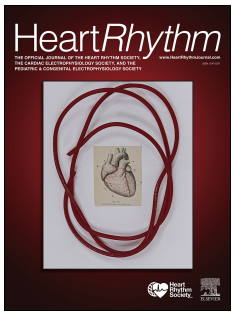
Journal Pre-proof



2026 HRS/EHRA Scientific Statement on Pulsed Field Ablation for Cardiac Arrhythmias

Atul Verma, MD, FHRS, Co-Chair, Mélèze Hocini, MD, FHRS, Co-Chair, Jason Andrade, MD, Edward Gerstenfeld, MD, FHRS, Suraj Kapa, MD, Dhanunjaya Lakkireddy, MD, FHRS, Damijan Miklavcic, PhD, Andrea Natale, MD, FHRS, Jonathan Piccini, MD, FHRS, Boris Schmidt, MD, Melanie A. Gunawardene, MD (Scientific Documents Committee Liaison)

PII: S1547-5271(26)00124-4

DOI: https://doi.org/10.1016/j.hrthm.2026.02.006

Reference: HRTHM 11762

To appear in: *Heart Rhythm*

Received Date: 9 February 2026

Accepted Date: 9 February 2026

Please cite this article as: Verma A, Hocini M, Andrade J, Gerstenfeld E, Kapa S, Lakkireddy D, Miklavcic D, Natale A, Piccini J, Schmidt B, Gunawardene MA, 2026 HRS/EHRA Scientific Statement on Pulsed Field Ablation for Cardiac Arrhythmias, *Heart Rhythm* (2026), doi: https://doi.org/10.1016/j.hrthm.2026.02.006.

2026 HRS/EHRA Scientific Statement on Pulsed Field Ablation for Cardiac Arrhythmias

Atul Verma, MD, FHRS (Co-Chair);[1] Mélèze Hocini, MD, FHRS (Co-Chair);[2,3] Jason Andrade, MD;[4] Edward Gerstenfeld, MD, FHRS;[5] Suraj Kapa, MD;[6] Dhanunjaya Lakkireddy, MD, FHRS;[7] Damijan Miklavcic, PhD;[8] Andrea Natale, MD, FHRS;[9] Jonathan Piccini, MD, FHRS;[10] Boris Schmidt, MD;[11] Melanie A. Gunawardene, MD (Scientific Documents Committee Liaison)[11,12]

From [1]McGill University Health Centre, Montreal, Canada; [2]Bordeaux University Hospital, Bordeaux, France; [3]Liryc Research Institute, Pessac, France; [4]Vancouver General Hospital, Vancouver, Canada; [5]University of California San Francisco Medical Center, San Francisco; [6]Mayo Clinic, Rochester, Minnesota, United States; [7]Kansas City Heart Rhythm Institute, Overland Park, Kansas, United States; [8]University of Ljubljana, Ljubljana, Slovenia; California, United States; [9]St. David's Medical Center, Austin, Texas, United States; [10]Duke University Medical Center, Durham, North Carolina, United States; [11]Cardiovascular Center Bethanien, Frankfurt, Germany; [12]Centre for Heart Rhythm Disorders and Royal Adelaide Hospital, Adelaide, South Australia, Australia

ABBREVIATIONS 3D = three-dimensional; **AF** = atrial fibrillation; **AI** = artificial intelligence; **AKI** = acute kidney injury; **AVNRT** = atrioventricular nodal reentrant tachycardia; **AVRT** = atrioventricular reentrant tachycardia; **CTI** = cavotricuspid isthmus; **ICD** = implantable cardioverter-defibrillator; **ICE** = intracardiac echocardiography; **LAA** = left atrial appendage; **LET** = lethal electric field threshold; **MRI =** magnetic resonance imaging; **MSK-S** = musculoskeletal stimulation; **MVI** = mitral valve isthmus; **PFA** = pulsed field ablation; **PV** = pulmonary vein; **PVC** = premature ventricular contraction; **PVI** = pulmonary vein isolation; **PWI** = posterior wall isolation; **RF** = radiofrequency; **SVC** = superior vena cava; **SVT** = supraventricular tachycardia; **VF** = ventricular fibrillation; **VT** = ventricular tachycardia; **WPW** = Wolff-Parkinson-White

Correspondence: Heart Rhythm Society, 1455 Pennsylvania Ave NW, Suite 400, Washington, DC 20004; email: documents@hrsonline.org

This statement was developed in collaboration with and endorsed by the European Heart Rhythm Association.

