catheter (Achive) behind the balloon, (B) with, and (C) without contrast medium, different LAO views.

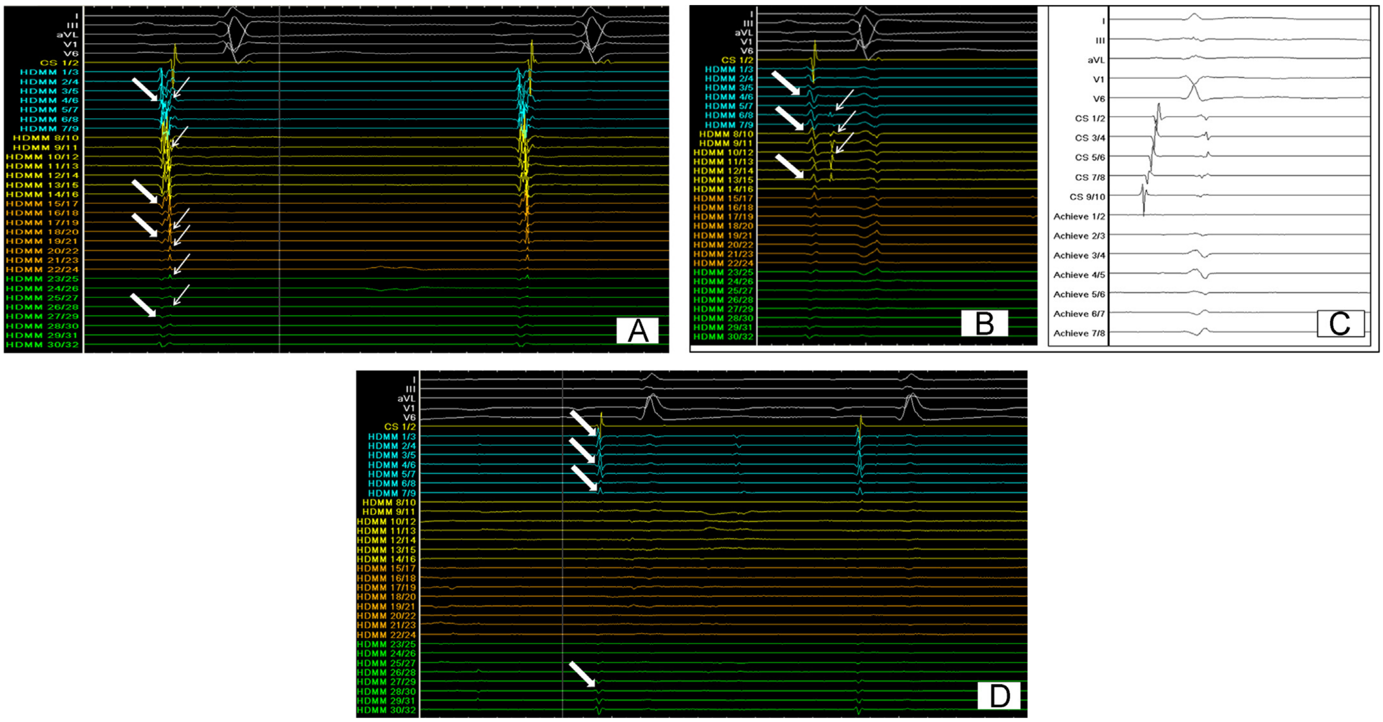

Fig. 4. (A) Endocardial signals of the High Density Mesh Mapper (HDMM) prior cryoballoon ablation. Confirmation of Pulmonary Vein Potentials (PVP's) in 4 of 4 quadrants. Proof of clumsy atrial signals (thick arrows) and tiny PV-signals, latter indicated by the thin arrow, directly after the atrial signal. Some of the atrial and PVP's are more or less fused. Arrangement of ECG leads and catheter, see Fig. 1. (B) Re-map with the High Density Mesh Mapper (HDMM, B) and the Achive Catheter (AC, C) after Cryoballoon ablation. Proof of tiny Pulmonary Vein Potentials (PVP's) remaining in two quadrants, between HDMM 6/8 and 12/14. PVP's, indicated by the thin arrows, prior to that the typical clumsy atrial signals, here indicated by the bulky arrows. Due to the ablation, there is already a certain delay between the two signals as compared to Fig. 1, where the signals are more or less fused. (C) No further PVP's are recorded in the same position. (D) Re-map with the High Density Mesh Mapper (HDMM) after Re-ablation. Reapplication of further energy to the same Pulmonary Vein, now demonstrating complete isolation of the PV also with the HDMM. There are no longer any tiny PV-signals traceable, whereas the bulky atrial signals are still present (thick arrows). Arrangement of ECG leads and catheter, see Fig. 1.

