

How to Perform Open Window Mapping and Ablation in Patients with Wolff-Parkinson-White Syndrome: A Comprehensive Technical Guide Using CARTO™ and EnSite Electroanatomic Mapping Systems

Wolff-Parkinson-White Sendromlu Hastalarda Open Window Haritalama ve Ablasyon Nasıl Yapılır: CARTO™ ve EnSite Elektroanatomik Haritalama Sistemleri Kullanılarak Kapsamlı Teknik Kılavuz

Wolff-Parkinson-White (WPW) syndrome arises from the persistence of one or more accessory pathways (APs) that bypass the atrioventricular (AV) node, leading to pre-excitation. These pathways may conduct in an antegrade, retrograde, or bidirectional manner and may exhibit either decremental or non-decremental properties. Clinically, patients may present with orthodromic atrioventricular reciprocating tachycardia (AVRT), antidromic AVRT, or pre-excited atrial fibrillation, each with distinct risk profiles. Ablation success hinges on precise anatomical and electrophysiological localization of the AP's atrial and/or ventricular insertion.¹ Conventional local activation time (LAT)-based sequential point-by-point activation mapping or differential pacing strategies can be limited by conduction directionality, far-field overlap, signal distortion, and poor catheter-tissue contact. Open Window Mapping (OWM) overcomes these limitations by integrating anatomical and temporal data into a high-resolution, automated annotation schema that surpasses conventional mapping approaches. The subsequent sections elaborate on how OWM addresses these challenges.

Peri-Procedural Strategy

Surface Electrocardiography

Algorithmic localization of APs in patients with WPW syndrome is a critical step in guiding ablation strategy. Validated electrocardiographic algorithms should be employed to predict the anatomical location of the AP based on surface electrocardiogram (ECG) findings. This involves systematic analysis of delta wave polarity across all 12 leads, along with evaluation of the QRS axis and morphology. Notably, variability in QRS patterns may suggest the presence of multiple APs. Furthermore, intermittent pre-excitation observed on ECG or ambulatory monitoring implies variable antegrade conduction, which can affect both risk assessment and procedural planning. Holter or event monitoring complements the diagnostic work-up by quantifying arrhythmia burden, assessing fluctuations in pre-excitation, and detecting episodes of orthodromic or antidromic AVRT or pre-excited atrial fibrillation—both of which are important in risk stratification and therapeutic decision-making.

Cardiac Imaging

Cardiac magnetic resonance imaging (MRI) or computed tomography (CT) is recommended for patients with structural cardiac anomalies or previous failed ablation attempts, as these modalities offer detailed anatomical visualization that is essential for pre-procedural planning and risk assessment (Video 1). In addition, intracardiac echocardiography (ICE) serves as a valuable tool during electrophysiological procedures by providing real-time imaging guidance. ICE facilitates safe and precise transseptal puncture and supports accurate navigation around the annulus, thereby enhancing procedural efficacy and reducing complications in complex structural settings.

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Although imaging is primarily recommended in the presence of structural cardiac anomalies or previous failed ablation attempts, it can also provide significant procedural advantages in anatomically normal hearts. First, pre-procedural imaging—particularly cardiac MRI or CT—provides high-fidelity three-dimensional (3-D) anatomical reconstructions that can be integrated into the electroanatomic mapping (EAM) system. This integration improves the anatomical accuracy of chamber geometry, facilitates orientation in anatomically complex regions (e.g., annular structures), and reduces reliance on fluoroscopy. Second, ICE, used intra-procedurally, provides real-time visualization of catheter position and tissue contact, which is particularly advantageous when performing high-density mapping along the atrioventricular annulus. Even in structurally normal hearts, such imaging optimizes the spatial correlation between anatomical landmarks and electrophysiological data, thereby reducing mapping errors related to catheter instability, far-field signal interpretation, or anatomic misregistration.

The imaging data might be co-registered with the EAM system before initiation of OWM. This step allows for more precise delineation of atrial and ventricular boundaries and facilitates targeted mapping along the true annular plane. As a result, the anatomical model used during OWM is highly congruent with the patient's native anatomy, improving localization of AP breakthrough sites and, ultimately, increasing mapping accuracy and procedural efficiency.

Diagnostic/Mapping Catheters

Diagnostic catheter placement includes a quadripolar catheter in the high right atrium, a quadripolar catheter at the His bundle region, a decapolar catheter in the coronary sinus (CS), and a quadripolar catheter at the right ventricular apex. For high-density EAM, the CARTO™ system utilizes either the PentaRay™, OctaRay™, or Optrell™ multipolar mapping catheter, while the EnSite system employs the Advisor™ HD Grid catheter. Ablation is performed using a 3.5 mm open-irrigated, contact force-sensing catheter such as the ThermoCool SmartTouch™, TactiCath™, or TactiFlex™ ablation catheter, with irrigation flow rates typically ranging from 17 to 30 mL/min.

Electrophysiological Study

A comprehensive electrophysiological study to evaluate AP conduction and arrhythmia inducibility typically includes incremental and programmed stimulation from both the atrium and ventricle, using decremental cycle lengths and extrastimulus protocols. Burst pacing may be employed to induce orthodromic or antidromic AVRT. Para-Hisian pacing is performed to differentiate a septal AP from AV nodal conduction. Isoproterenol is infused starting at 1 µg/min and titrated up to 5 µg/min as needed to enhance AP conduction, facilitate arrhythmia induction, or achieve a > 20% increase in sinus rate. Differential pacing maneuvers are also utilized to assess ventriculoatrial (VA) conduction and to exclude the presence of bystander pathways.

Conventional mapping remains a widely used electrophysiological technique for localizing APs, either through identification of the earliest retrograde atrial or anterograde ventricular activation, or by direct recording of discrete AP potentials. This method involves the acquisition of bipolar electrograms (EGMs), which are recorded either from a single electrode pair or simultaneously

from multiple electrode pairs using multielectrode catheters. Conventional mapping may be performed with or without the integration of 3-D EAM systems.

When employed without 3-D guidance, the technique relies on the manual correlation of EGM signals with anatomical landmarks and fluoroscopic imaging, which may limit spatial precision. In contrast, the use of 3-D EAM systems enhances this approach by enabling real-time spatial localization of catheter positions within the cardiac chamber. These systems, equipped with automated annotation algorithms, facilitate more accurate mapping by allowing operators to annotate and visualize EGM data within a reconstructed anatomical model.

