Hwang *et al.*
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RESEARCH

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The efficacy of ultra-high-density mapping guided partial antral ablation for pulmonary vein isolation in atrial fibrillation patients

Jongmin Hwang[1], Seongwook Han[1*], Chun Hwang[2], Tae-Wan Chung[1] and Hyoung-Seob Park[1]

Abstract

Background The muscular discontinuities or lack of myocardial extensions around the pulmonary veins (PVs) antrum were previously reported. The objective of our study was to compare the efficacy of a partial antral ablation for PV isolation (PVI) using ultra-high density (UHD) mapping with a conventional wide antral circumferential ablation (WACA) in atrial fibrillation (AF) patients.

Methods A total of 119 patients medical records who received catheter ablation for AF in our hospital were analyzed. In one group of patients, detailed activation mapping of each PV was performed using a UHD mapping system. Each PV antral segment's activation pattern was classified into "directly-activated from the LA" or "passively-activated from an adjacent PV segment" patterns. The ablation applications were performed at the directly-activated PV antral segment only for the PVI when the PV had "passively-activated segments" (partial antral ablation; PA-UHD group). Another patient group received a conventional WACA for the PVI (WACA group).

Results Sixty patients received partial antral ablation (PA-UHD), and age/sex-matched 59 patients received WACA. In the PA-UHD group, passively-activated segments were observed in 58.3% of all PV segments. The success rate of a partial antral ablation for the PVI in PVs with passively-activated segments was 85%. The 1-year atrial tachyarrhythmia recurrence did not differ between the PA-UHD and WACA groups.

Conclusions Our study revealed the presence of passively-activated PV segments, which could potentially indicate muscular discontinuity at the PV-LA junction. In most PVs with passively-activated segments, PVI was successfully achieved by ablation with only directly-activated segments. The 1-year recurrence rate of atrial tachyarrhythmia in PA-UHD group was comparable to that observed in the WACA group.

Keywords Atrial fibrillation, Catheter ablation, Pulmonary vein isolation, Electroanatomical mapping

Introduction

The electrical isolation of the pulmonary veins (PVs) is the cornerstone strategy of the current procedural treatment for atrial fibrillation (AF) patients because the PVs are the most common trigger site for AF [1]. The identification of electrical triggers arising from the PVs led to the PV isolation (PVI) by focal radiofrequency (RF) ablation. However, this approach has shown only moderate success with severe complications such as PV stenosis. Therefore, a wide bi-antral circumferential ablation (WACA) encircling the PVs guided by a three-dimensional (3D)

*Correspondence:
Seongwook Han
swhan@dsmc.or.kr
[1] Division of Cardiology, Department of Internal Medicine, Keimyung University Dongsan Hospital, Keimyung University School of Medicine, 1035 Dalgubeol-Daero Dalseo-Gu, Daegu 42601, Republic of Korea
[2] Cardiology, Revere Health, Provo, UT, USA

electroanatomic mapping (EAM) system emerged as the standard of care with the endpoint of conduction block between the PVs and left atrium (LA) [2, 3]. However, the WACA technique requires a much larger number of ablation applications and higher energy to achieve a complete isolation [4] which can lead to cardiac tamponade and life-threatening collateral damage (especially to the esophagus). This procedural complexity causes a long learning curve and has limited its widespread utilization [5]. On the other hand, muscular discontinuities and abrupt changes in the fiber orientation in the human PV-LA junction have been previously reported, and an electrical PV isolation can usually be achieved without a complete circumferential ablation [6, 7]. Also, recently published computed tomography data regarding LA wall thickness demonstrated variations in wall thickness depending on the location of the antrum. After catheter ablation, patients with recurrent AF had thicker myocardium in reconnected PV antrum segments compared to non-reconnected segments [8]. However, the prior EAM systems have a limitation in understanding the complex anatomy and electrophysiology of the PV-LA junctional myocardium due to its relatively low resolution.

A recently developed ultra-high-density (UHD) EAM coupled with an automatic annotation algorithm and smaller, closely-spaced multielectrode catheters has allowed the rapid and accurate identification of critical isthmuses and low-voltage regions of interest. Using the UHD mapping system [Rhythmia 3D EAM system (Rhythmia HD system, Boston Scientific, Cambridge, MA)], we recently conducted detailed activation mapping around the PV-LA junction. Based on these results, we reported that electrical isolation could be achieved in a significant number of PVs without ablation in areas showing passive activation from an adjacent PV antral segment (partial antral ablation) [9].

