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ORIGINAL RESEARCH

CATHETER ABLATION - ATRIAL FIBRILLATION

In Atrial Fibrillation, Omnipolar Voltage Maps More Accurately Delineate Scar Than Bipolar Voltage Maps

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ABSTRACT

BACKGROUND Optimal method for voltage assessment in AF remains unclear.

OBJECTIVES This study evaluated different methods for assessing atrial voltage and their accuracy in identifying pulmonary vein reconnection sites (PVRSs) in atrial fibrillation (AF).

METHODS Patients with persistent AF undergoing ablation were included. De novo procedures: voltage assessment in AF with omnipolar voltage (OV) and bipolar voltage (BV) methodology and BV assessment in sinus rhythm (SR). Activation vector and fractionation maps were reviewed at voltage discrepancy sites on OV and BV maps in AF. AF voltage maps were compared with SR BV maps. Repeat ablation procedures: OV and BV maps in AF were compared to detect gaps in wide area circumferential ablation (WACA) lines that correlated with PVRS.

RESULTS Forty patients were included: 20 de novo and 20 repeat procedures. De novo procedure: OV vs BV maps in AF; average voltage 0.55 ± 0.18 mV vs 0.38 ± 0.12 mV; $P = 0.002$, voltage difference of 0.20 ± 0.07 mV; $P = 0.003$ at coregistered points and proportion of left atrium (LA) area occupied by low-voltage zones (LVZs) was smaller on OV maps (42.4% ± 12.8% OV vs 66.7% ± 12.7% BV; $P < 0.001$). LVZs identified on BV maps and not on OV maps correlated frequently to wavefront collision and fractionation sites (94.7%). OV AF maps agreed better with BV SR maps (voltage difference at coregistered points 0.09 ± 0.03 mV; $P = 0.24$) unlike BV AF maps (0.17 ± 0.07 mV, $P = 0.002$). Repeat ablation procedure: OV was superior in identifying WACA line gaps that correlated with PVRS than BV maps (area under the curve = 0.89, $P < 0.001$).

CONCLUSIONS OV AF maps improve voltage assessment by overcoming the impact of wavefront collision and fractionation. OV AF maps correlate better with BV maps in SR and more accurately delineate gaps on WACA lines at PVRS. (J Am Coll Cardiol EP 2023;9:1500–1512) © 2023 The Authors. Published by Elsevier on behalf of the American College of Cardiology Foundation. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

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Catheter ablation is a well-established treatment for atrial fibrillation (AF). Pulmonary vein isolation (PVI) remains the cornerstone of treatment; however, beyond this initial lesion set, the results from different strategies have been variable in both paroxysmal and persistent AF.[1]

Substrate based ablation strategies may offer an opportunity to improve outcomes but rely heavily on the correct identification and characterization of scar.[2,3] The recent low-voltage mapping and ablation randomized controlled trial highlights how effective this approach could become in routine practice.[3] Voltage maps are widely employed to represent scar as a nonhistological surrogate, most commonly with peak-to-peak bipolar voltage (BV) electrograms.[4] Bipolar electrogram voltage amplitudes may be misleadingly low in AF when compared with the same areas in sinus rhythm (SR), owing to effects of wavefront orientation relative to the recording electrodes, collision, and fractionation.[5-7] Bipolar electrograms are dependent on wavefront directionality whereby the relative orientation of interelectrode axis is dependent on the direction of the activation. To ensure an optimal bipolar electrogram, the wavefront is required to be parallel to the bipole.[8,9] In AF, because of the multiple wavefront activations and wavefront collisions,[10-12], the bipole orientation will not consistently remain parallel to the wavefront direction and thereby results in underestimation of the BV. Omnipolar technology (OT) is a novel algorithm that mitigates the effect of wavefront directionality and presents the maximal recorded local electrogram during AF.[12] OT overcomes the impact of directionality by using signals obtained from 3 noncolinear electrodes. These signals are used to determine the directionality of a traveling wave and consequently compute a local virtual bipolar signal that represents the largest possible bipolar peak-to-peak voltage.[12] Voltage assessment with OT may thereby provide a more accurate and reproducible characterization of scar in AF and thereby allow better prediction of AF recurrence[13] and scar homogenization.

In patients requiring repeat ablation for AF, ensuring PVI remains the first-line ablation strategy. The conventional technique of identifying PV reconnections with or without pacing with a catheter in the PV can be time consuming.[14] Substrate characterization of gaps in wide area circumferential ablation lines (WACAs) could offer a more efficient method to identify PV reconnection sites requiring treatment, with omnipolar voltage (OV) potentially being superior to BV in gap delineation.[15]

There are limited data describing the differences in voltage measurements with omnipolar and bipolar in patients with persistent AF. It is also not known which mapping technique is superior in identifying PV reconnection sites.

The aim of the study was to compare OV and BV maps in AF to BV maps in SR and investigate if discrepancies in low-voltage zones (LVZs) in AF correlated to areas of wavefront collision and fractionation and are thereby overcome by OV assessment. The aim was also to demonstrate that OV maps in AF are superior when compared with BV maps in identifying gaps in previous WACA lines that correspond to sites of PV reconnection.

ABBREVIATIONS AND ACRONYMS

AF = atrial fibrillation
BV = bipolar voltage
LA = left atrium
LVZ = low-voltage zone
OT = omnipolar technology
OV = omnipolar voltage
PVI = pulmonary vein isolation
SR = sinus rhythm
WACA = wide area circumferential ablation

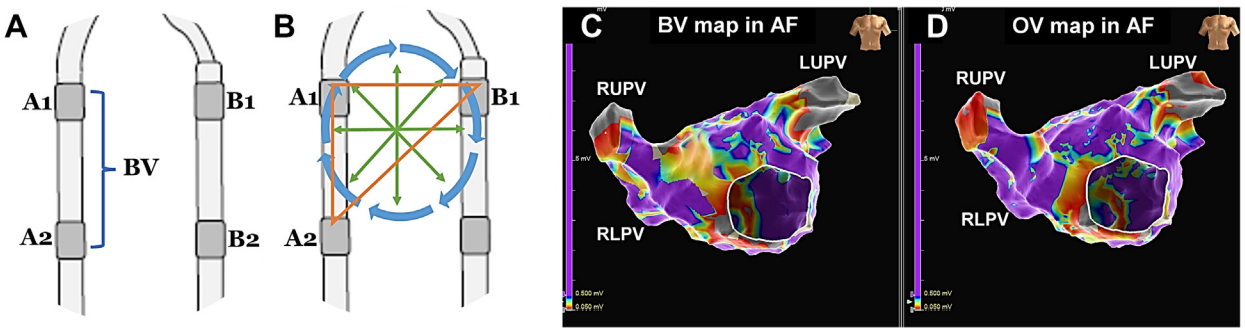
METHODS

The study consisted of 2 parts. All patients were prospectively enrolled. Part 1 enrolled patients undergoing catheter ablation for persistent AF (<24-month duration) with no previous AF ablation. Exclusion criteria included age <18 years and inability to provide informed consent. Patients provided informed consent for their study involvement, which was approved by the UK National Research Ethics Service (22/PR/0961). BV and OV maps in AF and BV maps in SR were compared. Discrepancies in voltage sites and their relationship with fractionation and wavefront collision were assessed. Part 2 included patients who underwent second procedures for persistent AF that had PVI at index procedure. Differences in the ability of OV and BV maps in AF to identify gaps in previous WACA lines that correlated to sites of PV reconnection were assessed. All patients provided informed consent. This part of the study also complied with the Declaration of Helsinki and was registered and endorsed by the Barts Health NHS Trust Clinical Effectiveness Unit (registration ID: 13224).