The introduction of 3-D navigation-compatible, sensor-enabled mapping catheters, particularly multipolar catheters with closely spaced electrodes, permits high-density point acquisition and improves the spatial resolution of EGM recordings. This improved resolution, in association with AP conduction, can lead to more accurate identification of the earliest atrial or ventricular activation sites relative to a reference point.²

Electrophysiological Principles of OWM

Open Window Mapping is an advanced EAM strategy designed to overcome the spatial and temporal limitations of traditional LAT mapping. By annotating LATs to a stable reference—typically the surface QRS complex or a pacing spike—OWM establishes a user-defined temporal interval, called the window of interest (WOI) or roving acquisition interval (RAI), to isolate physiologically relevant electrogram activity. Within this constrained window, the system automatically identifies the earliest near-field local activation by prioritizing steep unipolar negative dV/dt signals or sharp bipolar deflections, thereby reducing or eliminating the need for manual annotation. Thus, it is not necessary to distinguish between atrial, ventricular, or accessory pathway EGMs. Moreover, all signals within the WOI/RAI are included during annotation. This decoupling from global chamber activation enables accurate detection of breakthrough sites across the AV annulus, particularly at AP insertions. High-density point collection (> 1,000 evenly distributed annotations) under respiratory gating ensures spatial resolution below 2 mm, and breakthrough identification is validated by cross-referencing bipolar and unipolar electrograms. OWM therefore provides a temporally and spatially precise representation of AP conduction, independent of wavefront direction. If available, the use of automatic algorithms indicating a line of block may help identify block sites and AP conduction breakthroughs at the AV annulus. OWM can be performed during tachycardia, under atrial or ventricular pacing, or during fully pre-excited sinus rhythm.

CARTO™ System-Based OWM Protocol

The use of high-resolution EAM systems—particularly the CARTO™ 3 platform integrated with advanced modules such as CONFIDENSE™—has significantly improved the identification and characterization of AP insertion sites in patients with WPW syndrome. Key features include:

1. Continuous mapping filters such as cycle length range and stability, pattern matching, position and LAT stability, and density;
2. System filters including tissue proximity indication (TPI) and respiration gating;

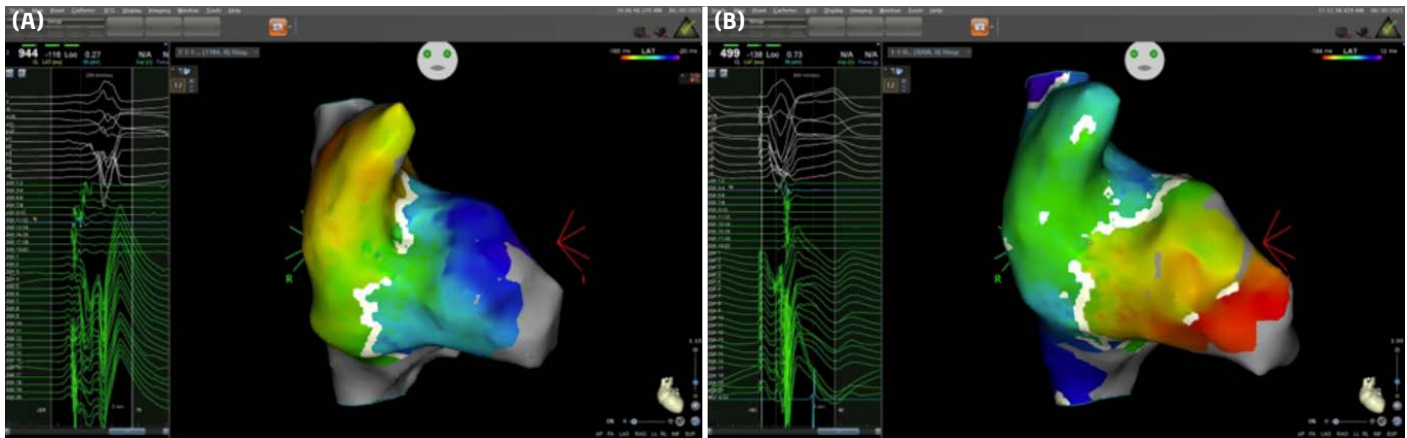


Figure 1. Color-coded LAT mapping derived from the Carto EAM system showing localization of a right-sided free-wall AP using both the OWM and EEML algorithms during sinus rhythm with full pre-excitation (A) and during ventricular pacing (B). The left panels display an extended WOI along with bipolar and unipolar EGMs recorded from the multielectrode mapping catheter, with automatic annotation of the selected point on the map.

AP, Accessory pathway; EAM, Electroanatomic mapping; EEML, Extended early-meets-late; EGM, Electrogram; LAT, Local activation time; OWM, Open Window Mapping; WOI, Window of interest.

3. Map consistency; and especially
4. The wavefront annotation algorithm, which uses both bipolar and unipolar EGMs to generate activation maps and indicate the localization and propagation direction of APs.

The automated wavefront annotation algorithm analyzes the rate of voltage change (dV/dt) in the unipolar EGM. The point exhibiting the steepest dV/dt slope on the unipolar EGM is expected to correspond to a feature on the associated bipolar EGM. Subsequently, the LAT is marked on the unipolar EGM. This dual-signal approach enhances spatial and temporal resolution, allowing the system to distinguish true local electrograms from far-field artifacts with greater confidence.

Previously mentioned additional optimization features, including continuous mapping filters, TPI, respiratory gating, and the map consistency algorithm, are utilized to ensure high-fidelity data capture and to eliminate erroneous or noisy points that are incongruent with their spatial neighbors. Furthermore, these features improve beat discrimination accuracy and reduce reliance on manual LAT reannotation.

The extended early-meets-late (EEML) algorithm, particularly when set at low thresholds (e.g., 15–85%), is employed alongside high-density (HD) Coloring to quantify temporal gradients between adjacent points and to visualize conduction discontinuities, including functional blocks and bridging areas where the AP transmits impulses between chambers.^{3,4}

The OWM strategy involves delineating a custom-defined WOI based on the timing of the surface electrocardiogram or a stable intracardiac reference signal (such as CS signals), typically determined using the Advanced Reference Annotation (ARA) algorithm. This window is carefully selected to encompass the earliest and latest atrial and ventricular activations, capturing the full sequence of electrical propagation—from the sinoatrial nodal region to the ventricular basal region—including, in particular, across the AV annulus during sinus rhythm; from the

atrial or ventricular pacing site to the region of latest activation in the opposite chamber during continuous pacing; or, during orthodromic or antidromic AVRT, from the ventricle to the atria or vice versa, thereby enabling full chamber acquisition. For instance, in the referenced protocol, a 300 ms WOI is established around the QRS end marker (0 ms), ranging from –225 ms to +75 ms. This allows comprehensive mapping of both the atrial and ventricular chambers, including the atrial and ventricular insertion zones of the AP, during sinus rhythm. Similarly, a 270 ms WOI, centered around the QRS end marker (0 ms) and ranging from –190 ms to +80 ms, enables comprehensive mapping of both the atrial and ventricular chambers, including the atrial and ventricular insertion zones of the AP, during ventricular pacing (Figure 1, Video 2).

Mapping point acquisition is executed using a multielectrode, high-density mapping catheter (the 20-pole PentaRay™ catheter with 2 mm interelectrode spacing), which provides finely resolved spatial data across the cardiac chambers. The CONFIDENSE™ module facilitates automated and continuous point collection while enforcing strict acquisition criteria: narrow cycle length range/stability ($\leq \pm 20$ ms, 5%), high pattern-matching threshold ($\geq 95\%$), low position stability (≤ 4 mm), low LAT stability (≤ 5 ms), maximum density, and map consistency with automatic calculation, with TPI and respiratory gating enabled. Filtering parameters are tailored to preserve signal fidelity (bipolar: 30–500 Hz; unipolar: 0.5–100 Hz; notch filters disabled).