Table of Contents

Introduction 3

Basic PFA concepts 4

Procedural workflow of PFA procedures 7

General ablation complications highlighted in the PFA era 18

PFA for non-AF arrhythmias 20

Future directions for PFA 22

Recommendations 24

Acknowledgments 24

Tables 25

Figures 41

Appendix 1 Writing committee member disclosure of relationships with industry and other entities 71

Appendix 2 Peer Reviewer disclosure of relationships with industry and other entities 74

Introduction

Preamble

The Heart Rhythm Society (HRS) has developed scientific and clinical documents guiding the management of cardiac arrhythmias since 1996. This HRS-led scientific statement was developed in collaboration with the European Heart Rhythm Association (EHRA). This statement discusses the use of pulsed field ablation for cardiac arrhythmias.

Editorial independence

The statement is sponsored by the HRS and was developed without commercial support. All writing committee members and peer reviewers volunteered their time to the writing and reviewing efforts.

Organization of the writing committee

The writing committee included experts in clinical electrophysiology and clinical research science, bringing together a range of perspectives essential to the topic. HRS strives to ensure that each writing committee reflects both the requisite subject matter expertise and diverse representation from the broader medical community. This includes thoughtful consideration of participants' clinical experience, career stage, and other demographic and professional characteristics.

HRS has rigorous policies and methods to ensure that documents are developed without bias or improper influence. The HRS policy on relationships with industry and other entities can be found in Appendix C of the *Hearth Rhythm Society Code of Ethics & Professionalism* and in the *HRS Scientific Documents Methodology Manual*. **Appendix 1** is a comprehensive list of relationships with industry and other entities disclosed by the writing committee members. **Appendix 2** is a comprehensive list of RWI disclosed by the peer reviewers.

Document review and approval

This statement was approved by the writing committee and underwent internal review and approval by the HRS Scientific Documents Committee. The statement was reviewed and endorsed by EHRA.

Document updates

The HRS Scientific Documents Committee reviews each scientific document for currency every 2-5 years after publication.

Document scope and rationale

In a seminal publication, the initial technique given for cardiac ablation was connection of a diagnostic catheter to an external defibrillator and delivery of a sizable electrical shock to the atrioventricular nodal region[1]. The underlying mechanism of action was at least, in part, electroporation, which causes injury to the cell plasma membrane, increasing its conductivity and permeability and disturbing cell homeostasis, leading to cell death[2]. However, the large electrical current and long pulses were found to cause secondary thermal effects, catheter damage, and barotrauma, demonstrating severe limitations of the approach[3]. Since then, thermal ablation has dominated our field[4].

It took many years and several technological developments to bring electroporation back into cardiac ablation. By dividing the energy delivery into multiple pulses lasting only nanoseconds to microseconds and delivering bursts of these pulses over a few milliseconds to seconds, large voltages

could be used to safely and irreversibly electroporate cardiac tissue[2]. The resulting pulsed field ablation (PFA) methodology created a clinical revolution, demonstrating efficacy similar to that for thermal ablation but with better efficiency and safety[5]. The technology became one of the most rapidly implemented advances in the history of cardiac ablation. However, despite the rapid adoption of PFA, including treatment of hundreds of thousands of patients since 2021, there is still much to be learned about the mechanistic details and physiological responses to electroporation and pulse delivery. Furthermore, while current PFA tools have had promising results, they also revealed some unexpected adverse events, such as hemolysis and coronary vasospasm[5]. In this document, we intend to provide contemporary knowledge about the science, appropriate clinical implementation, and avoidance of adverse events of PFA to give both physicians, and ultimately patients, the best possible outcomes.