Procedures were performed under either conscious sedation or general anesthetic as per the clinician and patient's preference. All procedures were performed on uninterrupted anticoagulation therapy with administration of heparin during the procedure to maintain an activated clotting time of >300 seconds.

ELECTROPHYSIOLOGICAL MAPPING. For both study parts the EnSite X (Abbott) system was used. Left atrial (LA) anatomical maps were created using the HD grid-mapping catheter (Abbott). All patients were in AF at the start of the procedure. A high-density OV and BV map was created in AF for all patients. For BV assessment, the bipole obtained from the electrodes along the spline of the HD grid was used (**Figures 1A to 1D**). The window of interest (WOI) was set to exclude

FIGURE 1 Bipolar and Omnipolar Voltage Methodology



(A) An HD grid catheter that highlights a bipole was used to determine the bipolar voltage. **(B)** HD grid catheter that highlights 3 colinear electrodes **(red triangle)** that make up a clique. These are used to calculate the BV in all directions over 360 degrees **(green arrows)**. The BV with the largest bipolar peak-to-peak voltage is then used to compute a local virtual bipolar signal that represents the OV. **(C)** BV map in AF. **(D)** OV map in AF. The maps demonstrate a discrepancy in the low voltage distribution. On the BV map, the anterior wall has extensive low voltage, whereas this is not as marked on the OV map.AF = atrial fibrillation; BV = bipolar voltage; HD = high definition; LUPV = left upper pulmonary vein; OV = omnipolar voltage; RLPV = right lower pulmonary vein; RUPV = right upper pulmonary vein.

the QRS complex. The number of atrial beats within the WOI was dependent on the AF cycle length and the ventricular rate in AF. The largest peak-to-peak voltage point was then determined from all the atrial beats in the WOI. Following this, all peak-to-peak voltage points identified within a 1-mm sphere were then identified. The best duplicate algorithm was then applied, whereby the timing annotations of all these points were analyzed. The extreme outliers were excluded. The remaining points were analyzed, and the average timing annotation was calculated. The point with the largest voltage with timing near the average timing was used for the final BV. For OV assessment, signals were obtained from 3 noncolinear electrodes that make up a clique. These are used to calculate the BV in all directions over 360 degrees. The BV with the largest bipolar peak-to-peak voltage is then used to compute a local virtual bipolar signal that represents the OV (Figures 1A to 1D). Following this, all peak-to-peak voltage points identified within a 1-mm sphere were identified. The voltage point with the highest OT certainty (numeric value ranging from 0 to 1, indicating how certain the calculated activation direction is), and the largest voltage amplitude is then used for the final OV.

Points ≥3 mm from the geometry surface were considered as not being in contact with the myocardium and were removed. All points acquired were respiratory gated to optimize the accuracy of anatomical location. A minimum of 2,000 points was collected per patient, with the aim to ensure adequate atrial coverage. The interpolation threshold was set to 5 mm for surface color projection, and points were collected aiming for complete LA coverage (ie, with no area >5 mm from a data point). To compare the voltage measurements with omnipolar and bipolar, electrogram, point coordinates and geometry data were exported from the EnSite X mapping system and analyzed through an automated algorithm in Mathlab (Mathworks).

In Part 1 of the study, following OV and BV map collection in AF, patients were cardioverted to SR. Post cardioversion the geometry was assessed to ensure that there was no geometry shift. If there was a geometry shift, a repeat geometry was created for the SR BV map. Repeat BV maps were created following cardioversion to SR. LVZs were defined as sites with a voltage of <0.5 mV.[16] All patients then underwent PVI with bilateral WACA lines using the Tactiflex ablation catheter (Abbott), using 45 W for 15 seconds anteriorly and 12 seconds posteriorly. A minimum contact force of 5 g was used.

In Part 2 of the study, following OV and BV maps in AF, PV reconnection sites were mapped and ablated. The operator was blinded to the OV and BV maps. PV reconnection sites were mapped by identifying the earliest site of activation on the HD grid-mapping catheter in AF. Live view, a dynamic, beat-to-beat mapping algorithm (Abbott) was used to aid in mapping the PVs and isolating the veins. The PV reconnection site was defined as either the site of PVI with ablation or a change in PV activation with the ablation, suggesting breakout from an alternative WACA site. Subsequent changes in the PV-signal activation following ablation were mapped and ablated, and this process was repeated in turn until PVI. Following PVI, additional ablation was performed at the operator's discretion. If SR was not achieved with ablation, the

patient underwent DC cardioversion to SR. All PVs were checked in SR to ensure PVI. The study method is summarized in Supplemental Figure 1.

PART 1: COMPARISON OF OMNIPOLAR VOLTAGE AND BIPOLAR VOLTAGE MAP LOW-VOLTAGE ZONES IN ATRIAL FIBRILLATION. The average voltage obtained on the OV maps was compared with the BV maps. The difference in voltage at a colocating site assigned by OV and BV was determined. The proportion of the LA area, excluding the PVs and mitral valve annulus occupied by LVZs, was compared across the 2 maps. The percentage of points that were assigned as low voltage points (<0.5 mV) was also compared between the 2 maps.

COMPARISON OF WAVEFRONT COLLISION AND FRACTIONATION ON OMNIPOLAR VOLTAGE MAPS AT BIPOLAR VOLTAGE LOW-VOLTAGE ZONES. The OV and BV maps in AF were superimposed. LVZs identified on the BV maps and not on the OV maps were identified. At these sites (denoted as BV islands), the OT activation vector and fractionation maps, created by the EnSite X mapping system ,were reviewed to identify sites of wavefront collision and fractionation. OT activation vector mapping allows wavefront directionality to be determined in AF.[17] It does not require a fixed reference, as each electrode acts as its own reference. OT uses electrical characteristics obtained from 3 neighboring electrodes—that is, clique—and uses this information to create a traveling wave to predict wavefront directionality.[17] Fractionation maps were created through reviewing the number of deflections seen in the window of interest for the BV maps (300-ms window). Fractionation secondary to functional slow conduction was defined as sites that demonstrated fractionation in the context of normal voltage (≥0.5 mV) on the SR BV map. Fractionation secondary to pathologic slow conduction was defined as sites that demonstrated fractionation in the context of low voltage (<0.5 mV) on the SR BV map.