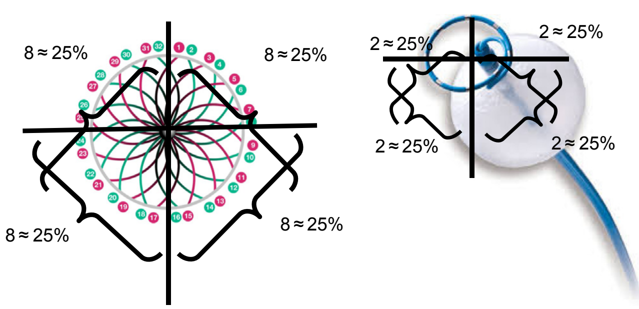

Fig. 5. Technical structure of the High Density Mesh Mapper (HDMM) and the Achive Catheter (AC). Division of the HDMM, 32 poles, panel on the left, and the AC, 8 poles, panel on the right in four quadrants. Due to the number of electrodes, the HDMM consists of $4 \times 8 = 32$ poles and the AC of $4 \times 2 = 8$ poles. To map and describe the entire circumference of both catheters, each quadrant is equivalent to 25% (8 poles in each quadrant in the HDMM, 2 poles in each quadrant of the AC. 1 Quadrant equates 1–8 PVPs in the HDMM and 1-2PVPs in the AC, this means 25% PVP circumference, 2 Quadrants equates 9–16 PVPs in the HDMM and 3–4 PVPs in the AC, this means 50% PVP circumference, consistent for the next two 100% PVP circumference. For example: HDMM 32 PVPs, AC 8 PVPs (equivalent 100% / 100%); HDMM 19 PVPs in 3 of 4 quadrants (equivalent 75%), AC 5 PVPs in 3 of 4 quadrants (equivalent 75%).

2.6. Assessment of electrical isolation with the HDMM

The mesh construction of the HDMM was utilized to derive endocardial EGM information. Based on previous HD-mapping [8–10], a 32-bipolar signal display was programmed and displayed on the LabPro EP recording system (Bard Electrophysiology). The displayed signals were analyzed as follows: in sinus rhythm, the first component of a composed signal was interpreted as originating from antrum myocardium. The second component was related to the electrical activity of PV myofibrils (Figs. 1 and 4A). During AF, the two electrical components are unable to be distinguished. The acute endpoint of the ablation procedure was either elimination or dissociation of PV antrum potentials recorded by the HDMM and/or exit block from the PV. In the case of residual PVPs (Fig. 4B), the CB had to be re-inserted into the LA and energy delivered until signals from the HDMM were lost (Fig. 4D). When signals could no longer be captured, the residual signal was indexed as far-field (Fig. 4A-D).

2.7. Mapping signals comparison of the HDMM and AC

During the procedure, we mapped PVPs both before and after CB ablation using the 32-pole HDMM and 8-pole AC. We counted all PVPs identified by the HDMM and AC (with a range of 0–32 in the HDMM and 0–8 in the AC, due to the number of electrodes). A conversion formula made it possible to compare the different numbers of mapping electrodes between the AC and HDMM. Therefore, we divided the mapping catheter electrode pairs into the four quadrants, Q1–Q4. Each quadrant of the AC consisted of 2 poles, and each quadrant of the HDMM of 8 poles (Fig. 5). Each quadrant was defined as 25% of the entire circumference. The last step allowed us to compare the number of PVPs in both catheters.

2.8. Long-term outcomes after CBA comparing AC mapping alone with additional HDMM mapping (study group)

To validate the net clinical outcome of the study group (24 patients) with additional mapping properties throughout HDMM mapping, we compared these patients after 3 and 6 months with all 167 patients from our laboratory, who were ablated in the same period with the standard approach using the AC as the only

Table 1
Clinical characteristics of the patients included in the study.

Variable	$N=24$
Age (years)	61.8 ± 10.1
Sex (males)	13 (54.2%)
Atrial fibrillation	
Paroxysmal	15 (62.5%)
Persistent	9 (37.5%)
AF duration (months)	16.3 ± 15.3
LA diameter (mm)	3.8 ± 2.9
No coronary vessel disease	19 (79.2%)
LV ejection fraction	
Normal	22 (91.7%)
Complete Pulmonary Vein Isolation	24 (100%)
Total procedure time (min)	127.5 ± 36.1
Fluoroscopy time (min)	32.9 ± 12.6

Values are expressed as mean ± SD or n (%). AF=Atrial fibrillation. *Chi-Quadrant-test $P = 0.002$.