In this study, we aim to compare the 1-year atrial tachycardia/fibrillation (AT/AF) free survival rates between the group that underwent partial antral ablation and the group that underwent conventional WACA. Through this comparison, we intend to evaluate the efficacy of partial antral ablation.

Methods

Study population

This was a single-center retrospective study. We reviewed the medical records of 60 patients who received partial antral ablation for PVI using the Rhythmia 3D EAM system (Rhythmia HD system, Boston Scientific, Cambridge, MA) (PA-UHD group) between October 2018 and March 2019. For comparison, we selected age, sex, AF type, and follow-up duration-matched 59 patients from a historical cohort (January 2016–September 2018). In this group, the patients received a conventional WACA for the PVI under the guidance of a Carto 3 3D EAM system (Carto system, Biosense Webster, Diamond Bar, CA) (WACA group).

Ablation procedure in the PA-UHD group

We previously published the detailed method of the general ablation and PA-UHD ablation procedure [9]. In brief, LA geometry and activation mapping were obtained with a 64-pole basket mapping catheter (IntellaMap Orion, Boston Scientific, Cambridge, MA) during mid-coronary sinus pacing with a cycle length of 600 ms. After mapping was completed, the activation patterns around the PVs and antrum were judged by a propagation video and were classified into the following two types: “directly activated from the LA” or “passively activated from an adjacent PV segment.” Activation of the passively-activated segments started at least 40–45 ms later than the firstly activated PV segment. Representative images of a PV antrum with passively-activated segments are shown in Fig. 1.

After determining the activation pattern of each segment, ablation was initially performed on the PV antrum of directly-activated segments. A “successful partial antral ablation” was deemed if the PVI was achieved by ablation at the directly-activated segments only. However, if the PVI is not achieved despite the ablation of all directly-activated segments, then the procedure is considered a “failed partial antral ablation,” and a circumferential ablation is performed instead. In cases where the PV does not contain any passively-activated segments, a circumferential antral ablation was carried out on those PVs. Examples of ablation according to the activation pattern are shown in Fig. 2. The activation maps of Fig. 2 patient recorded in various views were provided in the Additional files 1, 2, 3 and 4.

Ablation procedure in the WACA group

In the WACA group, the procedure was guided by a Carto system with a 20-pole circular mapping catheter (LASSO®, Biosense Webster, Diamond Bar, CA). A circumferential PVI, including the carina, was performed, and an irrigated ablation catheter (THERMOCOOL® SMARTTOUCH™ catheter, Biosense Webster, Diamond Bar, CA) was used with the same ablation settings as in the PA-UHD group. A contact force of 10–15 g was targeted during ablation. Even though the PV potentials disappeared without a circumferential lesion, additional ablation was performed to close the WACA circles without creating a gap. A representative example of a WACA group lesion set image is shown in Fig. 3.