Basic PFA concepts

Electroporation and the electric field

Cell electroporation occurs when a cell is exposed to a sufficiently high electric field and duration[6]. When a potential difference between the catheter tip and return electrode (monopolar delivery) or two or more electrodes on the catheter (bipolar delivery) is established, the electric current (voltages applied in the range of 1500-3000 V will result in a current of 10-30 A or more) will flow through the tissues and blood and will distribute based on their conductivity. The current will be accompanied by an electric field, and the degree of the field that the cell is exposed to will depend on its location. Specifically, the electric field (in units of V/cm) is highest close to the catheter/electrode and drops rapidly with distance[7] (Figure 1). If cells are exposed to a high enough field and duration, electroporation may cause severe cellular damage resulting in cell death, which is known as irreversible electroporation[8,9]. If the field does not cause sufficient disruption in cellular homeostasis, the cell may recover, which is called reversible electroporation[9]. For ablation of cardiac tissue, it is desirable to maximize the ratio of irreversible to reversible electroporation while minimizing adverse effects such as tissue heating.

The electric field distribution in the tissue is critical since a field exceeding a specific threshold value will determine the size of created lesion[10]. The lethal electric field threshold (LET) refers to the electric field strength, typically measured in volts per centimeter (V/cm), at which cell death is induced[11]. The LET varies depending on tissue type and pulse parameters, but for cardiac tissue it generally falls within the range of 300-700 V/cm[11]. LET is dependent on the pulse parameters, including pulse duration, and the number of pulses and pulse trains; increased values of these parameters will decrease the LET. The electric field cannot be measured in the tissue and can only be calculated numerically[12,13]. The current and electric field vary with the tissue type and conductivity, which also increases with temperature and electroporation onset. Since cardiac tissue is also anisotropic (tissue property that varies with different directions), numerical models used for electric field calculations are complex and must be vigorously validated in order to best predict lesion dimensions created by a particular waveform and catheter[14-16]. The most important point is that the lesion achieved depends on electric field distribution and is often and easiest described by LET.

Designing optimal pulse parameters

There are several pulse parameters that can be adjusted (Figure 2), each with their own implications (Figure 3). In general, designing the optimal pulse parameters involves compromises between efficacy of the lesion (tissue depth) and minimization of unwanted effects such as musculoskeletal stimulation (MSK-S), excessive heating, and injury to non-cardiac tissues. The choices

made are also intimately linked to electrode (size, architecture, and distance between electrodes), catheter design, and vectoring of PFA[17]. Most PFA systems today provide lesion depths of 4-7 mm, which is not that different from the lesion depth in thermal ablation (Figure 4)[18-31]. A few key parameters will be detailed in this section.

Phase and polarity

Phase refers to the relative direction of current flow during pulse delivery. Monophasic pulses generate an electric current that flows exclusively in a single direction, producing only a positive waveform component with a defined peak voltage. In contrast, biphasic pulses deliver current in two sequential phases—first in one direction during the positive phase and then in the opposite direction during the negative phase (Figure 2). Use of monophasic pulses is very efficient for achieving electroporation, but these pulses also result in considerable electrolysis (chemical reactions at the electrode–tissue interface caused by electric current, leading to potential gas formation and extreme local pH changes), severe MSK-S, pain, and discomfort. Consequently, most PFA systems use short biphasic pulses, but higher voltages are often required to achieve comparable electroporation and consequent lesion volume[32-34]. Short biphasic pulses also have the added advantage of being less arrhythmogenic (inducing atrial or ventricular arrhythmias) and may therefore be delivered omitting R-wave gating[35,36]. While the positive and negative phases of a pulse are often symmetrical, asymmetric phases may also be used but have been far less explored[37-39]. Most pulses are composed of square waves, but different shapes, such as a sinusoidal wave, can be used[40,41]. Finally, the delivery of pulses across different electrodes (eg, skipped electrodes) and use of different combinations on multielectrode catheters are used to achieve larger and circumferential lesions without repositioning the catheter[42,43] (Figure 5).