With the aid of all these features, anatomical reconstructions of both the atria and the ventricle are created in real time. Activation mapping is superimposed to detect the breakthrough zone across the AV annulus, typically visualized as compact regions of continuous activation (mid-range colors on the color bar), in contrast to other annular regions that show discontinuity in color mapping. These regions are confirmed by the presence of unipolar QS morphology and by early, high-amplitude, fused atrial and ventricular bipolar signals that precede the delta wave onset of the surface QRS complex (Figure 1, Video 2).^{5,6}

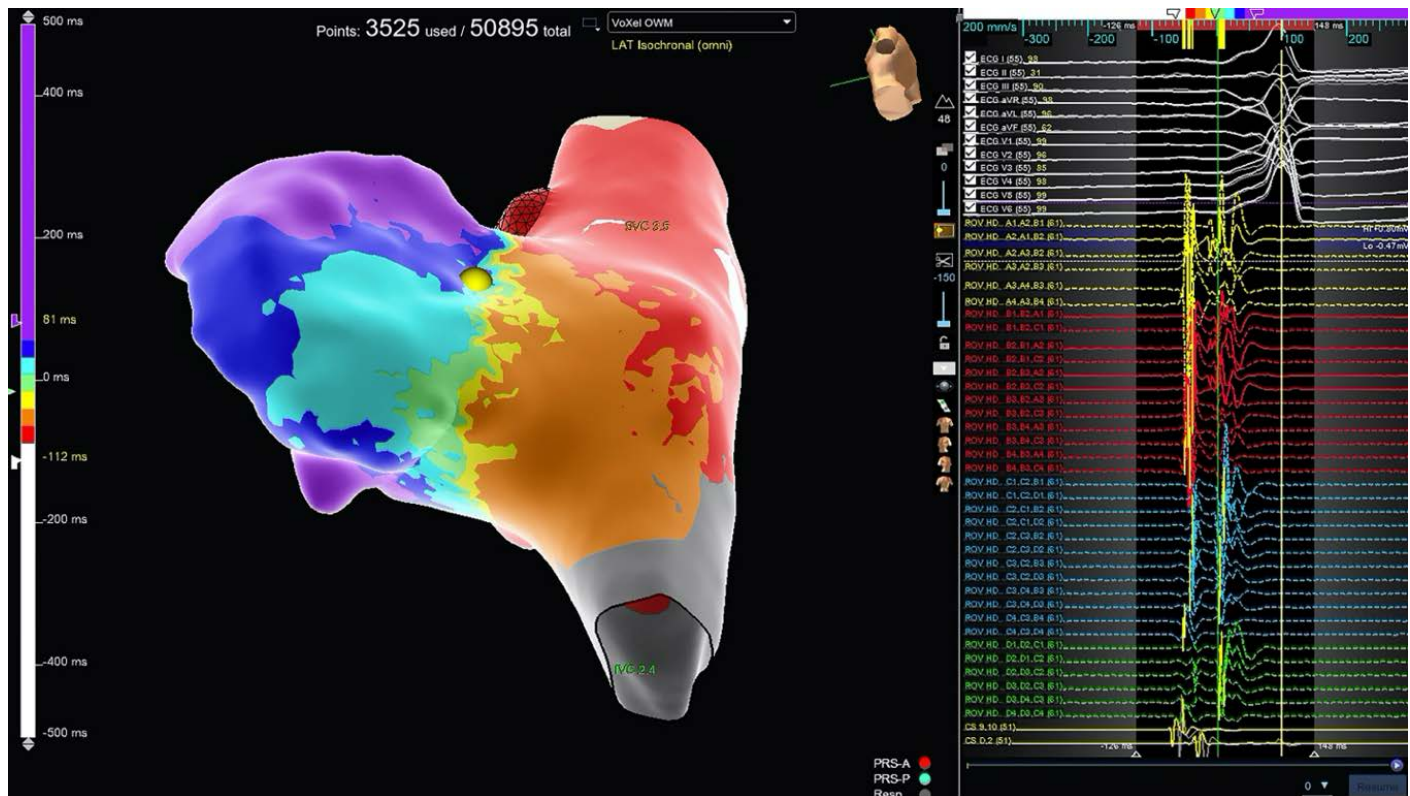


Figure 2. Color-coded LAT mapping derived from the EnSite X EAM system showing localization of a right-sided posteroseptal AP using both the OWM and OT algorithms during sinus rhythm with full pre-excitation. The right panel displays an extended RAI along with bipolar EGMs recorded from the multielectrode mapping catheter, with automatic annotation of the acquired points. The yellow tag indicates the His region.

AP, Accessory pathway; EAM, Electroanatomic mapping; EGM, Electrogram; LAT, Local activation time; OT, Omnipolar technology; OWM, Open Window Mapping; RAI, Roving acquisition interval.

Collectively, this comprehensive and technically rigorous approach to high-density mapping allows for a nuanced, physiologically informed visualization of the AP substrate. It enables electrophysiologists to accurately identify true AP insertion sites, differentiate them from bystander conduction pathways, and plan targeted ablation strategies with maximal precision and efficiency.

EnSite System-Based OWM Protocol

The integration of advanced EAM technologies—namely Omnipolar Technology (OT)—with high-density catheter systems such as the Advisor™ HD Grid has markedly improved the precision and reliability of intracardiac mapping in the evaluation of APs and complex arrhythmogenic substrates. The HD Grid catheter, configured in a 4 × 4 electrode matrix comprising 16 equidistant electrodes, is uniquely designed to capture electrical signals in multiple directions using orthogonal bipolar pairs. This multidirectional configuration allows enhanced spatial sampling of wavefront propagation, particularly in regions with complex conduction patterns or anisotropic tissue properties. Building on this structural advantage, OT further elevates mapping fidelity by combining unipolar and bipolar electrogram data derived from triads of adjacent electrodes, referred to as cliques. This novel omnipolar signal-processing strategy generates local, beat-to-beat quantitative assessments of peak voltage, activation vector orientation, and conduction velocity, all while remaining

independent of the catheter's positional alignment relative to the wavefront—thereby overcoming one of the critical limitations of traditional bipolar mapping.

During mapping procedures, OT permits dynamic assessment of the directionality of electrical activation and provides intuitive vector-based visualization of local conduction. In clinical contexts such as AP-related tachycardia, omnipolar activation vectors have been shown to facilitate accurate identification of the electrical insertion site of accessory fibers. Concurrently, the EnSite mapping system enables automated acquisition and annotation of LATs, based on either a surface QRS reference, pacing spike, or intracardiac reference. LAT annotations are algorithmically determined by identifying either the steepest negative slope (maximum dV/dt) or the absolute dV/dt of unipolar signals within a tailored RAI²—typically set as a 250–300 ms interval around the reference (Figures 2 and 3). Signal acquisition fidelity is tightly regulated using a combination of automated filters and threshold-based criteria within the AutoMap module. These include a morphology template match score exceeding 80, cycle length tolerance confined to ±20 ms, a speed limit of 10–20 mm/s, distance criterion set to OFF, signal-to-noise ratio between 3 and 5, and enhanced noise rejection set to ON (OFF during pacing). Additionally, map display features are configured with interior projection set to 5 and interpolation to 10.