COMPARISON OF VOLTAGE MAPS IN ATRIAL FIBRILLATION TO VOLTAGE MAPS IN SINUS RHYTHM. The BV and OV maps in AF were compared with the BV maps in SR. Voltages were compared to determine which maps in AF better correlated to the BV maps in SR. Voltage points on the OV and BV maps in AF were coregistered to voltage points on BV maps in SR in accordance with xyz coordinates. A point was defined as colocating to another point if they were within a geodesic distance of <3 mm. The voltage points were compared to determine differences in the assigned voltage at an anatomical site across the 3 maps. Patients were also subdivided into 3 groups in accordance with the proportion of the LA area occupied by LVZs on the BV maps in SR: <30% LVZs; 30% to 60% LVZs; and >60% LVZs. The proportion of the LA area occupied by LVZs on the OV and BV maps in AF compared with BV maps in SR were reviewed separately for the 3 groups to ensure the findings were consistent, regardless of the underlying proportion of the LA area occupied by LVZs.

PART 2: IDENTIFICATION OF GAPS IN PREVIOUS WIDE AREA CIRCUMFERENTIAL ABLATION LINES THAT CORRELATE TO PULMONARY VEIN RECONNECTION SITES ON OMNIPOLAR VOLTAGE AND BIPOLAR VOLTAGE MAPS. OV and BV maps in AF were reviewed and the number of gaps identified determined. A gap was defined as an area in the previous WACA line with a voltage ≥0.5 mV. An 11-segment anatomical model (Supplemental Figures 2A and 2B) was used to identify the anatomical site of the gaps. The correlation between tagged PV reconnection sites to the gaps identified on the voltage maps was determined. A tagged PV reconnection site was defined as colocating with a WACA line gap if they were within a geodesic distance of <3 mm.

STATISTICAL ANALYSIS. All statistical analyses were performed using SPSS (IBM SPSS Statistics, Version 25, IBM Corp). Continuous variables are displayed as mean ± SD. Categorical variables are presented as a number and percentage. Paired Student's *t*-test was used to compare BV and OV measurements in AF with BV measurements in SR with regard to the global voltage, proportion of points assigned as LVZs, proportion of LA area occupied by LVZs, and difference in voltage at coregistered points on AF and SR maps. A point-to-point comparison of the voltage obtained with OV and BV in AF was also performed with Bland-Altman analysis to assess for agreement. A *P* value of <0.05 was deemed significant. The statistical tests performed in this study were reviewed and approved by a statistician.

RESULTS

PART 1. A total of 20 patients were included (mean age 61.7 ± 10.6 years, 17 of 20, 85.0% male). The baseline characteristics are presented in **Table 1**. The majority of procedures were performed under sedation (14 of 20, 70%) and as a day case procedure (18 of 20, 90.0%). The average procedural time was 154.2 ± 48.5 minutes, with a fluoroscopy time of 2.8 ± 1.1 minutes and dose-area product (DAP) of 30.8 ± 11.6 cGycm^2. The average ablation time was 20.2 ± 3.5 minutes. All patients were in AF at the start

TABLE 1 Baseline Characteristics for Part 1 and 2 of the Study

	Part 1 Cohort (n = 20)	Part 2 Cohort (n = 20)
Age y	61.7 ± 10.6	61.5 ± 12.4
Male	17 (85.0)	13 (65.0)
Diabetes mellitus	3 (15.0)	0
Hypertension	11 (55.0)	7 (35.0)
Transient ischemic attack/cerebrovascular attack	1 (5.0)	1 (5.0)
Ischemic heart disease	5 (25.0)	1 (5.0)
Cardiac surgery	0 (0)	1 (5.0)
Left ventricular ejection fraction ≥55%	12 (60.0)	18 (90.0)
Left atrium size, cm^2		
20-30	0 (0)	17 (85.0)
30-40	2 (10.0)	3 (15.0)
>40	18 (90.0)	0
AF duration months	19.1 ± 13.1	18.5 ± 6.2
Previous AT ablation (including patients with AT and AF) cavotricuspid isthmus-dependent flutter	3 (15.0)	2 (10.0)
Current antiarrhythmic or rate-controlling strategy		
Beta-blockers, including sotalol	18 (90.0)	11 (55.0)
Amiodarone	7 (35.0)	5 (25.0)
Flecainide	2 (10.0)	1 (5.0)
Current anticoagulation strategy		
Warfarin	0 (0)	6 (30.0)
Novel oral anticoagulants	20 (100)	14 (70.0)

Values are mean ± SD or n (%).
AF = atrial fibrillation; AT = atrial tachycardia.

of the case. All patients had an OV and BV map created in AF before undergoing direct current cardioversion to SR followed with a BV map created in SR. All patients underwent PVI with bilateral WACAs. Three patients also had a roof line ablated, and 1 had a cavotricuspid isthmus (CTI) line for previously documented atrial tachycardia-atrial flutter. All procedures were successful, with no acute complications.

COMPARISON OF VOLTAGE MEASUREMENTS ON OMNIPOLAR VOLTAGE AND BIPOLAR VOLTAGE MAP IN ATRIAL FIBRILLATION. A total of 20 OV maps and 20 BV maps in AF were created. Voltage was assessed across 81,397 ± 56,237 points per patient. In AF, the average voltage calculated from OV maps differed significantly to the BV maps (0.55 ± 0.18 mV vs 0.38 ± 0.12 mV; $P = 0.002$). When comparing the voltage at coregistered points, OV was significantly higher than BV, with an average difference of 0.20 ± 0.07 mV, $P = 0.003$. The proportion of the LA area occupied by LVZs using OV was also significantly lower (42.4% ± 12.8% OV vs 66.7% ± 12.7% BV; $P < 0.001$), with an average difference of 24.3% ± 5.9%. Using omnipolar mapping, the proportion of points assigned as low voltage was lower (65.3% ± 12.4% OV vs 77.4% ± 10.3% BV; $P = 0.001$), with an average difference of 12.4% ± 3.3% of points assigned as low voltage (Figures 1A to 1D). For the point-to-point comparison of the OVs and BVs for points in AF, a total of 216,707 points comparisons were included. The OVs displayed a significant disagreement with the BVs by Bland-Altman analysis, whereby there was a significant lack of agreement within 2 SDs of the difference in measurements (mean difference: 0.221 mV; 95% CI: 0.219-0.222; $P < 0.001$). The difference in measurements was consistently greater than zero, indicating that the OVs for the points were consistently greater than the BVs for the points (Figure 2). Further to this, the plots also trended positively, whereby the difference in voltage between OV and BV was directly proportional to the average voltage measured.