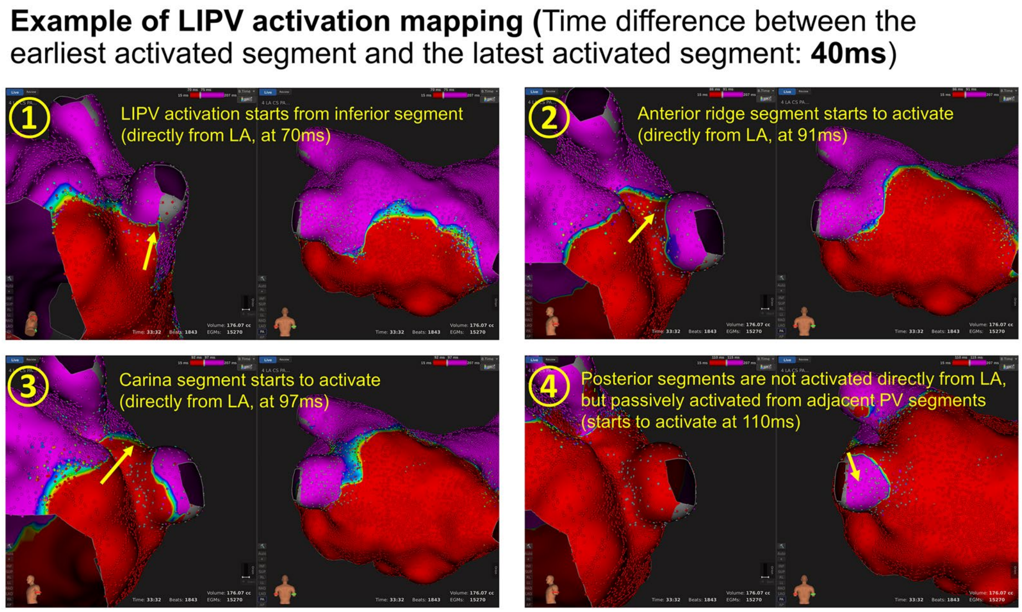

Fig. 1 Examples of a left inferior pulmonary vein (LIPV) antral activation sequence. The figure is arranged according to the time (from ① to ④), which shows the presence of segments in a left atrial pulmonary vein antrum that passively-activated from an adjacent segment. Activation mapping was performed during coronary sinus pacing. Each sub-figure is comprised of lateral and posterior views of the LIPV. ① Most of the LIPV is not activated at this time, and the activation is initiated from the inferior ridge and inferior segment. ② After 21 ms, the anterior ridge segments are activated first. ③ After 6 ms, the carina segment is activated. ④ After 13 ms, the posterior segment starts to activate. The posterior segments are not activated directly from LA, but passively-activated from adjacent PV segments

Follow-up

Anti-arrhythmic agents were discontinued after a 3-month blanking period. An electrocardiogram (ECG) and 24-h Holter monitoring were obtained right after the procedure. All patients were regularly seen in the outpatient clinic after the procedure: 1-week, 1-month, 3-month after the procedure, and every 3-month thereafter. At every visit, the patients received a 12-lead ECG. Holter monitoring was performed at 3 months and 12 months. An ECG and Holter monitoring were also performed whenever the patient had symptoms suggesting a tachyarrhythmia. A documented symptomatic or asymptomatic atrial tachyarrhythmia episode lasting > 30 s was defined as a recurrence.

Primary and secondary endpoints

The freedom from any atrial tachyarrhythmia recurrences during the 1-year follow-up period between the two groups was the primary endpoint. The total procedure time/fluoroscopy time, total delivered ablation energy, and any procedural complications were the secondary endpoints.

Statistical analyses

For the statistical analysis, a Student t-test or Mann–Whitney U test was used for the comparison of the continuous variables between the groups, and a Chi-Squared or Fisher's exact test was used for the categorical data. Atrial tachyarrhythmia-free survival curves between the two groups were analyzed using Kaplan–Meier estimates and compared with the log-rank test. A two-tailed P value of < 0.05 was considered statistically significant. Baseline statistical analyses were performed using the MedCalc® Statistical Software version 19.5.3 (MedCalc Software Ltd, Ostend, Belgium), and the survival analysis was performed using Prism 8.0.

Results

Baseline and procedural characteristics

A total of 119 drug-refractory AF patients were included in this study. Of those patients, 60 and 59 patients were enrolled in the PA-UHD group and WACA group, respectively. The baseline and procedural characteristics are summarized in Table 1. There were no differences in age (mean age 57.8 ± 5.8 years vs. 58.3 ± 8.7 years; $P = 0.339$), sex (male, 66.2% vs. 76.3%; $P = 0.103$), or other baseline demographical characteristics between the two groups. Patients with paroxysmal AF accounted for more than 80% of both groups.

The ablation time and fluoroscopy time were significantly lower in the PA-UHD group than WACA group.