Polarity refers to the relative position and distance between the positive and negative poles of the delivery system. Bipolar systems will deliver pulses through adjacent electrodes on the catheter itself (eg, between the splines). This will create a high electric field close to the electrodes on the catheter and allow for large area lesions but with limited depth. Unipolar systems will deliver pulses from a catheter to a return patch on the patient's skin (or a separate catheter within the patient) and may achieve larger depth but perhaps not necessarily as broad a lesion as that achieved with bipolar delivery[44]. Polarity also influences the spatial distribution of current within the tissue volume and modulates MSK-S, with unipolar energy delivery generally associated with a greater propensity for neuromuscular capture[2]. In general, large single-shot, multi-electrode catheters tend to be bipolar, whereas single-point (focal, either large or small) catheters tend to be unipolar.

Voltage, pulse width, and trains

Lesion size (depth and width) increases with voltage applied—2000 V will create larger lesion than 1500 V—keeping all other parameters and catheter geometry equal[15]. It is known from experience that longer pulses are more efficient at creating lesions than shorter ones[45]. However, increasing voltage will also increase MSK-S, ohmic heating, and other unwanted effects. By convention, the voltages reported for these systems refer to the amplitude measured from baseline to the peak of the positive phase. Consequently, the true peak-to-peak voltage—spanning the full excursion from the negative to the positive peak—is twice this baseline-to-peak value. Most systems operate in a range of 1500-3000 V (peak to baseline)[2 2]. Maximum delivered voltage is limited by increasing thermal effects, and at very high voltages arcing across electrodes may occur as well as char formation. However, it is not a given that a system claiming to use a higher voltage will create more effective lesions than another system using a lower voltage, given all the differences in other pulse parameters and catheter design between two such systems.

Pulse width is a critical parameter in achieving electroporation and lesion. Longer pulses require lower voltage compared with shorter pulses[46,47]. The longer the pulse, the more efficient it is in creating cell death but also in eliciting MSK-S, contraction, pain, and heating. Most currently existing PFA systems use pulse widths in the sub-microsecond to low-microsecond range (0.3-5 μs). As the pulse width decreases, there may be a decrease in MSK-S, but to obtain a similar lesion depth and width, an increase of voltage would be required to maintain the same lesion efficacy[33,48,49]. In this range of pulse width/duration, the intensity-duration curve is very steep, so even a change in pulse width of one microsecond can cause substantial changes in lesion depth and MSK-S[50].

To some extent, the effectiveness of electroporation can be increased by increasing the number of pulses. Several pulses delivered in sequence is called a pulse train (sometimes called a burst or train). Often, PFA systems will deliver several pulse trains (each composed of several pulses) over a few seconds to increase efficacy. Pauses between the delivery of trains of pulses can be used to allow cooling/heat dissipation and avoid excessive heating[34]. Repetition of applications effectively translates into a reduction of the LET, which increases efficacy. However, a decreased gain is observed with an increasing number of trains and pulses, indicating a plateau effect[15,51]. For a given set of parameters, electric field modeling predicts a predetermined lesion depth, and excessive repetitive applications will not create further lesion depth based on LET value.

Terminology of PFA

The specific terms to describe waveforms and pulses are detailed in Table 1. A PFA application refers to the total PFA dose that is delivered with a single button push of a PFA generator. A single application often consists of many pulses broken up into pulse trains delivered over a few seconds that may or may not be R-wave gated. The application delivered by one PFA system, however, cannot be compared with the application by different PFA system. A group of applications—called an application set—may be required to isolate a structure like a pulmonary vein (PV).

Thermal effects of PFA and microbubbles

A certain degree of tissue heating is inevitable during PFA, as the passage of electrical current through biological tissue inherently generates thermal energy and leads to a measurable rise in temperature. The heating is proportional to the square of current and increases with the pulse amplitude, pulse duration, and number of pulses delivered[2,52]. If pulses are delivered in a very short time (high duty cycle), they may heat the tissue beyond temperatures causing thermal damage. Delivering pulses with low duty cycle will allow dissipation of part of the generated heat, resulting in lower maximal temperatures and avoidance of thermal damage[2,52].