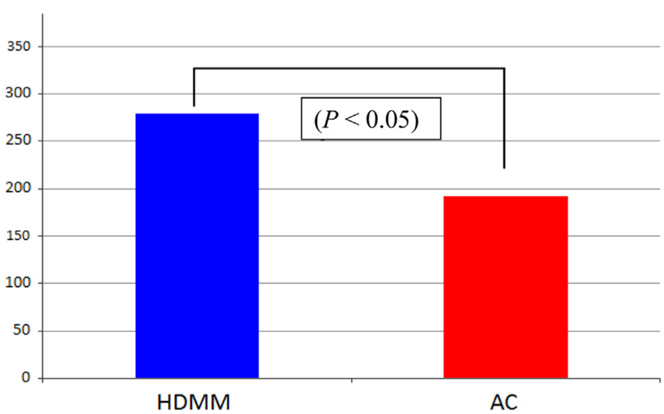

Fig. 6. Mapping results in 24 patients with the High Density Mesh Mapper (HDMM) and the Achive Catheter (AC) prior to ablation (*X*-axis). *Y*-axis: number of quadrants. Analysis in each quadrant for both catheters. Of 384 PV-quadrants/24 patients analyzed, identification of PVPs in 279/384 quadrants in the HDMM group = 73% and identification of PVPs in 192/384 quadrants in the AC group = 50%, ($P < 0.05$).

mapping catheter. All patients were evaluated for medical history, ECG at rest, ECG after exercise, and a 7-day Holter-ECG.

2.9. Statistical analysis

All data was presented as mean ± standard deviation. A SPSS 22.0 software package was used for statistical analysis. The Student t-test and Pearson Chi-square test were used to determine the statistical significance of differences between numerical and categorical data. A *P* value of < 0.05 was statistically significant.

3. Results

3.1. Characteristics of 24 AF patients

Table 1 shows the baseline characteristics of the 24 consecutive AF patients undergoing PVI with CB therapy. The patients were 61.8 ± 10 years old on average and suffered from highly symptomatic PAF (63% paroxysmal) with an average duration of 16.3 months (duration ranged from 1–60 months). In the three-dimensional, computed tomography reconstruction of the LA, we found PV anatomy in all patients to be normal.

3.2. PVP mapping details

We analyzed 96 veins in 24 patients. Each PV was analyzed four times, before and after CB ablation, and with HDMM and AC, respectively. Regarding all PVs in one patient before ablation, we detected an average of 83.6 ± 4.8 PVPs and 20.9 ± 10.5 PVPs per PV by the HDMM. Due to significantly fewer electrodes, we detected an average of 14.5 ± 1.3 PVPs in all PVs and 3.6 ± 2.7 PVPs by the AC in one PV before ablation, respectively. Both catheters identified more PVPs in the upper PVs, with the most identified in the LSPV, and the fewest in the RIPV. Overall, the HDMM identified a total average of 20.9 ± 10.5 PVPs per PV, LSPV: 26.3 ± 6.6, LIPV: 19.9 ± 12, RSPV: 22.4 ± 8.7, and 14.8 ± 10.8 in the RIPV. The AC Catheter identified a total average of 3.6 ± 2.7 PVPs, LSPV: 5.2 ± 2.6, LIPV: 2.8 ± 2.2, RSPV: 4.2 ± 2.7, and 2.4 ± 2.3 in the RIPV.

3.3. PV-quadrant mapping details

In order to make the results of both catheters comparable and to overcome the different numbers of electrodes, each PV was analyzed by dividing the PV circumference into four quadrants. Therefore, 4 quadrants per PV were analyzed, which means 16 quadrants per patient and 384 quadrants of the study population in total were analyzed.

Of the 384 PV-quadrants/24 patients analyzed, the HDMM could identify PVPs in 279 and the AC in 192 quadrants ($P < 0.05$, Fig. 6). The HDMM identified an average of 2.2 ± 1.4 quadrants per PV with PVPs, LSPV: 2.9 ± 1.3, LIPV: 3.5 ± 1.3, RSPV: 3.0 ± 1.0, and 2.2 ± 1.4 in the RIPV. The AC Catheter identified an average of 1.3 ± 1.2 quadrants with PVPs, LSPV: 2.6 ± 1.3, LIPV: 2.8 ± 1.4, RSPV: 2.4 ± 1.4, and 1.3 ± 1.3 in the RIPV. The differences between the analysis results of the two catheters in each PV were significant ($P < 0.05$).