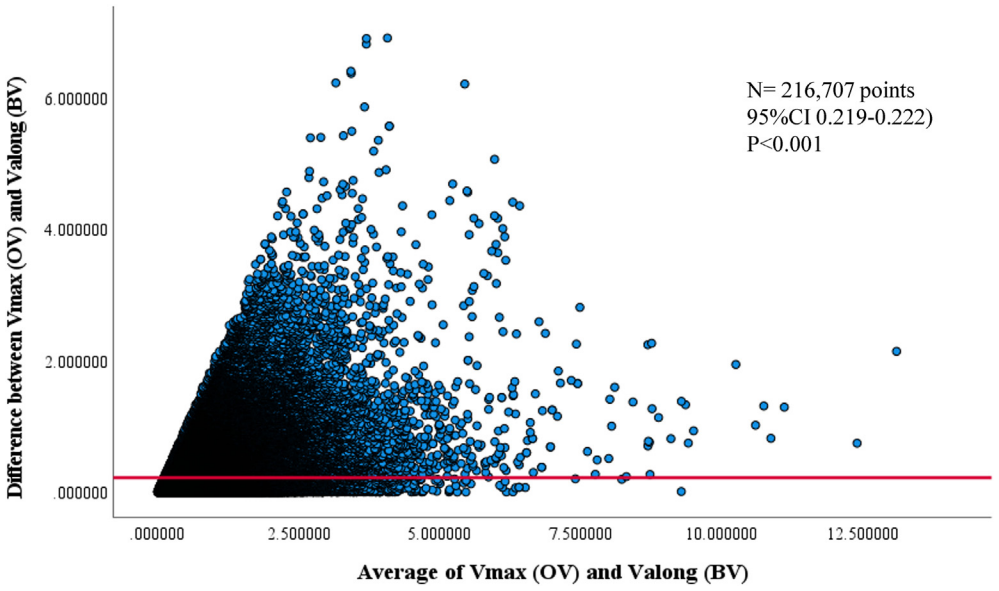
WAVEFRONT COLLISION AND FRACTIONATION AT SITES OF LOW-VOLTAGE ZONES DISCREPANCY ON OMNIPOLAR VOLTAGE AND BIPOLAR VOLTAGE MAPS. In AF, a total of 76 (3.8 ± 1.8) islands of LVZs were only seen on the BV maps. The activation vector maps were reviewed to elicit sites of wavefront collision. Across the 20 OV maps, a total of 85 (4.3 ± 1.9) wavefront collision sites were identified. Out of these sites, 69 (81.2%) sites correlated with the islands of LVZs only seen on BV maps.

Reviewing the fractionation maps, a total of 81 (4.1 ± 1.6) sites of fractionation were identified. Of the 81 fractionation sites identified, 42 (51.9%) sites correlated to low voltage on the BV maps in SR and was defined as pathologic slow-conduction sites. The remaining 39 (48.1%) sites correlated to normal voltage on the BV maps in SR and were defined as functional slow-conduction sites.

Out of 81 fractionation sites identified, 42 (51.9%) correlated to islands of LVZs seen on both the BV maps and OV maps in AF. The remaining 39 (48.1%) sites correlated to islands of LVZs only seen on BV maps in AF. Therefore, of the 76 islands of LVZs only seen on the BV maps, 39 (51.3%) correlated to sites of fractionation (Central Illustration A to E). Combining the presence of wavefront collision and fractionation, out of the 76 islands of LVZs only seen on the BV maps, 72 (94.7%) correlated to sites of wavefront collision and fractionation.

COMPARISON OF VOLTAGE MAPS IN ATRIAL FIBRILLATION TO VOLTAGE MAPS IN SINUS RHYTHM. Across 17,333.7 ± 4,233.3 points, BV maps in SR demonstrated an average voltage of 0.62 ± 0.19 mV. The proportion of the LA area, excluding

FIGURE 2 A Bland-Altman Plot, Whereby the OV Measurements (Vmax) Were Compared With BV Measurements (Valong) Across 216,707 Points



The y-axis represents the difference between OV and BV measurements. The x-axis represents the average of OV and BV measurements. As shown in the Bland-Altman plot a majority of the differences fall above the CIs as shown as the **red line** on the plot. Abbreviations as in Figure 1.

PVs and mitral valve annulus, with LVZs was 42.8% ± 13.1%. The proportion of points defined as low voltage was 63.2% ± 10.8%.

Although the average voltage on the BV maps in SR did not differ significantly from the average voltage on the OV maps in AF (0.62 ± 0.19 mV vs 0.55 ± 0.18 mV; $P = 0.16$), it did differ significantly when compared with BV maps in AF (0.62 ± 0.19 mV vs 0.38 ± 0.12 mV; $P = 0.002$). This was also the case for the proportion of points defined as low voltage and proportion of the LA area with LVZs (Table 2, Figures 3A to 3C, Supplemental Figure 3).