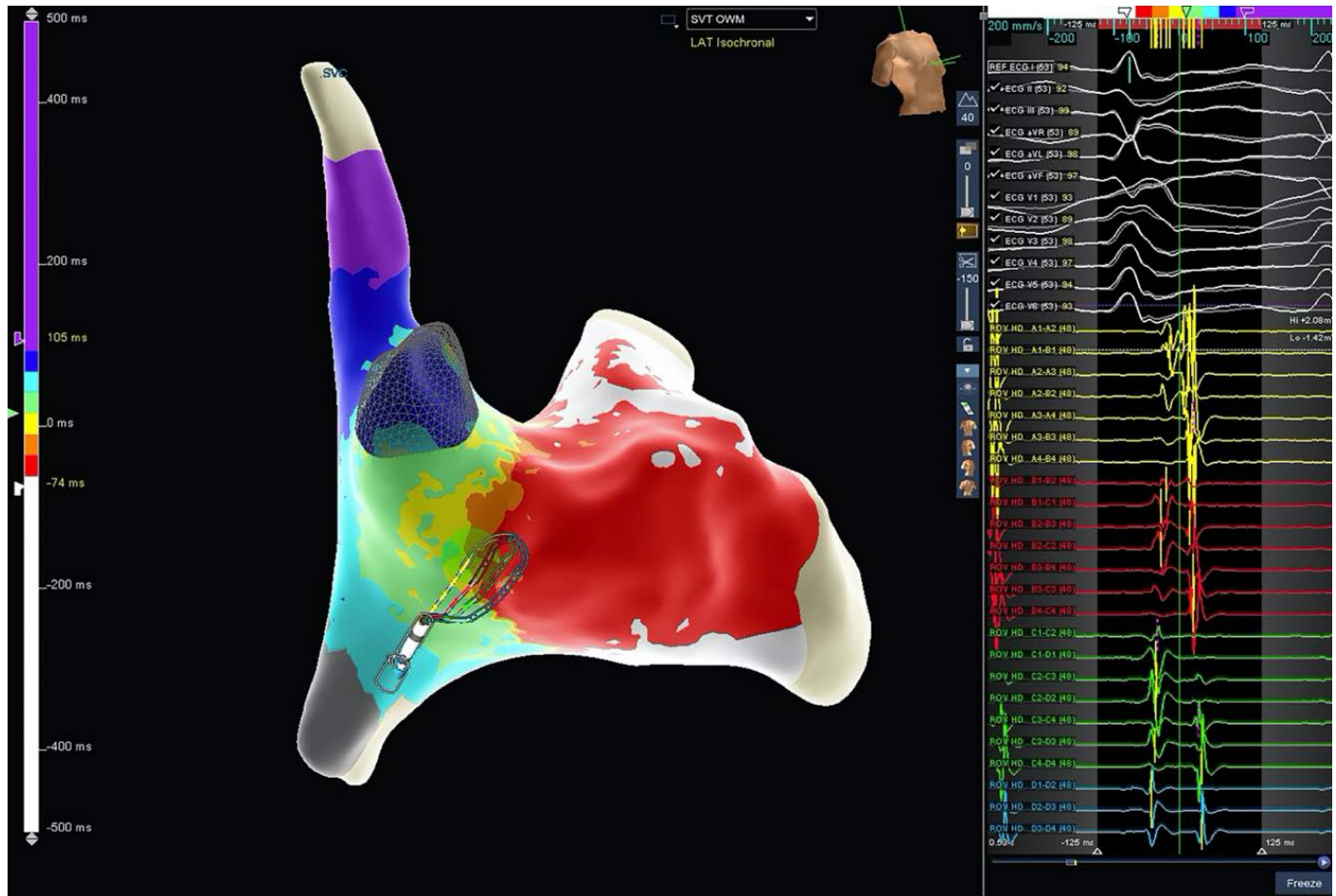


Figure 3. Color-coded LAT mapping derived from the EnSite Precision EAM system showing localization of a right-sided free-wall AP using the OWM algorithm during orthodromic AVRT in a 16-year-old female patient. The right panel displays an extended RAI along with bipolar EGMs recorded from the multielectrode mapping catheter, with automatic annotation of the acquired points using absolute dV/dt. The earliest atrial signal was recorded from the distal bipoles of the yellow spline.

AP, Accessory pathway; AVRT, Atrioventricular reciprocating tachycardia; EAM, Electroanatomic mapping; EGM, Electrogram; LAT, Local activation time; OWM, Open Window Mapping; RAI, Roving acquisition interval.

In both activation and propagation maps, early activation regions are denoted in white, with progressive isochronal contours delineating concentric propagation outward from the AP insertion point. The identification of closely spaced isochrones around the suspected site of insertion, combined with unipolar QS morphology and consistent near-field signals across orthogonal vectors, supports precise and reproducible localization (Figures 2 and 3, Videos 3 and 4).

Collectively, the use of omnipolar electrogram analysis in tandem with automated annotation technologies and a high-density, orthogonal electrode configuration offers an unprecedented level of anatomical and functional resolution. This integrated strategy not only facilitates the detailed characterization of APs and their insertion sites but also provides a robust platform for guiding ablation therapy with greater efficiency and confidence, particularly in challenging arrhythmia substrates where conventional mapping may fail due to limitations in directional sensitivity and signal reproducibility.

General and System-Specific Workflows for OWM

For clarity and ease of application, the complete OWM procedural sequence and key system-specific variations are summarized in Figure 4 and Table 1, which visually complement the detailed protocols described earlier.

While the fundamental workflow of OWM is consistent across platforms, the CARTO™ and EnSite systems incorporate distinct algorithmic, hardware, and visualization features that can influence procedural strategy. Table 2 summarizes the key system-specific advantages relevant to WPW ablation.

OWM integrates anatomical and temporal datasets to generate high-resolution automated maps, mitigating the limitations of conventional techniques related to conduction directionality, signal distortion, and suboptimal catheter-tissue contact.