The magnitude of the temperature rise in most PFA systems is often in the order of a few degrees Celsius (3-10°C), which is not enough to create coagulative necrosis of the tissue (caused by temperatures higher than 50°C)[52]. The duration of the applications is also short enough that the heat exposure is not long enough to create thermal damage. However, there is thermal latency, and if the biphasic pulses or trains are not sufficiently interspaced, this can lead to local heat stacking, microbubble formation, protein denaturation, and clot formation[2,17,52].

Because of different pulse parameters and catheter designs, the heating profiles of PFA systems differ[53]. Heating may be higher in current pentaspline, variable loop, and small sphere platforms compared with a 9-electrode gold array[53,54]. This has led to some differences between systems causing microbubble formation, potential coagulation, and stroke[55]. Ohmic heating will be highest where the maximal current density (A/cm^2) is located[8]. Catheter design is critically important for heating since

current density is highest at the edges of an electrode (the edge effect) because of the finite geometry of an electrode[56]. If the edges are not sufficiently rounded and/or insulated, the heating can cause tissue coagulative necrosis and can also trigger blood coagulation. Similarly, if the energy delivery parts of a catheter are mobile and can overlap one another, the current density may be excessive and subsequently cause excessive heating[57,58].

Microbubbles can be observed with some PFA systems on intracardiac echocardiography. There are multiple possible causes for microbubbles, including hydrolysis caused by the electrical current, degassing of the blood (eg, nitrogen), and blood heating caused by the electrical current[34]. For most biphasic PFA systems, heating seems to be the main cause of microbubble formation. Even if heating is below boiling temperature, temperatures may be high enough to cause protein denaturation, coagulation, and char formation[34]. Ideally, PFA systems should minimize if not eliminate microbubble formation.

PFA effects on extra-cardiac structures

PFA was introduced as a "cardiac tissue-specific" energy source for cardiac ablation. It is true that esophageal and nerve tissues seem to be more "resistant" to PFA damage, but the LET for cardiac tissue ablation may be closer to the thresholds of these other tissues than previously believed[11]. PFA using systems in commercial development or currently approved has demonstrated the ability to create acute esophageal lesions extending into the muscle layers[59]. However, since PFA does not seem to disrupt the vascular supply and extracellular matrix of the affected area, progenitor cells are able to repopulate and heal the lesion within weeks (Figure 6). PFA has also demonstrated the ability to stun the phrenic nerve [60-63]. Pre-clinical models and clinical experience suggest that the function of the nerve recovers within minutes (to hours) with repair of the myelin sheath surrounding nerve axons[64]. However, an excessive thermal footprint can cause unintended thermal damage to collateral/adjacent structures if a PFA system is poorly designed[17].

Studies have suggested that endocardial application of PFA does not seem to permanently ablate autonomic ganglia and cause autonomic changes that thermal ablation has demonstrated previously[65]. Whether this is important to the outcome of atrial fibrillation (AF) ablation is not well known[66]; however, studies demonstrating that PFA has similar AF freedom to thermal ablation with less autonomic denervation suggest that denervation is not as important as achieving permanent pulmonary vein isolation (PVI)[65]. Hypotheses may be that PFA is not creating deep enough lesions to reach the ganglia or that the ganglia are protected by insulating fat. Ganglia themselves are not resistant to PFA since ganglia consist of cell bodies (not axons like nerves) and have demonstrated excellent sensitivity to PFA[67,68].

Procedural workflow of PFA procedures

Indications and patient selection

The pivotal trials of PFA thus far have led to approvals for catheter ablation of AF. Prospective single-arm studies of PFA that have included patients with both paroxysmal and persistent AF and observational data have been favorable[30,69-76]. To date, these studies have shown that PFA is more time efficient and safer for adjacent tissue than thermal ablation. The comparative trials suggest that efficacy is so far non-inferior to thermal ablation[77-81]. Table 2 summarizes both the efficacy and safety outcomes for various studies of PFA technologies. The early and available prospective randomized trials that compare PFA with thermal methods of ablation have demonstrated advantages with PFA, including more efficient procedures, and one study showed reduced AF burden in follow-up, although a consistent

improvement in efficacy has not been demonstrated[82-84] (Table 2). Table 3 summarizes the characteristics of various approved PFA catheters and those that are in development. Thus far, surveillance databases suggest that PFA is not associated with PV stenosis or atrioesophageal fistula, in contrast to thermal ablation[85]. Durable phrenic nerve palsy also seems to be very rare[86]. Given the combined advantages of PFA, anyone indicated for AF ablation should also be considered for PFA[87,88]. In the future, PFA may also expand the populations of AF patients offered the procedure (older, earlier in the disease, heart failure)[87].

