Very High-Power Short-Duration Radiofrequency Ablation for Atrial Fibrillation: A Review of Technical Principles and Clinical Practice

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Abstract: As a pervasive cardiac arrhythmia with escalating global incidence, atrial fibrillation (AF) substantially elevates the risks of stroke and heart failure. Within the therapeutic arsenal, catheter-based pulmonary vein isolation (PVI) constitutes the cornerstone interventional strategy. Conventional radiofrequency ablation utilizing 30-50 W over 20-60 seconds per lesion, depends on conductive heating. This often leads to prolonged procedures, uneven lesion formation, and complications like esophageal injury. Very high-power short-duration (vHPSD) ablation is defined by 90 W applications lasting 4 seconds. represents a paradigm shift by favoring "resistive heating." This mechanism creates wider, shallower lesions that are theoretically better suited to the thin left atrial walls, enhancing efficiency and potentially reducing risks. This review synthesizes recent evidence on vHPSD's technical principles, dedicated systems like the QDOT MICRO catheter, clinical efficacy, and safety. vHPSD markedly shortens procedure, ablation, and fluoroscopy times while achieving PVI success rates >99.5%. Its long-term efficacy is non-inferior to conventional ablation, with 12-month sinus rhythm maintenance rates of 76-78%. vHPSD notably reduces serious esophageal injury risk. However, silent cerebral embolism (incidence 8-26%) and early catheter tip coagulum (since optimized to 0.8%) require attention. In conclusion, vHPSD signifies a progressive evolution towards safer, more efficient AF ablation. Future large-scale, long-term trials are needed to confirm lesion durability, standardize parameters, and develop personalized, image-guided strategies, solidifying its role in the therapeutic arsenal.

Keywords: Atrial Fibrillation; Catheter Ablation; Pulmonary Vein Isolation; Silent Cerebral Embolism

1. Introduction

AF is a prevalent cardiac arrhythmia. Epidemiological studies indicate that the AF prevalence among Chinese adults is approximately 1.6%, increasing with age [1], and rising to over 10% in individuals aged 80 and above [2]. This makes AF a significant public health concern. Beyond reducing quality of life, AF increases stroke risk by four-fold and mortality risk by more than two-fold [3]. Catheter-based Pulmonary vein isolation (PVI) is the standard of care for atrial fibrillation (AF), particularly after inadequate response to antiarrhythmic drug therapy [4].

However, conventional radiofrequency ablation (30-50W per point, 20-60s) primarily acts via "conductive heating," starting from the catheter-tissue interface, with energy slowly diffusing centrally into the myocardium and surrounding areas. This often leads to long procedure times (often >2 hours) and, due to uncontrolled heat conduction, potential injury to adjacent structures (e.g., esophagus, phrenic nerve, pulmonary veins), limiting its widespread adoption and safety profile [5, 6].

To overcome these limitations, the concept of high-power short-duration (HPSD) ablation emerged. Very high-power short-duration (vHPSD) ablation, referring to applications of ≥70 W for ≤5 seconds, represents the current state-of-the-art in this field. Supplementary research shows vHPSD can reduce procedure time to 88.2±34.9 minutes (vs. conventional 101±38 minutes) [7], and PVI procedure time to just 67.7±29.7 minutes in clinical settings [8], significantly enhancing clinical efficiency. Compared to traditional HPSD,

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a key advantage of vHPSD is the marked increase in the proportion of "resistive heating" despite a drastically reduced energy application time [9, 10]. This concentrates most energy in the superficial myocardial layer, achieving transmural and homogeneous lesions rapidly. Furthermore, heat readily conducts towards the endocardium but does not transmit to the epicardial side, thereby minimizing the risk of collateral damage to non-target tissues [11-13]. Since its clinical feasibility was demonstrated by Reddy et al. in the 2019 QDOT-FAST trial [12], vHPSD has become a focus in AF ablation.

Based on core international and domestic literature, this review summarizes the technical principles, core equipment, clinical efficacy, and safety evidence for vHPSD radiofrequency ablation. It objectively analyzes current controversies and issues, and discusses potential future directions for technical optimization, improvement, and clinical application, serving as a reference for cardiac electrophysiologists and researchers.