With respect to poor contact, although multipolar high-density (HD) mapping catheters such as the PentaRay™ or Advisor™ HD Grid do not measure contact force (CF) directly, OWM protocols integrate several indirect yet robust safeguards to preferentially acquire data

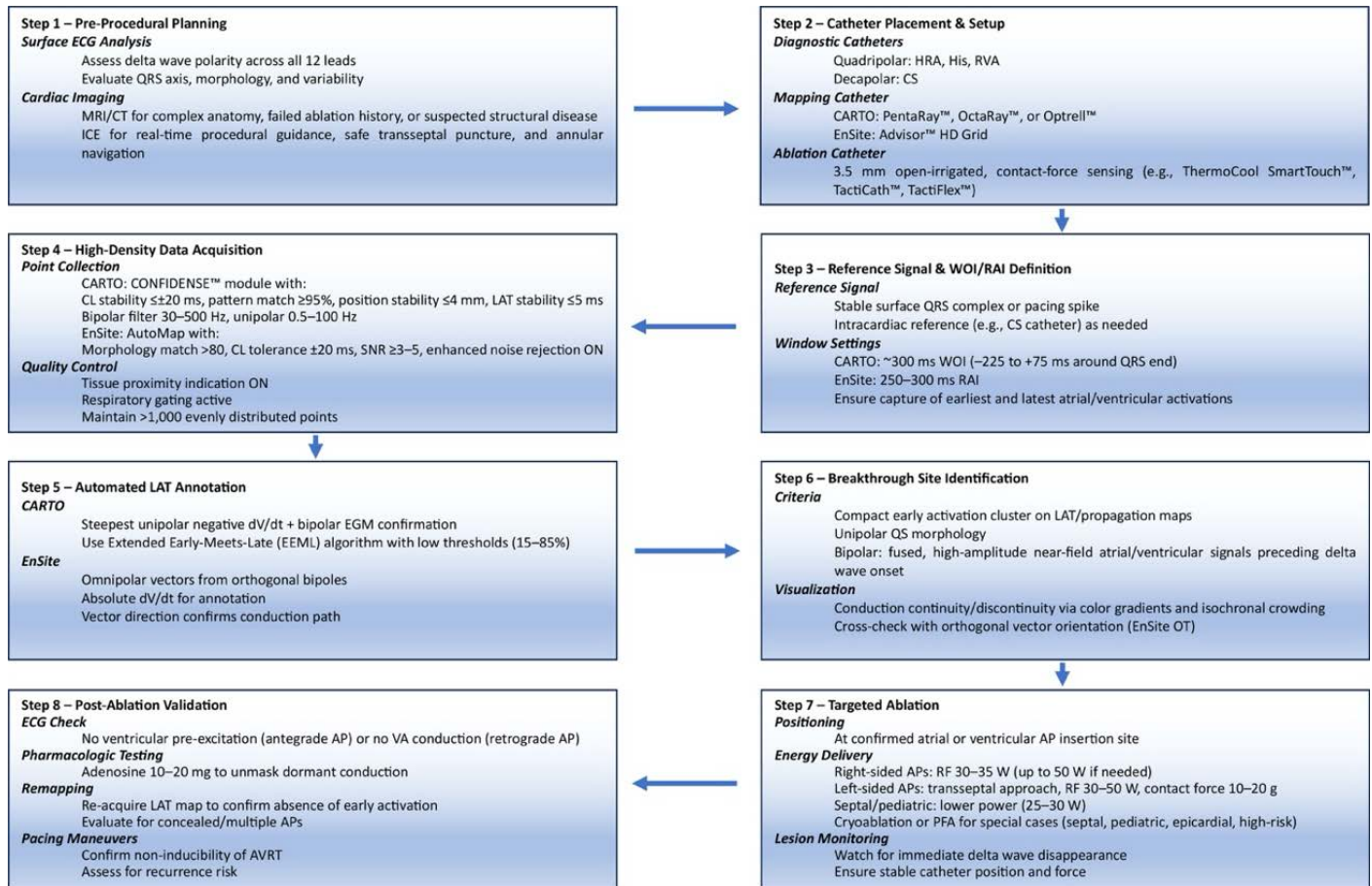


Figure 4. Flow diagram summarizing the stepwise OWM workflow for AP mapping and ablation.

AP, Accessory pathway; AVRT, Atrioventricular reciprocating tachycardia; CL, Cycle length; CS, Coronary sinus; CT, Computed tomography; ECG, Electrocardiogram; EGM, Electrogram; HRA, High right atrium; ICE, Intracardiac echocardiography; LAT, Local activation time; MRI, Magnetic resonance imaging; OT, Omnipolar technology; PFA, Pulse field ablation; RAI, Roving acquisition interval; RVA, Right ventricular apex; SNR, Signal-to-noise ratio; VA, Ventriculoatrial; WOI, Window of interest.

from adequately opposed electrodes. These include the use of tissue proximity indicator modules, which estimate contact quality through impedance- and location-based parameters, and the application of respiratory gating and map consistency algorithms to remove points exhibiting instability—features frequently associated with intermittent or poor contact. In addition, the acquisition process enforces strict positional and timing stability filters, which bias the dataset toward stable, well-positioned catheter contacts. Electrogram morphology criteria further refine data integrity by excluding points with attenuated amplitudes, excessive noise, or inconsistent near-field characteristics, all of which are typical markers of suboptimal tissue contact.

In terms of mitigating signal distortion, OWM employs a combination of anatomical integration and advanced signal-processing strategies. The automated annotation algorithm cross-validates unipolar and bipolar electrograms by identifying the steepest unipolar negative dV/dt and confirming temporal concordance with the sharpest bipolar deflection, thereby reducing the likelihood of far-field contamination. By constraining annotation to a user-defined WOI or RAI, the system isolates physiologically relevant activations and excludes spurious

deflections outside the targeted temporal range. Furthermore, with the Advisor™ HD Grid catheter, multidirectional signal capture via OT mitigates the directional sensitivity inherent to conventional bipolar recordings and ensures consistent earliest activation identification regardless of catheter orientation. Automated noise rejection and morphology-matching filters provide an additional safeguard against baseline wander, pacing artifacts, and other sources of distortion, thus preserving signal fidelity.

Collectively, these integrated hardware and software features allow OWM to compensate for the lack of direct CF sensing in HD mapping catheters and substantially attenuate the effects of signal distortion. This combination yields high-resolution, reproducible activation maps with superior spatial and temporal precision compared to conventional LAT-based mapping techniques, even in anatomically and electrically complex substrates.

Ablation Protocols

The cornerstone of successful AP ablation lies in precise target site identification, effective radiofrequency (RF) energy delivery tailored to pathway location, and rigorous endpoint validation to ensure durable lesion formation and long-term arrhythmia-free outcomes.