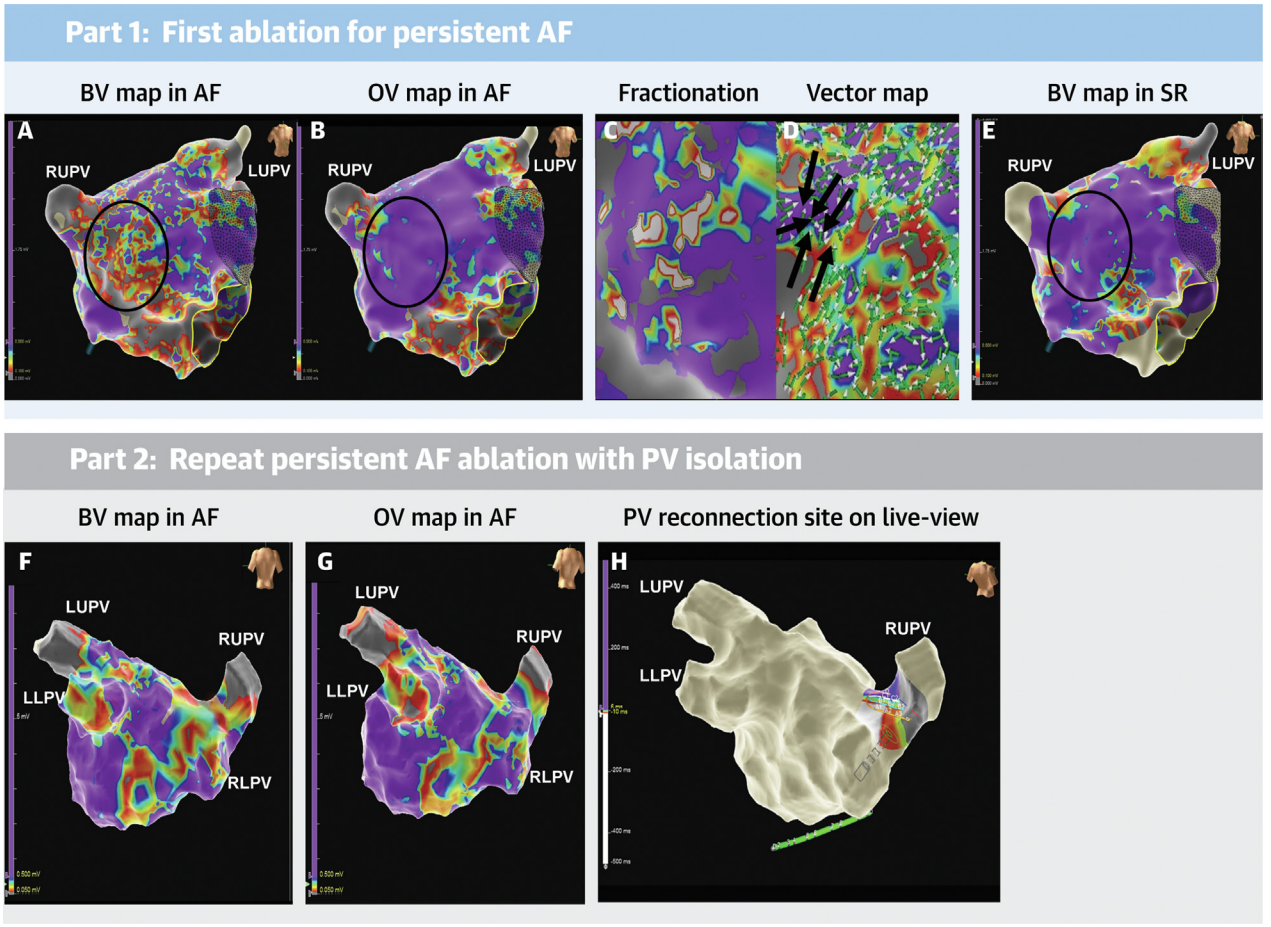
When comparing coregistered points on the OV maps in AF with the BV maps in SR, there was no significant difference in voltage (0.09 ± 0.03 mV, $P = 0.24$). When comparing coregistered points on the BV maps in AF with the BV maps in SR, there was a significant difference in voltage (0.17 ± 0.07 mV, $P = 0.002$).

There was no significant difference in the proportion of the LA area occupied by LVZs when comparing the OV maps in AF with the BV maps in SR across the 3 groups defined by the proportion of the LA area occupied by LVZs on the BV maps in SR (Table 2). BV maps in AF, however, demonstrated a significant difference (Table 2).

PART 2: IDENTIFICATION OF GAPS IN PREVIOUS WIDE AREA CIRCUMFERENTIAL ABLATION LINES ON OMNIPOLAR VOLTAGE AND BIPOLAR VOLTAGE MAPS AND CORRELATION WITH PULMONARY VEIN RECONNECTION SITES. Twenty patients undergoing repeat ablation for persistent AF were included (mean age 61.5 ± 12.4 years, 13 of 20, 65% male). Baseline characteristics are demonstrated in Table 1. All patients had undergone previous cryoablation to achieve PVI. The majority of procedures were performed under local anesthetic and sedation (17 of 20, 85.0%). The average procedure duration was 121.5 ± 56.5 minutes and median fluoroscopy time of 3.1 minutes (2.1 minutes). All patients underwent repeat PVI of at least 1 PV (range: 1 to 4), with an average of 2.4 ± 0.8 veins treated for reconnection. Of the 20 patients, 15 patients underwent additional ablation beyond PVI, which included roofline (6 of 15, 40.0%), mitral line (4 of 15, 26.7%), CTI line (6 of 15, 40.0%), and complex fractionated electrogram ablation (5 of 15, 33.3%). The average RF ablation time was 24.5 ± 15.3 minutes. All procedures were successful, with no acute complications.

A total of 48 PVs were reconnected (2.4 ± 0.8 PVs per patient). The right upper PV was the most reconnected (n = 14; 29.2% left upper PVs, n = 9,

CENTRAL ILLUSTRATION **Illustrative Summary of Study Findings**



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Part 1: **(A)** BV map in AF of the LA in an anterior-posterior view. **(B)** OV map in AF of the LA in an anterior-posterior view. The maps demonstrate a discrepancy in the low voltage distribution. On the BV map, the anterior wall has extensive low voltage, whereas this is not as marked on the OV map. The LVZ on the BV map that is not seen on the OV map corresponds to a site of wavefront collision and fractionation as shown on **(C)**, fractionation map. **(D)** Activation vector map. (E) BV map in SR that correlates better to the OV map in AF then the BV map in AF. LA = left atrium; LVZ = low-voltage zone; SR = sinus rhythm. Other abbreviations as in Figure 1. Part 2: **(A)** BV map in AF of the LA in a posterior-anterior view. **(B)** OV map in AF of the LA in a posterior-anterior view. The voltage maps demonstrate discrepancies in the identification of gaps in the previous WACA lines. The OV map in AF demonstrates additional gaps posterior and posterior-superior of the RUPV. **(C)** On mapping the RUPV, the live view demonstrates earliest breakthrough posteriorly. WACA = wide area circumferential ablation; other abbreviations as in Figure 1.

18.8% left lower PVs, n = 16, 33.3% right upper PVs, and n = 9, 18.8% right lower PVs). A total of 62 PV reconnection sites were ablated to achieve PVI (3.1 ± 1.0 PV reconnection sites per patient). The anatomical segments of these PV reconnection sites are demonstrated in **Table 3**. All patients had both OV and BV maps created in AF. A total 68 gaps in the previous WACA lines on the OV maps (3.4 ± 1.1 gaps per patient) and 42 gaps on the BV maps (2.1 ± 0.7 gaps per patient) were identified. The anatomical segments of these gaps are demonstrated in **Table 3**.