2. Technical Principles and Catheter Design of vHPSD

2.1 Biophysical Basis of Energy Delivery and Lesion Characteristics

The key to vHPSD technology lies in shifting the fundamental biophysics of energy delivery. According to Joule's Law ($Q=I^2Rt$), the heat generated during radiofrequency ablation ivaries with the square of the current, tissue resistance, and application time. Compared to conventional ablation:

Heating Mode: The 90 W setting in vHPSD creates an ultra-high current density at the catheter-tissue interface, enabling rapid resistive heating. This approach capitalizes on "resistive heating," whereby energy is predominantly absorbed within the superficial myocardial layer, swiftly achieving temperatures sufficient for irreversible cellular necrosis. Conventional ablation (30-50 W, >20 s), relying on "conductive heating," allows energy to diffuse deeper and laterally, increasing the risk of collateral damage [11-13]. Ex vivo porcine heart experiments further confirm that vHPSD produces lesion depths significantly shallower than Temperature/Flow Control (TFC) mode, with smaller volume. At 4mm inter-lesion spacing, vHPSD can form uniform continuous linear lesions, whereas at 6mm spacing, only TFC mode (Ablation Index 500) maintained continuity, providing experimental basis for setting inter-lesion spacing in different clinical areas [14].

Lesion Characteristics: Both animal experiments and ex vivo studies indicate that vHPSD produces lesions that are wider but have comparable or slightly shallower depth. [Studies show that] in porcine thigh muscle and in vivo heart models, vHPSD lesion diameter is significantly larger than conventional ablation, with similar depth, and no steam pops occur [15]. [In clinical human PVI applications, vHPSD lesion depth was 3.6±0.6mm, compared to 4.5±0.8mm for conventional RF (50W/10s), indicating vHPSD is slightly shallower; lesion width was 8.3±1.2mm for vHPSD vs. 6.5±1.0mm for conventional RF, showing vHPSD was wider ($P<0.05$) [9]. This trend of wider lesions with HPSD is consistent with Barkagan et al. [15]. This lesion morphology is more suitable for the average left atrial wall thickness, aiding in achieving transmural injury. Regarding safety, the situation is more complex: For the esophagus: Otsuka's study [6] reported comparable rates of esophageal lesions with both techniques; however, the lesions induced by 90W/4s vHPSD were significantly shallower, imparting a lower likelihood of deep esophageal injury. For the phrenic nerve palsy: Caution is warranted, as the same study noted that 90W/4s vHPSD caused physiological phrenic nerve injury extremely rapidly, representing a non-negligible risk; thus, its use should be avoided in areas like the superior vena cava near the phrenic nerve.] Wider lesion sets also allow for appropriate inter-lesion spacing (Front wall ≤4 mm, posterolateral wall ≤6 mm) [9], maintaining linear block continuity [6], thereby achieving higher procedural efficiency.

2.2 Core Catheter Technology: The QDOT MICRO Example

The effective implementation of vHPSD relies on dedicated catheter systems. The widely used QDOT MICRO (Biosense Webster) integrates three key technologies:

Multi-Thermocouple Temperature Monitoring and Smart Temperature Control: The catheter tip integrates six micro-thermocouples (each only 75 μm from the electrode surface) for real-time, accurate monitoring of the tissue interface temperature. In QMODE+ mode, using temperature control with a target set to 55-60°C, if any thermocouple detects the interface temperature ≥65°C, irrigation flow is increased

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(max 15 mL/min) and power output is reduced (min 60 W), preventing tissue charring and steam pops, with a reported incidence of 0-2% [6, 12]. A systematic review found that using temperature-controlled catheters like QDOT MICRO significantly reduced the incidence of Steam Pops (SPS) (0%), whereas power-controlled catheters (e.g., THERMOCOOL SMARTTOUCH) had higher SPS rates [16]. Additionally, real-time impedance monitoring (avoiding sudden drops ≥18Ω) and intracardiac echocardiography (ICE) monitoring for tissue whitening or bubbles can further reduce SPS-related complications [16].