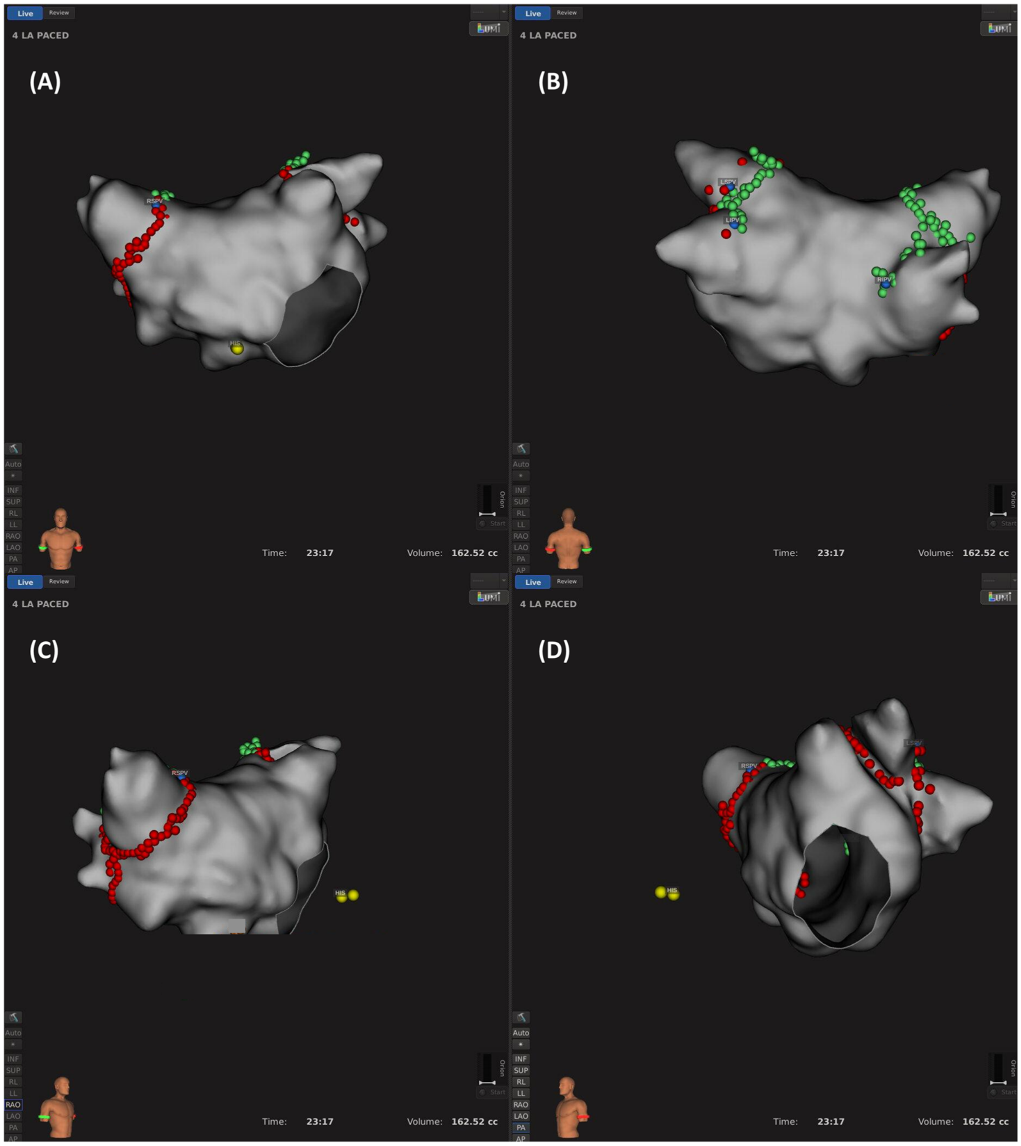

Fig. 2 Examples of ablation points in partial antral ablation **A** anteroposterior, **B** posteroanterior, **C** right anterior-oblique and **D** left anterior-oblique view of three-dimensionally reconstructed image of left atrium. Ablation points are simultaneously displayed. In this patient, the left and right superior pulmonary vein (PV) did not exhibit a passively-activated segment. Therefore, a circumferential ablation at the PV antrum was performed. However, the left inferior and right inferior PVs exhibited passively-activated segments, and electrical isolation of the PVs was obtained only with a partial antral ablation (successful partial antral ablation). The red dots indicate a 30 W ablation. The green dots indicate a 25 W ablation. The blue dots indicate the isolation point

However, the total procedure time was significantly higher in the PA-UHD group. In the PA-UHD group, one patient suffered from a groin hematoma after the procedure. Otherwise, there were no acute or late complications during the follow-up period in both groups.

Procedural characteristics of the PA-UHD group

We have already reported detailed results on this subject [9]. In brief, among 240 PVs, passively-activated segments were observed in 140 (58.3%) PVs. Both inferior PVs had more passively-activated segments than the superior PVs (superior 50 PVs vs. inferior 90 PVs, $P < 0.0001$), and the posteroinferior segment exhibited the highest proportion of passively-activated segments. The prevalence of PV segments for "directly activated from the LA" and "passively activated from an adjacent PV" are depicted in Fig. 4. The success rates of partial antral ablation for the PVI in PVs with passively-activated segments were 85%.