Tables 2a–2d shows each patient and the number of quadrants in each PV in which PVPs were identified by the HDMM and AC. Each quadrant showing PVPs was then defined as a quarter of the entire circumference. Table 2 demonstrates the frequency distribution within quadrants with PVPs, the HDMM versus the AC and the AC versus the HDMM. This table reflects the fact that the HDMM often found more quadrants with PVPs than the AC. For example, as shown in Table 2a, the AC could identify PVPs in 72.9 ± 32.2% of the quadrants of PVPs recorded by the basket catheter located at the LSPV. Therefore, the Achieve catheter underestimated 27.1% ± 32.2% of the quadrants of PV potentials by the basket catheter. In the same manner, underestimation of PV-potentials can be confirmed for the LIPV, RSPV, and in the RIPV (Tables 2b–2d). In summary, in the majority of cases, the HDMM is superior to, or at least as good as, the AC in detecting PV-signals prior to the ablation procedure.

3.4. PVI results of all AF patients

After an average of 2.1 applications in 24 patients/96 veins, reconnections of PVs were examined, first, with the AC directly after the CBA, and subsequently after the exchange of the mapping catheters with the HDMM. Of these patients, PVI was achieved in all 24 patients. This indicatedthat 100% of the PVs were successfully isolated, according to the AC results. However, complete PVI could be achieved in only 20 patients (83%) or 92 PVs (93.7%), when using the HDMM. Here, the RSPVs of 2 patients, the LIPV of 1 patient, and the RIPV of another patient

Table 2a
Left Superior Pulmonary Vein (LSPV): Pulmonary vein potentials in 24 patients identified by the High Density Mesh Mapper (HDMM) and the Achive Catheter (AC).

Patient	HDMM – LSPV Number of Quadrants (Q1 – Q4) with PVPs	HDMM – LSPV Percent of Quadrants with PVPs	HDMM – LSPV Number of PVPs in Quadrants (Q1 – Q4)	AC – LSPV Number of Quadrants (Q1 – Q4) with PVPs	AC –LSPV Percent of Quadrants with PVPs	AC - LSPV Number of PVPs in Quadrants (Q1 – Q4)	LSPV % HDMM detection	LSPV % AC detection
1	4	100	32	1	25	2	100	25
2	4	100	27	4	100	8	100	100
3	4	100	32	3	75	5	100	75
4	4	100	32	1	25	2	100	25
5	3	75	19	2	50	3	100	66.7
6	4	100	26	2	50	4	100	50
7	3	75	24	4	100	8	75	100
8	4	100	32	4	100	8	100	100
9	3	75	20	4	100	8	75	100
10	3	75	20	1	25	2	100	33.3
11	2	50	16	2	50	4	100	100
12	4	100	32	1	25	2	100	25
13	4	100	32	4	100	8	100	100
14	3	75	26	2	50	4	100	66.7
15	3	75	24	2	50	4	100	66.7
16	4	100	32	4	100	8	100	100
17	4	100	32	2	50	4	100	50
18	4	100	24	4	100	8	100	100
19	3	75	18	2	50	4	100	66.7
20	4	100	32	4	100	8	100	100
21	4	100	32	4	100	8	100	100
22	4	100	32	4	100	8	100	100
23	2	50	10	0	0	0	100	0
24	4	100	32	4	100	5	100	100
Mean Value	3.54	88.54	26.7	2.7	67.7	5.2	97.9	72.9
SD	0.66	16.45	6.65	1.33	33.36	2.63	7.1	32.2

The table shows the summarized results in the LSPV for each patient. On the left side, columns 2, 3, and 4 show the results for the HDMM. Column 2 shows the number of quadrants with observed PVPs; column 3 shows the percentage of quadrants in which PVPs were detected; column 4 shows the total number of PVPs in all 4 quadrants. The right sided columns show the same results for the 24 patients achieved with the AC. Each quadrant with PVPs was then defined as a quarter of the entire circumference (minimum 1 - equivalent 25%, maximum 4 - equivalent 100%). PV= Pulmonary Vein, HDMM = High density mesh mapper, AC = Achieve Catheter, LSPV = left superior PV, % HDMM detection = Percentage of the quadrants with PVP recorded by the HDMM to the quadrants with PVPs recorded by AC. %AC detection = Percentage of the quadrants with PVP recorded by the AC to the quadrants with PVPs recorded by HDMM.

Table 2b
Left Inferior Pulmonary Vein (LIPV): Pulmonary vein potentials in 24 patients identified by the High Density Mesh Mapper (HDMM) and the Achive Catheter (AC).