PFA beyond PVI ablation has less supporting data, including an absence of randomized studies. There is observational data to support the safety and efficacy of ablation of both typical and atypical atrial flutter[89-91]. Tricuspid and mitral flutter ablation locations are immediately adjacent to the coronary arteries, so use of radiofrequency (RF) ablation may be preferred given concerns over coronary artery vasospasm and potential lumen loss with PFA[92-94]. Ventricular arrhythmia ablation is also in nascent phases and is discussed later. Procedural and workflow elements for PFA are summarized in Figure 7.

Sedation, anesthesia, and adjuvant medication management

Electric pulses delivered during PFA might cause MSK-S, phrenic nerve capture, and procedure-related coughing[95]. Patients may also feel chest discomfort and pain separate from muscle contractions[33].

With most currently available PFA systems, the degree of skeletal muscle activation—including phrenic nerve capture—as well as procedure-related discomfort and coughing, typically necessitates the use of deep sedation or general anesthesia. There is debate about the optimal sedation strategy for patients undergoing AF ablation with PFA (Figure 7).

Data from single-center experiences and larger registries, including the European EUPORIA and MANIFEST registries[96,97], indicate that deep sedation without intubation of the patient can be used for PFA. Deep sedation typically involves use of anesthetic agents, such as propofol or dexmedetomidine without intubation of the patient. Use of such deep sedation protocols, however, are limited to specific geographies. In many jurisdictions, use of these agents, even without intubation, requires the presence of an anesthesiologist. However, deep sedation is the most common approach to date for procedures involving a pentaspline PFA catheter, used in 4 out of 5 patients[96-98]. Early reports from European centers suggest that deep sedation may also be feasible for monopolar PFA[99]. The choice of sedation medication varies, with several agents reported in the literature[100-102]. To date, only one randomized study (COOPERATIVE-PFA) has evaluated sedation strategies in PFA, showing that remimazolam-ketamine deep sedation significantly reduced sedation-related adverse events—particularly hypoxemia and hypotension—compared with both bolus and continuous propofol-opioid regimens[103]. Supplemental Table 1 includes examples of sedation and anaesthetic regimens for the readers' reference.

In centers where anesthesiology support is readily available, the majority of PFA procedures are performed under general anesthesia with endotracheal intubation and often the use of neuromuscular blocking agents. The principal advantage of this approach is the complete suppression of skeletal muscle contractions, patient movement, and the cough reflex, thereby facilitating more stable catheter positioning, improved mapping quality, and more controlled ablation delivery. However, general anesthesia will not eliminate vagal responses during PFA application around the PVs, particularly the left PVs. Deep sedation is an alternative when anesthesia resources are limited and has been associated with reduced mean laboratory occupancy time[99,104]. Deep sedation will not eliminate muscular contraction, patient movement, coughing, or vagal responses.

The use of adjunctive pharmacological agents may optimize procedural workflow and improve patient comfort during sedation. Procedure-related coughing is likely attributable to stimulation of bronchial C-fibers, which are the vagal afferents innervating the airways and/or stimulation of the J-receptors within the PVs[105,106]. To minimize cough, higher doses of opioids, such as fentanyl, can be used since opioids are effective cough suppressants. Peri-procedural administration of lidocaine may also be used (Table 4).

To mitigate vagal responses during PFA, especially around the left sided veins, pre-ablation administration of agents such as atropine or glycopyrrolate may be considered[107]. Contraindications, including glaucoma, urinary tract obstruction, or pyloric stenosis, should be carefully assessed prior to their use (Table 4). Atrial and ventricular pacing capability should be available during PFA in case pauses or vagally induced asystole occurs. There is also some limited evidence that starting PFA with the right PVs can reduce the vagal reflex associated with the left PVs[108].