Of the 62 PV reconnection sites identified, 58 (93.5%) correlated with gaps in the previous WACA lines identified on the OV maps (**Figures 4A to 4F**, Supplemental Figures 4A and 4B). The OV maps identified an additional 10 gaps that did not correlate with PV reconnection sites. The diagnostic accuracy of the OV maps identifying PV reconnection sites was

TABLE 2 Differences Between Voltage Parameters Among the OV Maps in AF, BV Maps in AF, and BV Maps in SR

	OV Maps in AF (n = 20)	BV Maps in AF (n = 20)	BV Maps in SR (n = 20)	*P* Value: OV AF vs BV SR	*P* Value: BV AF vs BV SR
Voltage, mV	0.55 ± 0.18	0.38 ± 0.12	0.62 ± 0.19	0.16	0.002
Proportion of voltage points assigned low voltage, %	65.3 ± 12.4	77.4 ± 10.3	63.2 ± 10.8	0.28	<0.001
Proportion of LA area occupied by LVZs, %	42.4 ± 12.8	66.7 ± 12.7	42.8 ± 13.1	0.23	<0.001
LVZs <30% on BV maps in SR	17.1 ± 11,1	29.1 ± 12.2	18.1 ± 10.8	0.42	0.003
LVZs 30%-60% on BV maps in SR	42.4 ± 13.1	57.7 ± 10,8	41.0 ± 11,1	0.34	0.001
LVZs >60% on BV maps in SR	70.9 ± 10.6	83.5 ± 13.1	68.8 ± 12.3	0.45	<0.001
Difference in voltage on AF maps with coregistered points on the SR map, mV	0.09 ± 0.03	0.17 ± 0 .07	-	0.24	0.002

Values are mean ± SD.
AF = atrial fibrillation; BV = bipolar voltage; LA = left atrium; LVZ = low-voltage zone; OV = omnipolar voltage; SR = sinus rhythm.

strong, with an area under the curve (AUC) of 0.89, $P < 0.001$ and with a sensitivity of 93.6% (95% CI: 84.3%-98.2%) and specificity of 76.2% (95% CI: 60.6%-88.0%). The positive and negative predictive value was 85.3% (95% CI: 77.1%-90.9%) and 88.9% (95% CI: 75.3%-95.4%), respectively.

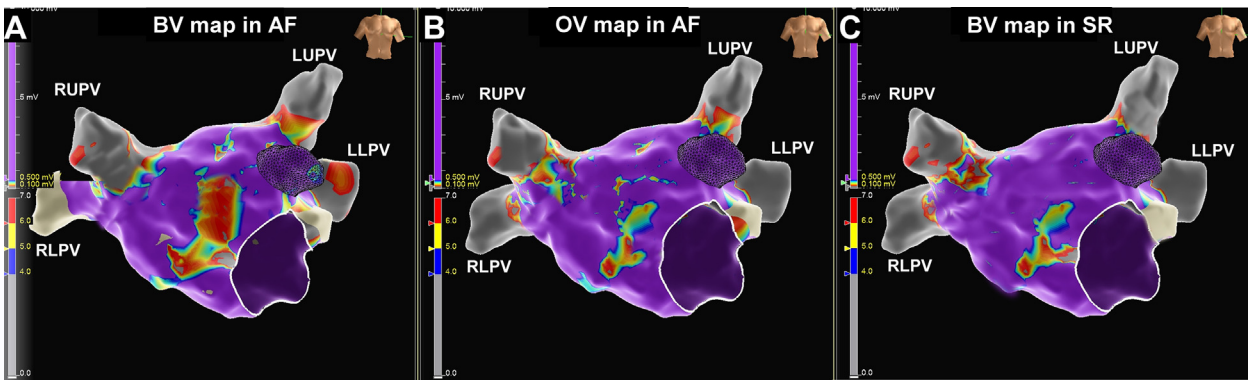
Out of the 62 PV reconnection sites identified, 38 (61.3%) correlated with gaps in the previous WACA lines identified on the BV maps. The BV maps identified 4 additional gaps that did not correlate to PV reconnection sites (**Figures 4A to 4F**, Supplemental Figures 4A and 4B). BV maps did not demonstrate as high diagnostic accuracy in identifying PV reconnection sites, with an AUC of 0.61, $P = 0.07$, with a sensitivity of 61.3% (95% CI: 48.1%-73.4%), and specificity of 88.9% (95% CI: 73.9%-96.9%). The positive and negative predictive value was 90.5% (95% CI: 78.7%-96.1%) and 57.1% (95% CI: 48.9%-65.1%), respectively.

DISCUSSION

This study evaluated the differences in voltage measurements obtained in AF using 2 different methods (omnipolar and bipolar) and compared them with BV maps in SR. The study also examined the clinical utility of these methods to identify gaps in previous WACA lines and their correlation with PV reconnection sites. The main findings of the study are as follows:

- Voltage measurements in AF are lower with bipolar vs omnipolar. The majority of the LVZs seen on the BV maps but not on the OV maps in AF correlated to sites of wavefront collision and fractionation (**Central Illustration**).
- Voltage measurements in AF obtained with omnipolar correlate better with voltage measurements obtained with bipolar in SR.

FIGURE 3 Voltage Maps in AF Compared to BV Map in SR



(A) BV map in AF in an anterior-posterior view that shows LVZ across the anterior wall. **(B)** OV map in AF in an anterior-posterior view that shows less scar across the anterior wall in comparison to the BV map. **(C)** BV map in SR in an anterior-posterior view that shows consistent findings to the OV map in AF with less scar across the anterior wall. LLPV = left lower pulmonary vein; LUPV = left upper pulmonary vein; RLPV = right lower pulmonary vein; RUPV = right upper pulmonary vein.

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TABLE 3 Anatomic Sites of the PV Reconnection and Sleeves on the OV and BV Maps on a Per-Patient Basis