Smart Irrigation System: Featuring a 56-hole multi-port design, it initiates high-flow pre-cooling 2 seconds before ablation. During ablation, irrigation flow is automatically adjusted based on temperature, and high-flow irrigation continues post-ablation to remove excess heat within seconds [6, 12]. Animal experiments show the maximum irrigation load during vHPSD ablation is 30 mL/min (dual-flow path design), with 360° irrigation, 95% irrigation uniformity, and no temperature deviation from unilateral cooling insufficiency. In contrast, the average irrigation fluid volume for vHPSD is reduced to about 380 mL, lower than conventional catheters, reducing fluid load without compromising cooling efficacy [6, 12, 17], which is safer for patients with heart dysfunction.

Microelectrode Technology: Three microelectrodes on the catheter tip provide high-resolution local potentials, with a signal-to-noise ratio approximately three times higher than standard electrodes. This technology allows precise identification of scar borders, viable myocardium, and pulmonary vein potentials before ablation, making it particularly suitable for complex substrate mapping and ventricular tachycardia ablation [6, 12, 17].

2.3 Optimization of Key Operational Parameters

Clinical application of vHPSD requires strict control of relevant parameters, establishing an effective evidence-based "ultra-tight protocol."

Contact Force (CF): In vHPSD mode, maintaining a contact force >5g throughout the ablation cycle is recommended to achieve target lesions (impedance drop >10Ω) [9]. Bismpos et al. [18] proposed a "16-gram window," suggesting maintaining CF between 6-22g is appropriate. Low CF may cause insufficient energy delivery; high CF can cause tissue compression injury and crater formation. However, some scholars suggest that within the 4-second vHPSD application, increasing CF beyond 5g might not be necessary for successful lesion creation [9].

Ablation Time and Power with Regional Variation: A recent study identified left atrial wall thickness and local bipolar voltage as the primary determinants of conduction gaps following vHPSD ablation. The right pulmonary vein ridge is prone to first-pass isolation failure, while the left ridge is prone to spontaneous reconnection or dormant conduction, indicating that thick-walled, high-voltage areas may require parameter adjustment (e.g., reducing power to 70-80W or extending duration) [19]. Standard vHPSD parameters are 90W/4s. To mitigate esophageal thermal risk, ablation time should be shortened to 3 seconds on the left atrial posterior wall due to its close proximity to the esophagus [20]. Other areas (anterior wall, lateral wall, etc.) can maintain 4s. In significantly thickened areas (pulmonary vein ridges), switching power to 50W with increased ablation time [10] or using personalized power adjustment is also an option.

Impedance Monitoring and Lesion Spacing: An impedance drop ≥10 Ω predicts effective lesion formation in real time [9]. To ensure continuous transmural lesion lines, inter-lesion spacing is recommended to be ≤4 mm on the anterior wall and ≤6 mm on the posterior wall. Heeger's [21] study on the "CLOSE protocol" showed it indeed improves first-pass isolation rates and results in low long-term pulmonary vein reconnection rates, confirming that tight spacing enhances lesion continuity and durability.

Furthermore, studies confirm that a larger distance between ablation lines (DBL) and a higher DBL to left atrial transverse diameter ratio (DBL/TD) are associated with lower AF recurrence risk, and this ratio is not correlated with impedance levels. This suggests that increasing ablation line spacing while maintaining an appropriate DBL/TD ratio is an important aspect of optimizing ablation strategy [22].

3. Clinical Efficacy Evidence for vHPSD

3.1 Significant Improvement in Procedural Efficiency

Current prospective and RCT results indicate that vHPSD substantially shortens time parameters in AF ablation procedures, representing a breakthrough.