Table 1. System-specific OWM workflow variations

Step	CARTO™ 3 Workflow	EnSite Precision/X Workflow
Reference Definition	Advanced Reference Annotation (ARA): select a stable reference from surface QRS, pacing spike, or intracardiac signal (e.g., coronary sinus). Used to align the WOI to capture earliest atrial and ventricular activations.	Select a stable reference from surface QRS, pacing spike, or intracardiac signal (e.g., coronary sinus). LAT annotations determined from the steepest unipolar dV/dt or absolute dV/dt within the RAI.
WOI/RAI Setting	Typical: 300 ms WOI around QRS end marker (0 ms); e.g., -225 ms to +75 ms for sinus rhythm; 270 ms (-190 ms to +80 ms) for ventricular pacing.	Typical: 250–300 ms RAI around reference; adjustable to match conduction scenario.
Point Acquisition Module	CONFIDENSE™: automated continuous mapping with strict criteria—cycle length stability $\leq \pm 20$ ms (5%), pattern match $\geq 95\%$, position stability ≤ 4 mm, LAT stability ≤ 5 ms, high density, map consistency ON, tissue proximity and respiratory gating enabled.	AutoMap: morphology match $\geq 80\%$, cycle length tolerance ± 20 ms, speed limit 10–20 mm/s, SNR 3–5, noise rejection ON (OFF during pacing), distance criterion OFF, interior projection 5, interpolation 10.
Key Mapping Algorithm	Wavefront annotation: steepest unipolar negative dV/dt aligned with bipolar deflection; dual-signal concordance reduces far-field artifacts. Filtering: bipolar 30–500 Hz, unipolar 0.5–100 Hz, notch filters OFF.	Omnipolar Technology (OT): uses orthogonal bipoles in HD Grid “cliques” to generate vectorbased LAT and conduction velocity independent of catheter orientation.
Conduction Gap Visualization	Extended Early–Meets–Late (EEML) at low thresholds (e.g., 15–85%) plus HD Coloring to reveal conduction discontinuities and AP breakthrough zones.	Isochronal crowding plus omnipolar vector plots to show breakthrough and conduction direction.
Mapping Catheter	PentaRay™ (20-pole, 2 mm spacing)/OctaRay™/Optrell™ for high-density mapping.	Advisor™ HD Grid (16 electrodes, 4 × 4 matrix) for multidirectional mapping.
Unique Strength	High-precision unipolar-bipolar concordance, submillimeter AP localization, robust noise filtering, continuous high-density acquisition.	Orientation-independent activation mapping with quantitative conduction vectors; robust in complex, anisotropic conduction.

LAT, Local activation time; OWM, Open Window Mapping; RAI, Roving acquisition interval; WOI, Window of interest.

Table 2. Comparative advantages of CARTO™ and EnSite Systems for OWM in WPW ablation

Feature/Capability	CARTO™ 3	EnSite Precision/X
Core OWM Algorithm	Wavefront annotation using steepest unipolar dV/dt aligned to bipolar deflection; Advanced Reference Annotation (ARA) for WOI definition	Roving Acquisition Interval (RAI) with steepest or absolute unipolar dV/dt detection; Omnipolar Technology (OT) for vector-based LAT assignment
High-Density Mapping Catheters	PentaRay™ (20 poles, 2 mm spacing), OctaRay™, Optrell™	Advisor™ HD Grid (16 electrodes in 4 × 4 matrix) enabling orthogonal bipolar pairs
Directional Sensitivity	Enhanced by combining unipolar and bipolar annotation; reduced far-field influence via automated LAT filters	Direction-independent LAT detection via omnipolar vectors, overcoming catheter-wavefront alignment issues
Continuous Mapping Automation	CONFIDENSE™ module with strict acquisition filters (cycle length stability, pattern match $\geq 95\%$, position stability ≤ 4 mm)	AutoMap with morphology match $\geq 80\%$, cycle length tolerance ± 20 ms, enhanced noise rejection
Noise & Artifact Management	Respiratory gating, tissue proximity indication, map consistency algorithms to reject spatially inconsistent points	Adjustable signal-to-noise ratio thresholds (3–5), speed limit control, interior projection and interpolation settings
Visualization of Conduction Gaps	Extended Early–Meets–Late (EEML) algorithm with HD Coloring for conduction discontinuity mapping	Isochronal crowding with omnipolar vectors; dynamic conduction velocity assessment
Best-Suited Scenarios	Detailed annular mapping in complex AP anatomy where unipolar-bipolar concordance is critical	Mapping in anisotropic tissue or complex conduction patterns where catheter orientation may limit bipolar accuracy
Unique Strength	Highly refined dual-signal annotation (unipolar + bipolar) with advanced map consistency tools	True vector-based omnipolar mapping providing orientation-independent LATs and conduction velocity

AP, Accessory pathway; LAT, Local activation time; OWM, Open Window Mapping; WOI, Window of interest; WPW, Wolff-Parkinson-White (syndrome).

Accurate localization of the AP insertion site is primarily guided by electrophysiological signals. A successful ablation target is characterized by the earliest local bipolar EGMs that precede the onset of the surface delta wave during atrial pacing or antidromic AVRT in antegrade conduction pathways, or by the earliest EGMs that precede the reference atrial electrogram during ventricular pacing or orthodromic AVRT in retrograde conduction. In either

conduction direction, early activation timing is critical and indicates proximity to the AP atrial or ventricular insertion site (Figures 5 and 6, Videos 4, 5, and 6).

Unipolar EGMs at the ablation site should demonstrate a QS morphology with a steep negative downstroke, reflecting the site of earliest depolarization with minimal far-field interference.



Figure 5. An irrigated tip force-sensing ablation catheter positioned at the atrial insertion site demonstrates a fused and earliest ventricular bipolar signal relative to the delta wave, with immediate abolition of the AP following ablation. This is evidenced by abrupt prolongation of the ventricular signal and disappearance of the delta wave on the surface electrocardiogram (ECG).

AP, Accessory pathway.

Additionally, local bipolar EGM amplitude should ideally exceed normal voltage thresholds, indicating robust, high-fidelity signals suggestive of close catheter-tissue contact and viable substrate.

Target sites are best selected when they exhibit compact, discrete, and reproducible early signals across sequential beats, with anatomical correlation to the annular insertion—particularly when using EAM systems. The integration of the OWM technique enables high-resolution visualization of LATs and facilitates accurate annotation of earliest activation clusters.

Radiofrequency energy parameters should be titrated according to the anatomical location of the AP, with careful consideration of lesion depth, power delivery, and procedural safety. For right-sided APs, RF power is typically initiated at 30–35 W and may be titrated up to 50 W, with lesion durations ranging from 30 to 60 seconds. In specific cases—such as septal pathways or pediatric patients—power may be limited to 25–30 W due to the proximity of critical conduction tissue.

For left-sided APs, transseptal access is the preferred approach, offering superior catheter stability and a more favorable trajectory compared to the retrograde aortic route. RF power delivery typically ranges from 30–50 W, with contact force maintained between 10 and 20 grams.

When available, advanced lesion metrics—such as Ablation Index (AI), Lesion Size Index (LSI), or average impedance drop—should be used to guide lesion efficacy, serving as reliable surrogates for adequate lesion formation across most anatomical locations. Consistent catheter position and stable contact force throughout the application are essential to ensure transmural and durable lesion formation.

Cryoablation of APs—particularly those located in septal regions and in the pediatric population—is a technically demanding procedure due to the close anatomical proximity to the conduction system. Cryoablation offers a cryomapping phase at sublethal temperatures (typically around -30°C), allowing functional assessment of the target site before creating irreversible lesions at colder temperatures (-70°C to -80°C).

The use of 3-D EAM in conjunction with cryoablation enhances procedural efficacy and safety by enabling precise catheter navigation, real-time lesion annotation, and integration with intracardiac signals and imaging modalities.