Patient #	PVs Reconnected	PV Reconnected Sites	Anatomic Site of PV Reconnection	Number of Sleeves on OV Maps	Anatomic Location of Gaps	Number of Gaps on BV Maps	Anatomic Location of Gaps
1	LUPV RUPV	4	Posterior R Posterior- superior R Anterior L Anterior-superior L	4	Posterior R Posterior-superior R Anterior L Anterior-superior L	2	Posterior R Anterior L
2	LLPV LUPV RUPV	3	Anterior L Anterior-superior L Anterior R	5	Anterior L Anterior-superior L Anterior R Posterior R Posterior-inferior R	3	Anterior L Anterior R Posterior R
3	LUPV LLPV RLPV RUPV	5	Anterior-superior L Anterior-inferior L Posterior- inferior R Posterior R Anterior- superior R	5	Anterior-superior L Anterior-inferior L Posterior-inferior R Posterior R Anterior R	2	Anterior-inferior L Anterior-superior R
4	LUPV RUPV	2	Anterior L Posterior R	2	Anterior L Posterior R	2	Anterior L Posterior R
5	RUPV RLPV	3	Posterior R Posterior-inferior R Anterior R	3	Posterior R Posterior-inferior R Anterior R	1	Posterior R
6	RUPV RLPV LLPV	3	Posterior R Posterior-inferior R Anterior L	4	Posterior R Posterior-inferior R Anterior L Anterior-superior L	2	Posterior R Posterior-inferior R
7	RUPV LLPV LUPV	3	Posterior-superior R Inferior L Anterior L	4	Posterior- superior R Inferior L Anterior L Anterior-superior L	3	Posterior-superior R Inferior L Anterior L
8	LUPV	2	Anterior L Anterior-superior L	3	Anterior L Posterior-superior L Posterior R	1	Anterior L
9	RUPV RLPV	2	Anterior R Inferior R	2	Anterior R Inferior R	2	Anterior R Inferior R
10	LUPV LLPV RUPV	2	Anterior L Anterior R	2	Anterior L Anterior R	1	Anterior L
11	LUPV LLPV RUPV RLPV	5	Anterior-superior L Anterior L Inferior L Posterior R Anterior-inferior R	4	Anterior-superior L Anterior L Inferior L Posterior R	3	Anterior-superior L Anterior L Posterior R
12	LUPV	2	Anterior L Anterior-superior L	2	Anterior L Anterior-superior L	1	Anterior L
13	RUPV RLPV	4	Posterior-inferior R Inferior R Posterior R Posterior-superior R	4	Posterior-inferior R Inferior R Posterior R Posterior-superior R	2	Posterior-inferior R Inferior R
14	LUPV RLPV	2	Anterior-carina L Posterior-carina R	3	Anterior-carina L Posterior-carina R Posterior R	3	Anterior-carina L Posterior-carina R Posterior R
15	LUPV RUPV	3	Anterior-carina L Posterior-carina R Posterior-superior R	3	Anterior-carina L Posterior-carina R Posterior-superior R	2	Anterior-carina L Posterior-carina R
16	LUPV RUPV	2	Anterior L Anterior-superior R	2	Anterior L Anterior-superior R	2	Anterior-carina L Anterior-superior R
17	LLPV RUPV RLPV	4	Anterior-carina L Superior R Posterior-superior R Posterior-carina R	4	Anterior-carina L Superior R Posterior-superior R Posterior-carina R	3	Anterior-carina L Superior R Posterior-carina R
18	LUPV LLPV RUPV	4	Anterior-carina L Anterior L Posterior-inferior L Posterior-superior R	5	Anterior-carina L Anterior L Posterior-inferior L Posterior-superior R Posterior R	2	Anterior-carina L Posterior-inferior L

Continued on the next page

TABLE 3 Continued

Patient #	PVs Reconnected	PV Reconnected Sites	Anatomic Site of PV Reconnection	Number of Sleeves on OV Maps	Anatomic Location of Gaps	Number of Gaps on BV Maps	Anatomic Location of Gaps
19	LLPV RLPV	3	Anterior L Posterior-superior L Posterior-carina R	3	Anterior L Posterior-superior L Anterior-carina R	2	Posterior-superior L Anterior-carina R
20	LUPV RUPV	4	Posterior-carina L Anterior-superior L Anterior L Anterior R	4	Posterior-carina L Anterior-superior L Anterior L Anterior R	3	Posterior-carina L Anterior-superior L Anterior R

BV = bipolar voltage; L = left; LLPV = left lower pulmonary vein; LUPV = left upper pulmonary vein; LVZ = low-voltage zone; OV = omnipolar voltage; PV = pulmonary vein; R = right; RLPV = right lower pulmonary vein; RUPV = right upper pulmonary vein.

- OV maps in AF more effectively identify gaps in previous WACA lines that correlate to PV reconnection sites compared with BV maps (**Central Illustration**).

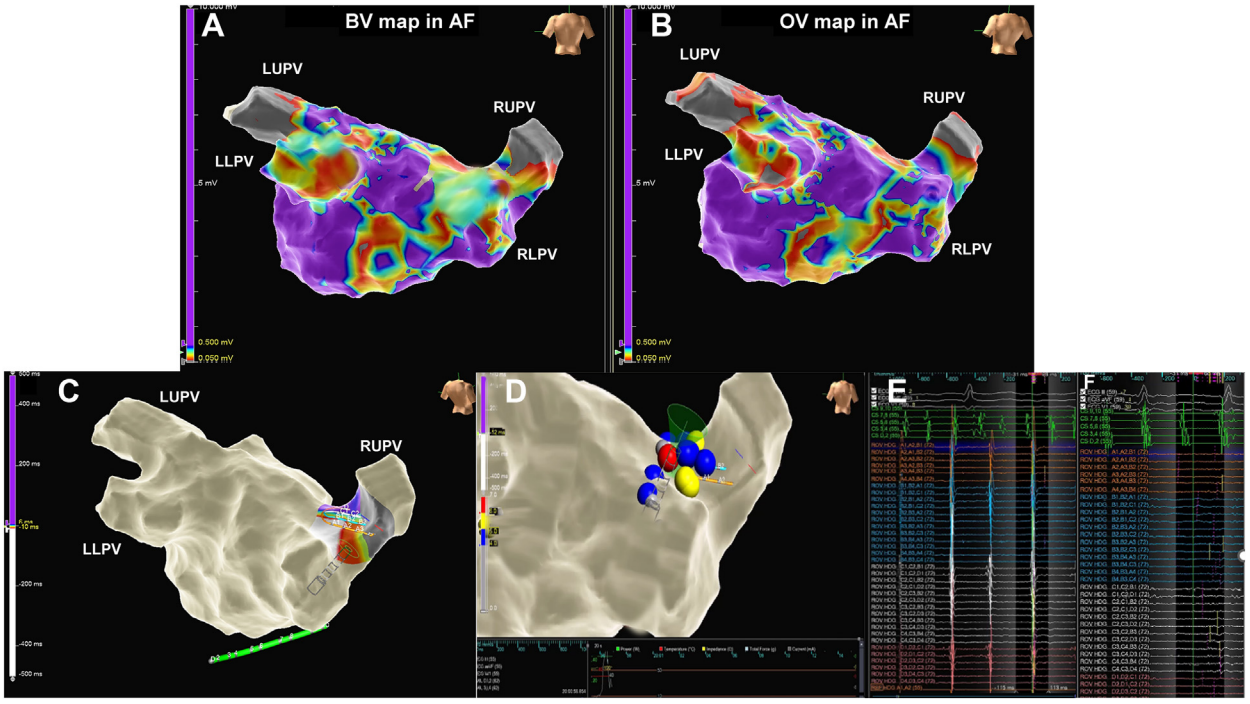
OMNIPOLAR VOLTAGE ATRIAL FIBRILLATION MAPS IMPROVE VOLTAGE ASSESSMENT BY OVERCOMING THE IMPACT OF WAVEFRONT COLLISION AND FRACTIONATION. Voltage maps obtained with a 3-dimensional mapping system have shown to effectively correlate to scar identified on histological samples.[16] Voltage maps are thereby used to gain a representation of LA scar as part of a catheter ablation. The burden of LVZs in the LA correlates with poorer outcomes from catheter ablation with a higher risk of AF recurrence.[4] In addition to being an important predictor of procedural success, LA substrate may also influence treatment strategies. Substrate modification where scar is homogenized with ablation has shown to be an effective treatment strategy in addition to PVI in patients with persistent AF.[3] For such substrate-based strategies to be successful, it is critical to delineate scar reliably to avoid unnecessary ablation, which can create sites of reentry.