Regarding total procedure time and left atrial

procedure time, A marked reduction in total procedure time was observed with vHPSD, as evidenced by Heeger's report [21], where the median duration was 55 minutes—less than half of the 105 minutes required for conventional RF ablation. Total and left atrial procedure times were significantly shorter with vHPSD-only ablation (88.2±34.9 and 59.4±23.6 min, respectively) than with a mixed-mode approach in the peQasus multicenter RCT [7] (P<0.01). Analyzing RF application time and fluoroscopy time separately quantifies the real-world application of the two ablation modes. Heeger's study [21] showed significantly shorter total RF time in the vHPSD group, reduced by approximately 79% compared to the conventional group. Furthermore, using a 3D electroanatomical mapping catheter reduced median fluoroscopy time to 3.5±2.6 min, with some advanced centers approaching "near-zero fluoroscopy," greatly reducing radiation exposure for medical staff and patients. A multicenter prospective study [23] (166 paroxysmal AF patients) reported a median fluoroscopy time of 9.1 minutes in the vHPSD group (90W/≤4s), longer than Heeger's study (likely due to inclusion of complex anatomy patients) but still significantly shorter than historical data for conventional RF ablation (15-20 minutes). The median RF time was only 8.0 minutes, a 68% reduction compared to the conventional group (25-30 minutes), further confirming vHPSD's advantage in time parameters. Indirect comparative studies showed that the QDOT catheter (vHPSD mode) shortened procedure time by 28% and fluoroscopy time by 55% compared to conventional contact-force catheters, with a significantly lower rhythm-monitoring corrected recurrence rate, further validating its efficiency advantage in real-world clinical practice [24]. Additionally, compared to emerging pulsed field ablation (PFA), vHPSD, while having a slightly longer total procedure time (100 min vs. 70 min), demonstrated significantly shorter fluoroscopy time (7 min vs. 15 min) and does not require general anesthesia, offering greater clinical flexibility in balancing efficiency and radiation protection [25].

3.2 Pulmonary Vein Isolation Success Rate

Study results show very high final PVI success rates (transient PVI success 99.5%-100%, comparable to known conventional ablation techniques) [7, 12, 26]. However, first-pass isolation (FPI) rates are debated. Bortone et al. [10] noted a marked disparity in FPI rates, with the 90W group achieving 49.3% compared to 81.3% in the 50W group, notably in thicker regions such as the left pulmonary veins. This is attributed to the shallower vHPSD lesions, which may not penetrate the full wall thickness in some thick areas with a single application, thus requiring precise spot ablation (each point ~4s), ultimately achieving the same final success rate without compromising overall procedural efficiency. In contrast, Szegedi et al. found no statistical difference in FPI rates between 90W and 50W groups (83% vs. 82%; P=1.0) [26]. Valeriano et al. [27] concluded that a simplified single-catheter PVI workflow using QDOT is feasible and safe, resulting in high FPI rates (86%) and low complication rates.

3.3 Long-Term Efficacy and Quality of Life Improvement

Sinus Rhythm Maintenance: Long-term follow-up data indicate stable efficacy for vHPSD. The Osorio trial [23] reported a 76.7% rate of freedom from atrial arrhythmia recurrence at 12 months in the vHPSD group. Results from Heeger et al. [7] showed a 12-month AF-free rate of 76.8% in the vHPSD monotherapy group, no different from the mixed strategy. Valeriano et al. [27] found no statistical difference in 12-month sinus rhythm maintenance rates between 90W and 50W.

vHPSD not only effectively maintains sinus rhythm but also significantly improves patient quality of life. Hussein's [28] study demonstrated that the AFEQT quality of life score improved from a baseline of 52 to 85 in the vHPSD group. Concurrently, post-procedure use of antiarrhythmic drugs, cardiovascular-related hospitalization rates, and emergency cardioversion rates were significantly reduced, indicating favorable long-term health cost-effectiveness.

Repeat procedure studies with long-term follow-up further confirm the durability of vHPSD PVI lesions. In repeat electrophysiological studies, 64% of patients maintained isolation in all pulmonary veins, with particularly high right pulmonary vein isolation rates (84%), significantly higher than the conventional ablation group (60%). Left pulmonary vein isolation rates (78% vs. 64%) also showed a favorable trend, suggesting lesion stability meets long-term efficacy requirements [29].

Furthermore, clinical studies under mild conscious sedation showed no significant differences in anxiety, discomfort, or pain scores between the

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vHPSD group and the cryoballoon group. Same-day discharge was achieved in 61% of vHPSD patients without increased anesthesia resource needs, further enhancing treatment accessibility and patient experience [30,31].

3.4 Beyond Pulmonary Veins: vHPSD in Other Ablation Targets

vHPSD demonstrates high flexibility and a broader application scope.

Superior Vena Cava (SVC) Isolation: Aizawa et al. [32] reported a 90% success rate for SVC isolation using vHPSD, with significantly shorter procedure times than conventional RF and no phrenic nerve injury, indicating good efficacy for non-pulmonary vein trigger ablation.