Recent feasibility studies have demonstrated the potential utility of pulse field ablation (PFA) for targeting APs in WPW syndrome, particularly in cases refractory to conventional RF ablation or involving epicardial substrates. Focal PFA has been shown to



Figure 6. An irrigated tip force-sensing ablation catheter positioned at the posteroseptal region demonstrates a fused and earliest ventricular bipolar signal relative to the delta wave. The AP is abolished within four seconds of ablation, as evidenced by abrupt prolongation of the ventricular signal and disappearance of the delta wave on the surface electrocardiogram (ECG).

AP, Accessory pathway.

achieve acute conduction block in various AP locations—including left lateral, posteroseptal, and right free wall—through both endocardial and coronary sinus approaches. Preliminary clinical data indicate high acute success rates and a favorable safety profile, with minimal procedural complications and no evidence of collateral damage to the atrioventricular node, coronary vasculature, or surrounding neural structures.^{7,8} However, long-term efficacy data remain limited, and further investigation through larger, controlled trials is warranted to establish PFA as a standard therapeutic option for AP-mediated arrhythmias.

Ablation efficacy is assessed using a combination of electrophysiological and pharmacologic criteria. The immediate disappearance of ventricular pre-excitation on the surface ECG during sinus rhythm serves as the primary endpoint for antegrade-conducting pathways. For retrograde-only pathways, the loss of VA conduction during right ventricular pacing indicates successful interruption of AP conduction. Non-inducibility of AVRT using programmed atrial or ventricular stimulation further supports procedural success.

A negative adenosine challenge test—administered as a rapid intravenous bolus of 10–20 mg—should confirm the absence of dormant or latent AP conduction. Adenosine transiently blocks AV nodal conduction and may unmask residual AP activity, making it particularly useful in borderline or equivocal cases.

A robust post-ablation protocol should include pacing maneuvers to assess for residual antegrade or retrograde conduction and to evaluate the presence of multiple or concealed APs. Remapping the previously successful ablation site using OWM or conventional point-by-point techniques is recommended to verify the absence of early local activation or residual AP potentials, thereby confirming durable pathway elimination. In cases of recurrence, remapping can help differentiate between inadequate lesion formation, epicardial or CS connections, and pathway recovery.

In summary, successful AP ablation requires a methodical approach incorporating detailed electrogram analysis, individualized RF energy application, and stringent validation of conduction block using both electrophysiological and pharmacologic endpoints. Advanced mapping technologies and lesion indices further enhance procedural safety and effectiveness, particularly in anatomically complex or high-risk substrates.

Troubleshooting During OWM and Ablation

Contact/Mechanical Artifacts

In our experience, catheter contact artifacts can occur when mapping catheters are positioned close to diagnostic catheters, such as the His bundle catheter. This is an acknowledged technical consideration during high-density EAM, particularly in septal AP cases where catheter trajectories converge. To minimize this risk, we employ several complementary strategies:

1. Maintaining clear fluoroscopic and electroanatomic spatial separation between mapping catheters and the His catheter;
2. Using TPI and respiratory gating features available in EAM systems to ensure that annotated points reflect true endocardial contact rather than incidental catheter-to-catheter interaction;
3. Validating suspected early activation points by cross-referencing bipolar and unipolar electrograms for near-field characteristics, including steep unipolar negative dV/dt and absence of mechanical artifact signatures; and
4. Repeating acquisitions from slightly adjusted mapping catheter positions if signal morphology suggests possible mechanical interference.

Importantly, when the mapping catheter inadvertently contacts the His catheter, we observe a reproducible mechanical deflection artifact that is distinct from true local activation—these points are excluded during map review. Through these procedural safeguards, we have found catheter contact artifacts to be rare and readily identifiable, and they have not compromised our localization accuracy.

Epicardial/Intramural APs

Although OWM offers high spatial and temporal resolution for most endocardial APs, its reliance on steep unipolar downstrokes or sharp bipolar deflections to determine local activation timing may present limitations in the setting of epicardial or intramurally located APs. In such cases, earliest activation may be attenuated, exhibit broad morphology, or demonstrate a delayed steepest dV/dt compared with true endocardial near-field signals, potentially leading to underestimation or mislocalization. To mitigate this, our protocol incorporates high-density point acquisition with bipolar-unipolar correlation, careful morphological assessment for QS patterns with low amplitude or broad deflections, and complementary mapping from the epicardium as well as from the CS or its branches—particularly for posteroseptal or free-wall pathways. ICE, contrast injection, and adjunctive conventional LAT or differential pacing maneuvers are employed when epicardial or intramural origin is suspected. In such scenarios, OWM findings are interpreted in conjunction with multimodal mapping and anatomical imaging to ensure accurate localization and avoid procedural misguidance.

Bystander APs

Open Window Mapping facilitates the distinction between true AP insertion sites and bystander conduction by temporally isolating physiologically relevant electrograms from unrelated activation. This is achieved through the use of a user-defined WOI or RAI referenced to a stable marker, such as the surface QRS complex, pacing spike, or intracardiac reference electrogram. Within this interval, the mapping system automatically identifies the earliest near-field local activation based on EGM characteristics—most notably the steepest unipolar negative dV/dt or sharp bipolar deflection—without requiring manual selection of atrial, ventricular, or pathway-specific signals. By constraining annotation to this physiologically relevant time frame, OWM effectively excludes far-field and sequential wavefront components that commonly obscure or mimic true AP signals in conventional mapping. In the resulting activation maps, true AP

insertion sites are visualized as compact, high-density clusters of earliest activation along the AV annulus. EGM analysis at these sites consistently reveals unipolar QS morphology with a steep negative downstroke, indicating immediate local depolarization, and fused, high-amplitude bipolar signals that precede the onset of the delta wave during antegrade conduction or the reference atrial signal during retrograde conduction. In contrast, bystander sites exhibit later activation within the WOI/RAI, lack unipolar QS morphology, and demonstrate electrogram patterns consistent with passive conduction from adjacent tissue rather than direct pathway insertion. Propagation maps further reinforce this distinction by showing conduction continuity across the annulus at true AP sites, whereas bystander regions display discontinuity or delayed wavefront progression. Through this combination of temporally constrained annotation, high-density spatial sampling, and morphology-based signal validation, OWM provides a physiologically faithful representation of AP conduction. This capability enables electrophysiologists to reliably differentiate true AP insertion points from non-conducting annular myocardium or passive conduction sites, thereby informing more targeted and effective ablation strategies.

Para-Hisian APs

Para-Hisian APs are widely recognized as one of the most challenging substrates for catheter ablation due to their close anatomical relationship with the His bundle and the presence of high-frequency His electrograms that can obscure accurate localization. However, the OWM approach remains a valuable tool for guiding ablation even in these complex scenarios. By integrating local activation timing with pace-mapping information and anatomical context, OWM allows accurate differentiation of true pathway potentials from near-field His activity. Importantly, the method helped avoid unnecessary ablation in the immediate vicinity of the His bundle while still enabling successful elimination of the pathway. This observation is in line with previous findings,⁵ where OWM proved particularly useful in mapping para-Hisian pathways and provided guidance in circumstances where high-frequency His electrograms might otherwise have caused confusion. These results support the applicability of OWM in difficult perinodal substrates and underscore its potential to improve both the safety and efficacy of ablation in such cases.