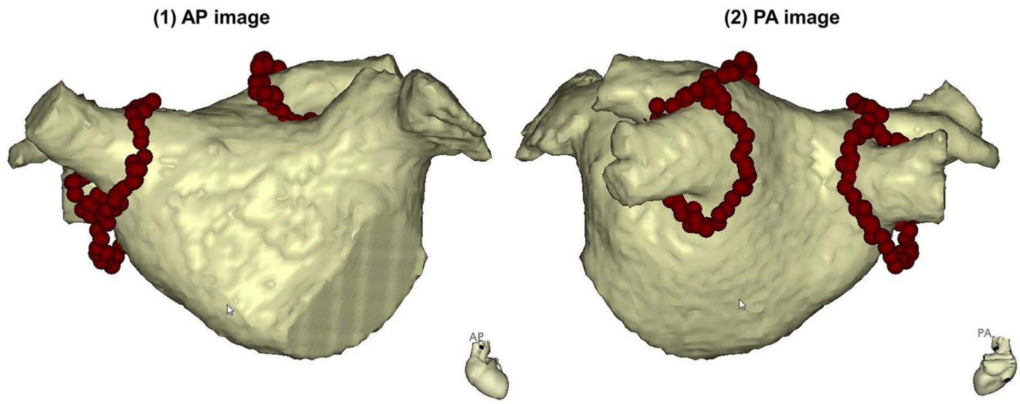

Fig. 3 Examples of ablation points in wide circumferential antral ablation for pulmonary vein isolation

Table 1 Baseline and procedural characteristics

Characteristic	PA-HD ($N=60$)	WACA ($N=59$)	*P* value
Male	50 (66.2)	45 (76.3)	0.339
Age (years)	57.8 ± 5.8	58.3 ± 8.7	0.103
Type of AF			0.655
Paroxysmal	49 (81.7)	50 (84.7)	
Persistent	11 (18.3)	9 (15.3)	
LV EF (%)	61.5 ± 6.3	62.3 ± 7.8	0.509
LA volume	90.2 ± 25.7	89.7 ± 22.3	0.906
History of hypertension	23 (38.3)	25 (42.4)	0.655
History of diabetes	8 (13.3)	9 (15.3)	0.766
CTI ablation	19 (31.7)	22 (37.3)	0.413
Procedure time (min)	202.9 ± 38.2	173.2 ± 47.8	0.004
Fluroscopy time (s)	1570.1 ± 473.8	1720.3 ± 396.0	0.114
Ablation time (s)	2764.2 ± 860.8	3677.7 ± 877.3	0.000
LA mapping points	16,446 ± 3852	4355 ± 666.7	0.000
AF recurrence at 1-year	10 (16.7)	9 (15.3)	0.411

Values are presented as n (%) or mean ± SD

PA-UHD group—partial antral ablation using Rhythmia 3D EAM system, *WACA*—wide antral circumferential ablation, *AF*—atrial fibrillation, *LV*—left ventricle, *EF*—ejection fraction, *LA*—left atrium, *CTI*—cavo-tricuspid isthmus

Clinical outcomes

The atrial tachyarrhythmia recurrence during the 1-year follow-up period was observed in 10 and 9 patients in the PA-UHD and WACA groups, respectively. In the PA-UHD group, three patients recurred with atrial tachycardia, and 7 patients recurred with AF. In the WACA group, 4 patients recurred with atrial tachycardia, and 5 patients recurred with AF. This difference was statistically not significant ($P=0.791$).

The Kaplan–Meier survival curves are shown in Fig. 5. The log-rank test of the survival rates between the two groups also did not show a statistical difference ($P=0.746$).

Discussion

Our study revealed the presence of passively-activated PV segments, which could potentially indicate muscular discontinuity at the PV-LA junction. Notably, in most PVs with passively-activated segments, PVI was successfully achieved even when sparing the ablation of the passively-activated segments. Moreover, the 1-year recurrence rate of atrial tachyarrhythmia in this group was comparable to that observed in the WACA group.

The clinical implications of these findings are as follows. Firstly, adopting a partial antral ablation approach can significantly reduce the amount of ablation required to achieve complete PVI. As a result, this approach minimizes myocardial damage, which could be particularly beneficial for patients with AF at the early stages of atrial cardiomyopathy, considering AF's progressive nature. Secondly, implementing the PA-UHD approach, especially by sparing the posterior segments of the inferior veins from ablation, may reduce the risk of collateral damage to critical structures such as the esophagus or descending aorta. This is particularly significant as collateral damage to these structures is known to be a major complication of AF RFCA.