Patient	HDMM – LIPV Number of Quadrants (Q1 – Q4) with PVPs	HDMM –LIPV Percent of Quadrants with PVPs	HDMM - LIPV Number of PVPs in Quadrants (Q1 – Q4)	AC - LIPV Number of Quadrants (Q1 – Q4) with PVPs	AC –LIPV Percent of Quadrants with PVPs	AC - LIPV Number of PVPs in Quadrants (Q1 – Q4)	LIPV % HDMM detection	LIPV % AC detection
1	4	100	32	1	25	2	100	25,0
2	4	100	27	4	100	8	0	0,0
3	4	100	32	3	75	5	50	100,0
4	4	100	32	1	25	2	100	25,0
5	3	75	19	2	50	3	100	0,0
6	4	100	26	2	50	4	100	0,0
7	3	75	24	4	100	8	100	0
8	4	100	32	4	100	8	100	75
9	3	75	20	4	100	8	100	100
10	3	75	20	1	25	2	100	75
11	2	50	16	2	50	4	100	100
12	4	100	32	1	25	2	100	100
13	4	100	32	4	100	8	0	100
14	3	75	26	2	50	4	100	50
15	3	75	24	2	50	4	100	50
16	4	100	32	4	100	8	100	100
17	4	100	32	2	50	4	100	66.7
18	4	100	24	4	100	8	100	66.7
19	3	75	18	2	50	4	0	0
20	4	100	32	4	100	8	100	66.7
21	4	100	32	4	100	8	100	0
22	4	100	32	4	100	8	100	100
23	2	50	10	0	0	0	100	0
24	4	100	32	4	100	5	100	75
Mean Value	3.54	88.54	26.7	2.7	67.7	5.2	85.4	53.1
SD	0.66	16.45	6.65	1.33	33.36	2.63	34.5	41.0

The table shows the summarized results in the LIPV for each patient. Legend, see 2a.

Table 2c
Right Superior Pulmonary Vein (RSPV): Pulmonary vein potentials in 24 patients identified by the High Density Mesh Mapper (HDMM) and the Achive Catheter (AC).

Patient	HDMM – RSPV Number of Quadrants (Q1 – Q4) with PVPs	HDMM –RSPV Percent of Quadrants with PVPs	HDMM - RSPV Number of PVPs in Quadrants (Q1 – Q4)	AC - RSPV Number of Quadrants (Q1 – Q4) with PVPs	AC –RSPV Percent of Quadrants with PVPs	AC - RSPV Number of PVPs in Quadrants (Q1 – Q4)	RSPV % HDMM detection	RSPV % AC detection
1	4	100	32	1	25	2	100	25
2	4	100	27	4	100	8	100	33.3
3	4	100	32	3	75	5	100	0
4	4	100	32	1	25	2	100	25
5	3	75	19	2	50	3	100	100
6	4	100	26	2	50	4	100	75
7	3	75	24	4	100	8	100	75
8	4	100	32	4	100	8	100	100
9	3	75	20	4	100	8	75	100
10	3	75	20	1	25	2	66.7	100
11	2	50	16	2	50	4	0	100
12	4	100	32	1	25	2	100	100
13	4	100	32	4	100	8	100	0
14	3	75	26	2	50	4	66.7	100
15	3	75	24	2	50	4	100	50
16	4	100	32	4	100	8	100	100
17	4	100	32	2	50	4	100	0
18	4	100	24	4	100	8	100	100
19	3	75	18	2	50	4	100	100
20	4	100	32	4	100	8	75	100
21	4	100	32	4	100	8	50	100
22	4	100	32	4	100	8	100	66.7
23	2	50	10	0	0	0	66.7	100
24	4	100	32	4	100	5	66.7	100
Mean Value	3.54	88.54	26.7	2.7	67.7	5.2	86.1	72.9
SD	0.66	16.45	6.65	1.33	33.36	2.63	24.3	37.9

The table shows the summarized results in the RSPV for each patient. Legend see 2a.

Table 2d
Right Inferior Pulmonary Vein. Pulmonary vein potentials in 24 patients identified by the High Density Mesh Mapper (HDMM) and the Achive Catheter (AC).