Left Atrial Posterior Wall Isolation: High acute isolation rates (>98%) were achieved for persistent AF when vHPSD was combined with posterior wall isolation. Due to its superficial lesion characteristics, the risk of esophageal injury is minimal, making it a feasible substrate modification approach [33], particularly suitable for patients with abnormal posterior wall substrate [34].

Ventricular Arrhythmia Ablation: Preliminary research found vHPSD applicable for right ventricular outflow tract premature ventricular complex ablation, with a success rate of 92%. The microelectrode technology enables precise localization [35], demonstrating the versatility of this technique.

4. Safety Profile and Risk Management of vHPSD

4.1 Overall Complication Spectrum Assessment

Overall, the incidence of major complications with vHPSD (approximately 2%-3.8%) is similar to conventional RFCA [20, 23], but the types of severe complications differ: cardiac tamponade is less frequent (0.2%-1.4%) [5] and closely related to catheter choice and operator experience; steam pops are rare (<2%) due to smart temperature control [9]; vascular complications are mostly minor bleeding or pseudoaneurysms (incidence 1.9%-7%) [28]; importantly, vHPSD significantly reduces symptomatic esophageal injury leading to atrioesophageal fistula. Most endoscopic follow-up studies on vHPSD report a 0% incidence of ulcers [36]. A single-center comparative study noted that only 7% of vHPSD ablation patients required opioid analgesics (fentanyl), significantly lower than the standard power ablation group (76%). Overall patient pain scores were significantly lower, and 62% of vHPSD patients completed the procedure with only benzodiazepine sedation, highlighting its unique advantages in reducing anesthesia dependence and improving patient pain tolerance [31, 37].

4.2 Key Safety Concerns

Silent Cerebral Embolism (SCE): SCE is a relatively common complication associated with vHPSD, with reported incidence varying across studies (8%-26%) [20, 36]. Most are small, asymptomatic cerebral infarct foci detected by MRI, often resolving completely within one month. Risk factors for SCE include: low baseline impedance (108±8Ω vs. 120±15Ω in no-SCE group), catheter loss of contact (CF <5g), insufficient intraprocedural anticoagulation (ACT <300s), and catheter tip coagulum [20]. Optimized generator algorithms, enhanced anticoagulation management, and meticulous operational techniques can reduce SCE incidence. The early version NGEN generator (software V1b) had an SCE rate of 11% [36]. After software update (V1c) and contact force optimization (maintaining 6-22g), the SCE rate decreased to <0.8%. Intraprocedural monitoring for low baseline impedance can substantially reduce this critical complication [5, 38].

Esophageal Injury: A major advantage of vHPSD is its excellent esophageal protection. Preclinical studies indicate a favorable safety profile for vHPSD regarding esophageal injury. The lesion depth in the esophageal mucosa is considerably shallower with vHPSD (~0.4 mm) than the lesions produced by conventional ablation, which typically exceed 0.8 mm in depth [6]. Clinically, endoscopy often reveals only small erythematous spots caused by vHPSD; these superficial epithelial changes are insufficient to cause significant deep mucosal esophageal injury [28, 36]. A single-center retrospective study assessing esophageal injury incidence with the QDOT catheter in HPSD mode found endoscopically detectable esophageal lesions in 16% of first-time ablation patients. Lower average contact force during posterior wall ablation was potentially an independent risk factor for EDEL, suggesting the need to balance contact force during posterior wall ablation to reduce esophageal injury risk [39].

Notably, a multicenter case report described 3 cases of cardiac perforation (incidence 1.6%) during ablation at the left lateral ridge with the

QDOT MICRO catheter, all located at the postero-inferolateral aspect of the left atrial appendage base. Analysis identified low impedance (<90Ω), transient high contact force (40-50g), and perpendicular catheter orientation as main risk factors, suggesting the need for strict contact force control (<20g) and current monitoring (avoid >750mA) when operating in this anatomical location [40].

4.3 Risk Factors and Prevention Strategies

Addressing the above risks requires comprehensive preventive measures.

Personalized Power Adjustment: Implement power stratification based on left atrial wall thickness or voltage: consider reducing power to 70-80W or extending duration at sites with LAWT >2.5mm; maintain standard power but reduce inter-lesion spacing in low-voltage areas to achieve transmurality while balancing safety [38, 41].