The Rhythmia HD mapping system allows for a detailed evaluation of the activation patterns of the PV antrum. Through this system, previously undiscovered passively-activated PV antral segments have been identified, suggesting the presence of muscular discontinuity at the PV-LA junction. A partial antral ablation strategy, based on HD activation mapping, proved to be both feasible and effective for PVI and reduced the number of radiofrequency energy deliveries required. Especially the 1-year atrial tachyarrhythmia recurrence rate was comparable to that of the current WACA strategy.

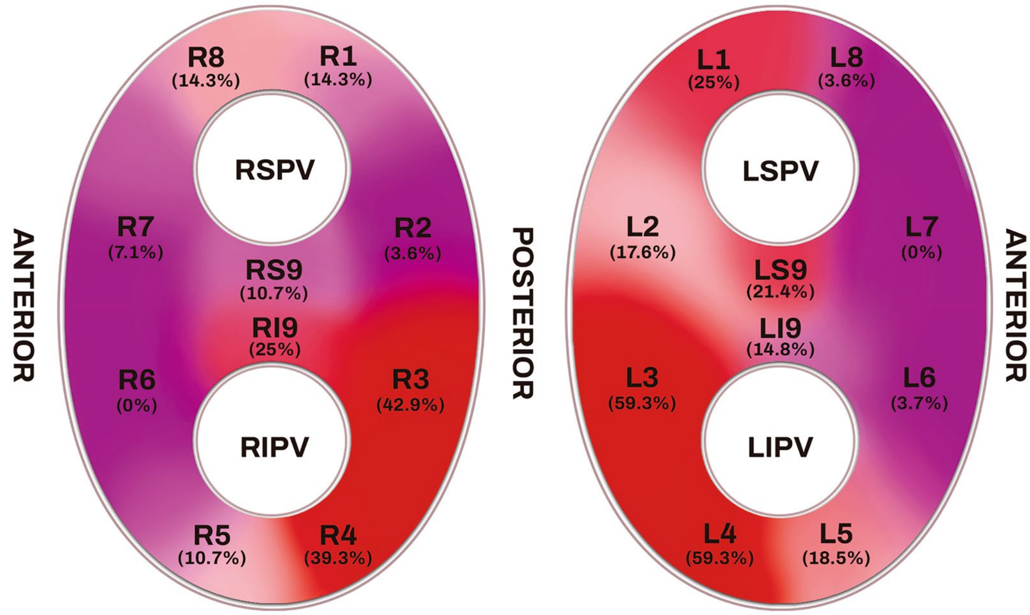

Fig. 4 The proportion of passively-activated segments at each pulmonary vein (PV) segment. The left side represents the right PV, and the right side represents the left PV. We divided the PV from posterosuperior to anterosuperior into segments 1–8 (R1-8, L1-8), with the carina as zone 9, further divided into superior and inferior. The presented values indicate the ratio of passively-activated segments in each segment (number of passively-activated segments/60). The areas with a higher ratio of passively-activated segments are depicted in red, while lower ratios are shown in purple

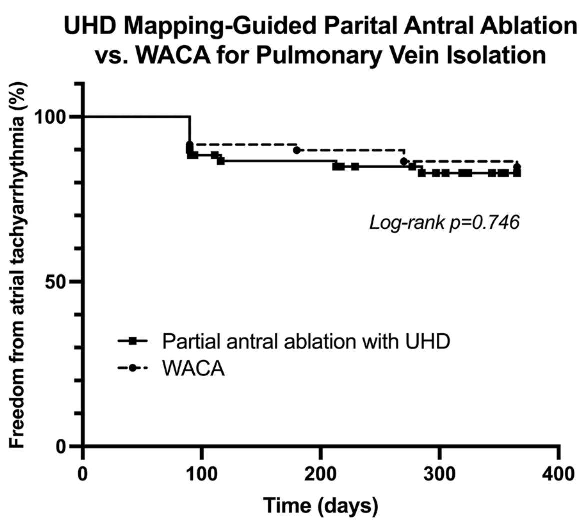

Fig. 5 A Kaplan Meier survival curve analysis. The freedom from atrial tachyarrhythmia recurrence did not differ between the two groups during the 1-year follow-up period

Anatomical and histological investigations of the human LA have uncovered a complex structure with considerable variations in both the PV-LA junction and the PVs [10]. These variations encompass gross anatomical differences and histological variances, particularly in the length, orientation, and thickness of the myocardial fibers that extend into the PVs.