Patient	HDMM – RIPV Number of Quadrants (Q1 – Q4) with PVPs	HDMM –RIPV Percent of Quadrants with PVPs	HDMM - RIPV Number of PVPs in Quadrants (Q1 – Q4)	AC - RIPV Number of Quadrants (Q1 – Q4) with PVPs	AC –RIPV Percent of Quadrants with PVPs	AC -RIPV Number of PVPs in Quadrants (Q1 – Q4)	RIPV % HDMM detection	RIPV % AC detection
1	4	100	32	1	25	2	100	25
2	4	100	27	4	100	8	0	0
3	4	100	32	3	75	5	100	0
4	4	100	32	1	25	2	100	100
5	3	75	19	2	50	3	100	100
6	4	100	26	2	50	4	50	100
7	3	75	24	4	100	8	100	66.7
8	4	100	32	4	100	8	100	100
9	3	75	20	4	100	8	100	0
10	3	75	20	1	25	2	0	0
11	2	50	16	2	50	4	20	100
12	4	100	32	1	25	2	0	0
13	4	100	32	4	100	8	100	0
14	3	75	26	2	50	4	75	100
15	3	75	24	2	50	4	100	50
16	4	100	32	4	100	8	100	0
17	4	100	32	2	50	4	100	50
18	4	100	24	4	100	8	100	33.3
19	3	75	18	2	50	4	100	33.3
20	4	100	32	4	100	8	100	50
21	4	100	32	4	100	8	100	50
22	4	100	32	4	100	8	100	0
23	2	50	10	0	0	0	100	66.7
24	4	100	32	4	100	5	100	50
Mean Value	3.54	88.54	26.7	2.7	67.7	5.2	81	44.8
SD	0.66	16.45	6.65	1.33	33.36	2.63	36.7	39.6

The table shows the summarized results in the RIPV. Legend see 2a.

were all incompletely isolated. These results led to additional ablation freezes in the non-isolated PV, finally resulting in 100% isolation of all PVs. The total procedural time was 127.5 ± 36 min. Minimal temperatures were an average of -52.2 $\pm$ 6.0 °C in the LSPV, -47.4 ± 5.5 °C in the LIPV, -51.5 ± 6.1 °C in the RSPV, and -45.1 ± 5.7 °C in the RIPV.

3.5. Long-term outcomes after CBA comparing AC mapping alone with additional HDMM mapping (study group)

Three and six months after CBA, we compared the study group of the 24 patients with all 167 patients from our laboratory, who were ablated in the same period with the standard approach, using the AC as the only mapping catheter. After 3 and 6 months, 82% and 79% respectively of the whole study group were still in sinus rhythm, whereas 83% and 76% respectively of the study group patients demonstrated sinus rhythm. Comparing both groups, based on sinus rhythm outcome with the Pearson Chi-square test, we could not find any significant differences after 3 ($P=0.78$) or after 6 months ($P=0.66$) respectively.

4. Discussion

Summarizing the results, the main findings of our study are as follows: high-density mapping with the HDMM identifies more residual PV-potentials after a single-shot CBA procedure. Despite the small-sized study group, consisting of only 24 patients, the differences are significant; the HDMM was able to identify PVPs in 279 quadrants, whereas PVPs were detected in 192 quadrants by the AC ($P<0.001$). These underestimations of PV potential mapping with the AC, in comparison with High Density Mapping, did not lead to an improvement of the net clinical outcome after 3 and 6 months in the HDMM ablation group. Residual PV-potentials following CBA were mainly found in the upper PVs. The HDMM guided CBA procedure led to the necessity of additional freezes, which then resulted in a final 100% success rate of the acute procedure.

The impact of precise mapping, both prior and subsequent to PVI, is still controversial. Von Bary et al. recommended the use of additional mapping catheters to improve the PV isolation rate when there is doubt concerning the signal quality in single-shot (stand-alone) strategies [11]. In a small study population of only 12 patients, Anter et al. were recently able to demonstrate the superiority of mini-basket catheters over circular lasso catheters for the detection of PVPs following PVI. The PV-potentials could be recorded with only the smaller and closely spaced, mini-basket electrodes [12]. The question of whether or not focus should be placed more on mapping properties to close the gap between responders and non-responders of the PVI procedure remains.

The “single-shot” ablation catheters commonly used today simplify the ablation procedure by allowing new developments to be mapped and ablation to be conducted in the same session (e.g., the second generation CB with its AC as an inner lumen mapping catheter [3–7]). As recently described, the results of CBA are comparable to those of the standard point-by-point radiofrequency ablation technique, as introduced for the ablation of PAF and PersAF [13,14]. Both techniques have a primary success rate range of 70–80% with a predefined recurrence rate in the follow-up period. Revisions of primary effective isolated PVs show a reconnection of the muscle sleeves between the LA and PV in most cases, thus leading to the necessity of additional ablation efforts. The question remains as to whether these reconnections are true reconnections or completely isolated PVs from the first ablation attempt, having been caused by ignored or false-negative mapping procedures.