AP Potential

Although a discrete AP potential was not visually evident in all of the presented examples, the earliest activation region identified on the 3-D electroanatomic map was systematically correlated with the corresponding bipolar and unipolar electrogram morphology. Specifically, the presence of an early and sharp bipolar deflection, together with a QS-pattern unipolar signal at these sites, was used to confirm local AP activation and to distinguish it from far-field atrial signals. In addition, to account for the well-described oblique course of AP activation, the mapping catheter was intentionally manipulated to record electrograms from different orientations at the same anatomical region, thereby reducing the likelihood of false annotations based solely on color coding. While it is true that the oblique nature of AP activation can occasionally obscure the discrete AP signal, integrating electrogram morphology with the spatial information provided by the activation map effectively mitigates this risk. Through this combined electroanatomic and

electrogram-based approach, we were able to reliably elucidate AP activation despite the absence of a clearly visible discrete AP potential in the raw signals.

Rare APs

In some cases, the earliest activation was recorded at sites projecting into the aortic root or within the CS. This finding does not invalidate the localization strategy, as the determination is based on relative electrogram timing rather than fluoroscopic appearance alone. Epicardial and para-annular pathways may project into these structures despite originating at the AV annulus, a phenomenon that has been described previously.^{9,10} Corroborative mapping of adjacent sites, including CS recordings when appropriate, consistently confirmed that these activation sites reflected true AP breakthrough. Accordingly, the method remains valid, provided the localization is interpreted alongside the complete electrophysiological dataset.

Procedure Time

Regarding procedural time, the OWM strategy demonstrates a statistically insignificant reduction in total mapping time, despite acquiring more than 1,000 mapping points compared with the conventional approach. Moreover, OWM is associated with decreased fluoroscopy time and RF time. With respect to overall procedural duration, our experience indicates that the improved targeting capability facilitates more efficient decision-making during ablation, thereby reducing the time required for iterative mapping and catheter repositioning. Although the present study was not specifically powered to assess procedural time as a primary endpoint, only a modest and insignificant reduction in total procedure duration was observed relative to the conventional approach. This is predominantly attributable to fewer mapping iterations and a more rapid final confirmation of ablation efficacy.

Manual Annotation

To avoid subjective bias and ensure reproducibility, all EGMs were annotated fully automatically using the OWM framework. Nonetheless, we recognize that noise and unstable catheter contact may adversely affect automated annotation. To minimize their influence, we implemented two complementary safeguards. First, EGMs with very low amplitude were removed during pre-processing, as they typically correspond to either non-contact or poor-quality recordings. Second, a confidence threshold was applied to the OWM annotations so that only activations with sufficient likelihood were retained. As a result, noisy or pseudo-fragmented signals were effectively excluded prior to subsequent analysis. We therefore emphasize that, although the proposed algorithm does not require manual correction of EGMs, a strict quality control procedure was implicitly incorporated to mitigate the effects of artifacts and noise.

Conclusion

The proposed framework is conceived as a complementary extension of standard 3-D EAM rather than a replacement of current technologies. Conventional mapping systems provide high-resolution anatomical reconstructions and allow for localization of electrograms in 3-D space; however, their ability to resolve spatiotemporal propagation patterns and functionally relevant conduction pathways remains limited. In contrast, the presented approach incorporates activation data directly

into the reconstructed geometry and thereby enables the visualization of functional propagation in a reproducible and operator-independent fashion. Importantly, the method relies on information that is already routinely obtained during clinical activation mapping and therefore does not require any additional acquisition step or dedicated hardware. The only modification to current clinical workflows would be a preprocessing step incorporating the reconstruction algorithm, which could be implemented in existing commercial mapping platforms. As such, the proposed approach is feasible in the clinical setting and could enhance current practice by enabling ablation strategies that are based on functional activation patterns rather than solely on local activation time differences.

Open Window Mapping offers a scientifically robust and clinically impactful strategy for the high-precision localization and ablation of APs in WPW syndrome. Unlike traditional activation mapping techniques, which are inherently limited by the confounding effects of global atrial or ventricular wavefront propagation and are subject to spatial averaging artifacts, OWM decouples local electrogram timing from chamber-wide conduction dynamics. This allows isolation of the true site of earliest activation corresponding to the AP insertion point, irrespective of the overall activation sequence. By temporally aligning local electrograms within a user-defined WOI/RAI, OWM creates a more physiologically relevant electroanatomic map that significantly enhances spatial and temporal resolution.

When integrated with high-density mapping catheters and contemporary EAM systems such as CARTO™ and EnSite Precision/X, OWM facilitates rapid and reproducible localization of AP insertion points with submillimeter precision. Both systems support advanced OWM workflows through tailored electrode configurations, real-time signal filtering, and adaptive windowing protocols.

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Video 1. Three-dimensional (3-D) reconstruction and importation of cardiac chambers and vessels into the CARTO EAM system in a patient with three previous failed ablation attempts, including an epicardial ablation. EAM, Electroanatomic mapping.

Video 2. Propagation maps illustrating the direction of activation from the earliest to the latest site, with breakthrough observed on the right lateral tricuspid annulus. This demonstrates the localization and insertion sites of the AP during sinus rhythm with full pre-excitation (left video) and during ventricular pacing (right video). AP, Accessory pathway.

Video 3. Color-coded LAT maps (upper left panel) and propagation maps—classical (upper right panel), sparkle (lower left panel), and full-color (lower right panel)—illustrating the direction of activation from the earliest to the latest site. Breakthrough is observed at the right posteroseptal tricuspid annulus, demonstrating the localization and insertion sites of the AP during sinus rhythm with full pre-excitation. AP, Accessory pathway; LAT, Local activation time.

Video 4. Color-coded LAT (upper left panel) and propagation maps—classical (upper right panel) and sparkle (lower left panel)—illustrating the direction of activation from the earliest to the latest site. Breakthrough is observed at the right lateral tricuspid annulus, indicating the localization and insertion sites of the AP during orthodromic AVRT. RF application at the site of the earliest atrial activation (lower right panel) eliminates the AP and terminates the tachycardia within a few seconds. AP, Accessory pathway; AVRT, Atrioventricular reciprocating tachycardia; LAT, Local activation time; RF, Radiofrequency.

Video 5. Corresponding to Figure 5, this video illustrates the ablation effect on the AP. The timeline on the right shows fused and earliest ventricular bipolar signals relative to the delta wave, along with a QS morphology on the unipolar EGMs. The AP is abolished just four seconds after the onset of ablation (see white bar and time marker at the bottom). AP, Accessory pathway; EGM, Electrogram.

Video 6. Corresponding to Figure 6, this video illustrates the ablation effect on the AP. The timeline at the bottom shows fused and earliest ventricular bipolar EGMs relative to the delta wave. The AP is abolished

just four seconds after the onset of ablation, as indicated by the RF session time in the box and the roving yellow line on the timeline. AP, Accessory pathway; EGM, Electrogram; RF, Radiofrequency.

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