Back in 2001, Ho et al. [11] conducted a postmortem histologic study, revealing highly variable myocardial architecture in normal pulmonary veins. Specifically, they noted that the sleeves in the superior veins were thickest at the inferior aspect and thinnest at the superior aspect, with the reverse arrangement in the inferior veins. Moreover, the sleeves were significantly thicker in the left superior veins, but no such difference was observed in the right veins. Cabrera et al. [12] conducted an intravascular ultrasound study on postmortem pulmonary veins, which revealed instances where an intermediate layer was absent due to the lack of myocardial extensions into the pulmonary veins. Furthermore, Tan et al. observed that more than half of the PV-LA segments exhibited muscular discontinuities and abrupt changes in fiber orientation, which are believed to be significant substrates for re-entry circuits [7]. All these research findings collectively support the rationale behind our PA-UHD strategy.

As mentioned earlier, PVI remains the cornerstone of interventional treatment for AF. Despite our previous report on the feasibility of partial antral ablation for PVI, WACA is still considered the standard approach, and recent technological advancements are focused on performing WACA faster and safer [Cryoballoon, Pulsed-field ablation (PFA)]. However, although PFA is one of the WACA techniques, it is considered a promising treatment option from the perspective of our study as well, that even in regions of the PV antrum showing a passively-activation pattern where there is little or no myocardium present, PFA can minimize collateral damage [13]. We hope for the future development of a technique that enables selective ablation of only the necessary antrum for PVI using PFA and UHD mapping.

The limitations of our PA-UHD strategy have already been reported [9]. The activation pattern of the PV antrum was investigated only under CS pacing. It has already been reported that the activation pattern and low-voltage areas in the LA and LA-PV junction may change depending on the pacing site [14]. It is important to note that procedural time and complexity have increased, which may be partially attributed to a learning curve. Moreover, we did not analyze PV durability in redo procedures, and we did not conduct follow-up imaging examinations to assess the extent of PV antral or collateral damage reduction compared to WACA. In addition, our study was a retrospective study that compared partial antral ablation and WACA using different mapping systems. Based on our study results, a large, randomized study is warranted with the same mapping and ablation system.

Conclusion

In summary, our study suggests that the utilization of UHD mapping and partial antral ablation can offer advantages in terms of reducing ablation energy, collateral damages, and complications, which lead to optimizing outcomes in patients undergoing catheter ablation for AF.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42444-023-00106-1.

Additional file 1. Left superior PV - No passively activated segment was observed. Circumferential ablation of all PV segments was performed.

Additional file 2. Left inferior PV - L3, L4 segments were identified as passively activated segments. Ablation was performed on L5-6-9 segments, and left inferior PV isolation was achieved with partial antral ablation.

Additional file 3. Right superior PV - No passively activated segment was observed. Therefore, circumferential ablation was performed, resulting in right superior PV isolation.

Additional file 4. Right inferior PV - R4, R5 segments were identified as passively activated. Ablation was performed on R9-6-3 segments, and right inferior PV isolation was achieved with partial antral ablation.

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Not applicable.

Author contributions
JH contributed to statistical analysis, data interpretation, manuscript drafting, and critical revision of the manuscript. SH contributed to data acquisition, data interpretation, statistical analysis, critical revision of the manuscript, and study supervision. CH contributed to data acquisition, data interpretation, statistical analysis, critical revision of the manuscript, and study supervision. TWC contributed to statistical analysis, data interpretation, manuscript drafting, and critical revision of the manuscript. HSP contributed to statistical analysis, data interpretation, manuscript drafting, and critical revision of the manuscript.

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Availability of data and materials
The datasets are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
The study was approved by the Institutional Review Board of Keimyung University Dongsan Hospital (DSMC 2018-07-008). All the patients provided written informed consent before enrollment. This trial was registered with ClinicalTrials.gov, registered 25 November 2018, https://classic.clinicaltrials.gov/ct2/show/NCT03759912.

Consent for publication
All authors consent to publication.

Competing interests
The authors declare that they have no competing interests.

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