We hypothesize in our study that the properties of basket catheters, as with the HDMM, provide high-density mapping and allow for more accurate identification of PVPs. Such identification is possible not only at the site of the earliest activation, but also at residual sites of activation at the end of circumferential ablation. The study is important because PVPs play a major role as a trigger for the occurrence of AF. Their elimination therefore remains a primary objective in the treatment of AF. However, this also means that suboptimal PVP mapping can allow them to go undetected, which increas the likelihood of AF recurrence.

In our study of 24 patients, we demonstrated the highly accurate identification of PVPs by using the HDMM. These findings aligned with several other studies applying high-density mapping catheters such as either the HDMM or other comparable basket catheters [9–11]. As confirmed by the study group of Neumann et al., as well as by our own study group, high-density guided mapping and ablation procedures not only lead to higher primary success rates, but also to excellent success rates in the follow-up period [8–10]. All procedures were carried out using a high-density mapping catheter and open-irrigated radiofrequency ablation.

In contrast, the combination of such a high-density mapping catheter, like the HDMM, with ablation propertiesmerged into one catheter, the High Density Mesh Ablator (HDMA), didfail in the detection of PVI over time. High-resolution, mapping guided ablation led to an excellent initial acute success rate [15–17]. However, and as having been demonstrated by both Steinwender et al. and our own study, the favorable acute success rates initially demonstrated, had high AF relapse rates in the long term [18,19]. The thin electrodes of the HDMA, which are able to precisely map the PV-ostium, were not suitable to induce a durable ablation scar.

The reasons for higher precision levels reached are varied and can mainly be explained by both the catheter construction itself and the anatomical aspects promoting one catheter over the other. The twice opposing 16 electrode pairs of the HDMM, being configured as a full circle mesh, allow for extremely close and narrow 32-bipolar electrogram mapping. The close circumferential contact between the catheter and the PV-ostium, as well as the inherent stability of the mesh catheter design itself, may have both contributed to the signal definition that was achieved during the course of this study. In contrast, a spiral catheter, like the soft and flexible AC, can usually be placed in a stable position within the ostium of a PV, but is less stable in the connective antrum when attempting to guarantee a perfect transmural circular ablation line only a few millimeters from the ostium.

In addition to catheter construction properties, anatomical aspects also play a role during the pre- and post-ablation mapping processes. In comparison to the AC, the HDMM detected more PVPs in total as well as within each vein. These differences were statistically significant. Reasons for false-negative mapping with the AC may be explained by the following: first, wide funnel that is often observed in the upper PVs maylead to a mismatch between mapping catheter and PV. Such a lack of contact may result in inferior results. Second, PV sleeves are typically shorter in the inferior veins compared to the superior veins. Early re-connection or inadequate isolation of the PVs could be seen in the form of tiny, residual potentials in the HDMM subsequent to ablation, but they remained “hidden” in the AC. The procedure, when conducted using the HDMM, led to additional freezes during the acute procedural phase, resulting in a final 100% success rate of our study. Further studies should be carried out to clarify if high density mapping properties are needed for optimal information gain at the atrial PV junction in different settings of PVI procedures.

5. Study limitations

The present study is a single center, non-randomized clinical trial. It describes the first direct comparison of two approved mapping catheters during a CBA procedure. Varying levels of experience with one or the other mapping catheter may have contributed to a bias. Nevertheless, our study team is very experienced in applying both techniques. The small number of patients showed an improvement with mapping properties during an acute ablation procedure, without a net clinical outcome benefit in the follow up period. These preliminary observations should therefore be confirmed by further studies with more patients.

6. Conclusion

High-density mapping with a Basket Catheter, such as the HDMM, detects PVPs that remain undetected when using the standard AC Catheter in a CBA procedure. The excess in mapping properties of the HDMM, which leads to more ablation efforts during the index procedure, did not lead to higher clinical success rates during follow-up.

Conflict of interest

The authors declare that there is no conflict of interest.