BV is measured by subtracting 2 unipolar signals and therefore removing far field data from the resultant electrogram. However, this is heavily dependent on wavefront directionality.[5,8,12] In AF, falsely low BVs may be caused by variable wavefronts, resulting in wavefront collision and fractionation[5,12] or may be caused by functional changes in substrate.[12] It has also been shown that BV measurements are dependent on activation rates, whereby electrograms demonstrate BV attenuation at reduced extra stimulus coupling intervals.[18] It has also been shown that for the BV maps in AF, lower voltage thresholds are required for LVZs for it to be compatible with the LVZs identified on BV maps in SR.[19] It has been proposed that by using high-density mapping, the impact directionality has on BV can be overcome.[20] However, this study only evaluated a single atrial beat rather than reviewing all the atrial beats in the WOI. Therefore, the impact multiple wavefronts and wavefront collision has on BV might not have been demonstrated when using a single atrial beat.

The omnipolar algorithm was designed to overcome these challenges by resolving signals from all possible directions around the mapping location and negate the impact of wavefront directionality.[21] Early work in an animal model demonstrated this, in which the omnipolar algorithm identified consistent LVZ in AF when compared with SR, unlike bipolar mapping.[12] Previous authors have demonstrated fractionation while mapping with BV in AF that was then not seen when remapping in SR, which indicates that the fractionation was functional in nature and a product of both wavefront collision and directionality.[22] This observation was confirmed with omnipolar mapping when investigated in dogs.[12] This is the first human study to confirm that in areas that have low BV and normal OV in AF, changes are affected by wavefront collision and fractionation. We also confirm the observation seen previously in an animal model that a substrate map in AF when mapped with OV correlates better with a BV map in SR, unlike a BV map in AF because of the omnipolar algorithm resolving the impact of wavefront directionality.[12]

OMNIPOLAR VOLTAGE MAPS ALLOW BETTER IDENTIFICATION OF GAPS IN PREVIOUS WIDE AREA CIRCUMFERENTIAL ABLATION LINES THAT CORRELATE TO PULMONARY VEIN RECONNECTION SITES. PVI remains the cornerstone for catheter ablation of AF; therefore, in patients who undergo repeat ablation for AF, the primary ablation strategy is to achieve PVI. Mapping sites of PV reconnection in AF can be time consuming, particularly if there is rapid firing from the PVs. An alternative approach would be to use the

FIGURE 4 Correlation Between Sleeves on WACA Lines With PV Reconnection Sites



(A) BV map in AF of the LA in a posterior-anterior view. **(B)** OV map in AF of the LA in a posterior-anterior view. The voltage maps demonstrate discrepancies in the identification of gaps in the previous WACA lines. The OV map in AF demonstrates additional gaps posterior and posterior-superior of the RUPV. **(C)** On mapping the RUPV, the live view demonstrates earliest breakthrough posteriorly. **(D)** Ablation here resulted in PV isolation and organization of AF into AT **(E and F)** that demonstrates CS and PV electrograms. AT = atrial tachycardia; CS = coronary sinus; PV = pulmonary vein; WACA = wide area circumferential ablation; other abbreviations as in Figure 1.

voltage map to identify gaps in the previous WACA lines that could be representative of the PV reconnection sites.[15]

The voltage maps would also allow assessment of the position of the previous WACA lines, which is particularly relevant with previous cryoablation that can result in the PVI to be achieved more ostial then planned, particularly in the presence of unusual PV anatomy. The voltage map can thereby aid in bringing the previous WACA lines further out and allow greater debulking of the atrium, a strategy that has been shown to improve outcomes in patients requiring repeat procedures.[14] If voltage maps were to be used to guide PVI and position of the repeat WACA lines, it is important that the voltage measurements represent the substrate characteristics accurately. In this study, we have shown that OV maps in AF identify more gaps in previous WACA lines compared with BV maps in AF, which is consistent with the findings of a previous study.[15] However, this is the first study that has correlated the gaps in the previous WACA lines with PV reconnection sites and thereby assessed the clinically significance of these sites. In this study, we have shown that gaps in the previous WACA lines on OV maps in AF are diagnostically more accurate in identifying PV reconnection sites compared with BV maps in AF. Targeting gaps identified on OV maps in AF could be used as an alternative of mapping PV reconnection sites. The clinical superiority of this need to be further evaluated in a randomized controlled trial.

STUDY LIMITATIONS. The patient numbers in this study are small; however, it is compatible with other mechanistic studies. Having evaluated an average of 80,000 voltage points per patient, this is likely sufficient to address the aims of the study. The superiority of voltage assessment in AF with omnipolar as seen in this study needs to be further evaluated in larger mapping studies. We have demonstrated that OV maps better identify gaps in previous WACA lines that correlate to PV reconnection sites compared with

BV maps. However, we did not evaluate whether using this approach for PVI would result in better procedural parameters and outcomes. This needs to be tested in a randomized controlled trial.

CONCLUSIONS

OT is a useful algorithm when mapping the substrate in patients with persistent AF undergoing ablation. It provides a closer representation of the underlying substrate when compared with bipolar mapping through overcoming the impact of wavefront collision and fractionation. OV maps in AF also delineate gaps more accurately within previous WACA lines that correlate to PV reconnection sites in patients undergoing repeat ablation, compared with BV maps in AF. OV maps in AF have the potential to guide substrate modification more accurately and PVI. The clinical utility of this approach needs to be evaluated in future randomized controlled trials.

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PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE: Atrial scar has been used to guide ablation strategies and provide prognostic indications in persistent AF catheter ablation. Patients undergoing ablation for persistent AF were included (de novo and first repeat procedure). All patients underwent voltage assessment in AF and SR. In this study, it was shown that OV in AF provides a closer representation of the underlying substrate as assigned by the BV map in SR when compared with BV in AF, through overcoming the impact of wavefront collision and fractionation. OV maps in AF were also shown to delineate gaps more accurately within previous WACA lines that correlated to PV reconnection sites compared with the BV maps in AF.

TRANSLATIONAL OUTLOOK: This study has demonstrated that OV maps in AF provide a more accurate assessment of atrial scar and identification of gaps in previous WACA lines compared with BV maps in AF. OV maps in AF have the potential to guide substrate modification more accurately and PVI. The clinical utility of this approach needs to be evaluated in future randomized controlled trials.

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KEY WORDS bipolar voltage, omnipolar voltage, persistent atrial fibrillation, pulmonary vein isolation

APPENDIX For supplemental figures, please see the online version of this paper.