Strict Anticoagulation Management: Adherence to uninterrupted oral anticoagulation pre-procedure, maintaining intraprocedural ACT ≥300s (checked every 30 min), and following standardized post-procedure anticoagulation protocols are foundational for preventing thromboembolic events [20].

Catheter Stability and Contact Force Control: Ensure stable catheter contact during ablation, avoiding low contact force <5g [5, 9] or discharging during significant cardiac motion, to achieve effective energy delivery and minimize complications.

Multimodal Esophageal Protection: Routine use of esophageal temperature monitoring (warning threshold 38.5°C) [6, 36] is recommended. Adjust ablation location/parameters based on esophageal position and peristalsis observed via intracardiac echocardiography, applying protective measures as necessary.

5. Current Controversies, Challenges, and Future Directions

5.1 Core Controversies

The lower first-pass isolation rate, particularly evident in the left pulmonary veins [10], raises the question: Does this indicate less durable lesion formation in thick-walled areas? Although short-term (one-year) vHPSD outcomes are ideal, some mid-term procedural studies (e.g., Heeger et al. showing 6-month PVI durability of 81% in the vHPSD group [21]) present specific characteristics. However, data from large, long-term follow-up studies exceeding two years are still lacking. Definitive evidence confirming the superiority of the new protocol for maintaining lesions in hypertrophic tissue is insufficient.

Clinically, most SCE foci are asymptomatic and resolve spontaneously, but their potential impact on long-term neurocognitive function remains unclear [20, 36]. Whether longer-term neuropsychological assessments would reveal effects requires further investigation.

Lack of Parameter Standardization: Currently, different centers lack consensus on vHPSD parameters, such as power selection (e.g., using 90W or 80W on the posterior wall), ablation duration (3s vs. 4s) [6, 42], contact force range, and lesion spacing [9]. No guidelines or standardized protocols based on high-level evidence exist, leading to variability in clinical practice across centers.

5.2 Future Research Directions

Conduct large-scale, long-term RCTs, carefully designed and executed across multiple centers, comparing vHPSD with conventional power ablation, cryoballoon, and pulsed field ablation regarding long-term efficacy (≥2-year AF-free survival), safety endpoints (especially long-term impact of SCE), quality of life, and cost-effectiveness.

Deepen research on "personalized" ablation techniques, exploring the integration of cardiac MRI fibrosis assessment, precise left atrial wall thickness measurement, and vHPSD technology. Develop personalized power, duration, and mode selection strategies based on individual patient anatomy and substrate characteristics.

Conduct evidence-based exploration of the clinical profile of vHPSD in special populations (e.g., AF with heart failure, long-standing persistent AF, elderly AF, giant left atrium) to fill relevant evidence gaps.

Technological Innovation and Integration: Continuously improve catheter design (e.g., more sensitive temperature sensing, enhanced irrigation) and optimize generator algorithms to reduce SCE and coagulum risks. Fully explore the integration of vHPSD with high-density mapping, AI-guided systems, and robotic-assisted platforms to enable more accurate, intelligent lesion delivery and better prediction of long-term outcomes.

6. Conclusion

Very high-power short-duration radiofrequency

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ablation represents an innovative advancement in the field of catheter ablation for atrial fibrillation. It shifts the energy delivery paradigm from previous "conductive heating" to "resistive heating." Utilizing intelligent ablation catheters like QDOT MICRO, coupled with precise temperature control and mapping, significantly enhances procedural efficiency, reduces complications, and notably decreases the incidence of severe esophageal injury. Current clinical data on the safety and efficacy of vHPSD for treating AF patients is substantial, demonstrating high treatment success rates and overall safety, making it suitable for both paroxysmal and persistent AF.

Although controversies persist regarding the safety of vHPSD technology—such as first-pass isolation rates, silent cerebral embolism, and catheter tip coagulum—many experts believe that standardizing operations, optimizing techniques, strictly controlling risks, and adhering to unified protocols can minimize complication rates. It is believed that future research, through larger long-term follow-up studies, more standardized personalized ablation parameters for specialized ablation, and broader adoption of the vHPSD approach, will lead to the wider application of multi-modality integrated new technologies. vHPSD is poised to become a major ablation modality for atrial fibrillation in the future.

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