References

[1] Calkins H, Kuck KH, Cappato R, et al. Heart Rhythm Society Task Force on Catheter and Surgical Ablation of Atrial Fibrillation. 2012 h/EHRA/ECAS expert consensus statement on catheter and surgical ablation of atrial fibrillation: recommendations for patient selection, procedural techniques, patient management and follow-up, definitions, endpoints, and research trial design: a report of the Heart Rhythm Society (HRS) Task Force on Catheter and Surgical Ablation of Atrial Fibrillation. Heart Rhythm 2012;9:632–96.
[2] January CT, Wann LS, Alpert JS, et al. American College of Cardiology/American Heart Association Task Force on Practice Guidelines. 2014 AHA/ACC/HRS guideline for the management of patients with atrial fibrillation: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and the Heart Rhythm Society. J Am Coll Cardiol 2014;64:2305–7.
[3] Neumann T, Vogt J, Schumacher B, et al. Circumferential pulmonary vein isolation with the cryoballoon technique results from a prospective 3-center study. J Am Coll Cardiol 2008;52:273–8.
[4] Andrade JG, Khairy P, Guerra PG, et al. Efficacy and safety of cryoballoon ablation for atrial fibrillation: a systematic review of published studies. Heart Rhythm 2011;8:1444–51.
[5] Chierchia G-B, Di Giovanni G, Ciconte G, et al. Second-generation cryoballoon ablation for paroxysmal atrial fibrillation: 1-year follow-up. Europace 2014;16:639–44.
[6] Chierchia GB, Namdar M, Sarkozy A, et al. Verification of pulmonary vein isolation during single transseptal cryoballoon ablation: a comparison between the classical circular mapping catheter and the inner lumen mapping catheter. Europace 2012;14:1708–14.
[7] Fürnkranz A, Bordignon S, Schmidt B, et al. Improved procedural efficacy of pulmonary vein isolation using the novel second-generation cryoballoon. J Cardiovasc Electrophysiol 2013;24:492–7.
[8] Dello Russo A, Pelargonio G, Casella M. New high-density mapping catheter: helpful tool to assess complete pulmonary veins isolation. Europace 2008;10(1):118–9 [Epub 2007 Nov 14].
[9] Meissner A, van Bracht M, Schrage MO, et al. Segmental pulmonary vein isolation in atrial fibrillation: new insights from the high density mesh mapper technique in an electrophysiologically guided approach. J Interv Card Electrophysiol 2009;25(3):183–92.
[10] Neumann T, Kuniss M, Erkapic D, et al. Acute and long-term results of PVI at antrum using a novel high-density mapping catheter without help of 3D electro-anatomic mapping in patients with paroxysmal and chronic atrial fibrillation. J Interv Card Electrophysiol 2010;27:101–8.
[11] von Bary C, Fredersdorf-Hahn S, Heinicke N, et al. Comparison of PV signal quality using a novel circular mapping and ablation catheter versus a standard circular mapping catheter. J Interv Card Electrophysiol 2011;31:131–9. http://dx.doi.org/10.1007/s10840-011-9546-4 [Epub 2011 Feb 12].
[12] Anter E, Tschabrunn CM, Contreras-Valdes FM, et al. Pulmonary vein isolation using the Rhythmia mapping system: verification of intracardiac signals using the Orion mini-basket catheter ME2. Heart Rhythm 2015;12:1927–34.
[13] Malmborg H, Lönnerholm S, Blomström P, et al. Ablation of atrial fibrillation with cryoballoon or duty-cycled radiofrequency pulmonary vein ablation catheter: a randomized controlled study comparing the clinical outcome and safety: the AF-COR study. Europace 2013;15(11):1567–73.
[14] Aryana A, Singh SM, Kowalski M, et al. Acute and long-term outcomes of catheter ablation of atrial fibrillation using the second-generation cryoballoon versus open-irrigated radiofrequency: a multicenter experience. J Cardiovasc Electrophysiol 2015;26(8):832–9.
[15] Mansour M, Forleo GB, Pappalardo A, et al. Initial experience with the Mesh catheter for pulmonary vein isolation in patients with paroxysmal atrial fibrillation. Heart Rhythm 2008;5:1510–6.
[16] Meissner A, Plehn G, van Bracht M, et al. First experiences for pulmonary vein isolation with the high density mesh ablator (HDMA). A novel mesh electrode catheter for both mapping and radiofrequency delivery in a single unit. J Cardiovasc Electrophysiol 2009;20:359–66.
[17] De Filippo P, He DS, Brambilla R, et al. Clinical experience with a single catheter for mapping and ablation of pulmonary vein ostium. J Cardiovasc Electrophysiol 2009;20:367–73.
[18] Maagh P, van Bracht M, Butz T, et al. Eighteen months follow-up of the clinical efficacy of the high density mesh ablator (HDMA) in patients with atrial fibrillation after pulmonary vein isolation. J Interv Card Electrophysiol 2010;29:43–52.
[19] Steinwender C, Hönig S, Leisch F, et al. One-year follow-up after pulmonary vein isolation using a single mesh catheter in patients with paroxysmal atrial fibrillation. Heart Rhythm 2010;7:333–9.