Newer PFA technologies utilizing alternative catheter designs (such as an insulated balloon) or modified PFA waveforms (prolonged deliveries with more pauses) may facilitate the use of lighter sedation protocols and even conscious sedation (eg, opioid plus midazolam)[69,109,110], although further studies are required.

Optimizing application strategies with PFA for PVI

In investigational device exemption studies, specific PFA dosing and applications protocols have been suggested based on bench and controlled 3-month remapping data[25,73,111,112]. In clinical real-world data, however, PVI durability with PFA is not yet optimal and may be due to inadequate catheter-tissue contact, insufficient numbers of applications, or poor overlap of lesions[113]. Therefore, additional workflow protocols examining optimized PFA application strategies have been studied[114-116]. A higher number of PFA applications than initially recommended by manufacturers appears to increase acute PVI durability and long-term success[115,116]. However, increased number of applications has also been associated with increased risk of hemolysis, as discussed later in this document.

The most promising strategy seems to involve initially targeting the ostium of the PV, or in some cases, the myocardial sleeves extending inside the PV before applying more antral lesions. With a more olive-shaped configuration of the pentaspline catheter targeting the PV myocardial sleeves, PV reconnection was significantly less frequent (13.6% [3 of 22 patients]) compared with a conventional strategy (45% [36 of 80 patients]; $p < 0.007$) in patients presenting for repeat ablation[114]. In another study, upon invasive 3-month remapping, PVI durability was 99% on a per-vein basis for the PULSE3 cohort using a large spherical single-shot PFA catheter, in which PVI was achieved by advancing the collapsed sphere into the targeted PV (aiming at the PV sleeves) and gradually retracting and expanding the lattice framework to the antral position[117]. For a circular array catheter, the recommended workflow is to apply at least four PFA applications ostially with rotation between applications prior to moving to the antral regions[70]. No PV stenosis has been reported in any PFA system targeting the PV sleeves[70,114]. Repeated applications of PFA in the same area can potentially increase depth but may also increase thermal footprint[118]. Also, as mentioned earlier, there is a plateau effect due to diminished gain with increasing number of repeat PFA applications[15,118].

In summary, protocol-mandated PV remapping studies are useful for the early evaluation of novel PFA devices in first-in-human or investigational device exemption studies, as they provide critical insights into the efficacy of various dosing parameters. To be robust, these remapping studies should have proper, blinded assessments of completeness and level of isolation and should not be limited to single-operator interpretation. Real-world data often show disparate and often inferior results to those

of remapping studies[113], which consequently illustrates the need to improve workflow and advance research into how we can assess completion of PFA lesions.

Ablation beyond PVI

Due to shorter ablation times associated with PFA and the apparent lack of collateral tissue damage, the addition of further ablation beyond PVI can be performed with little risk or additional procedure time. This includes additional isolation of the superior vena cava (SVC), posterior wall isolation (PWI), and ablation of non-PV triggers. Cavotricuspid isthmus (CTI) and mitral valve isthmus (MVI) line ablation[82] has also been performed, although with risk of coronary vasospasm.

Isolation of the SVC

Isolation of the SVC using PFA has been shown to be feasible in published case reports and two clinical studies[119-123]. In a single-center study involving 105 patients, transient phrenic nerve stunning and transient sinus node dysfunction were observed in 64% and 4.7% of cases, respectively[119]. These adverse effects appeared to be mitigated with the use of intracardiac echocardiography (ICE) allowing optimal placement of the catheter at the SVC-right atrial junction—high enough to avoid the sinus node, but low enough to avoid proximal phrenic nerve injury. In a subsequent prospective multicenter study involving 606 patients, in which ICE was systematically used, no cases of sinus node dysfunction and only one instance of transient phrenic nerve stunning were reported[120]. Although anatomical landmarks—specifically the junction of the SVC and the right atrium at the level of the inferior border of the pulmonary artery—have been used to guide PFA catheter positioning[120], the optimal dosing and precise application parameters remain inadequately defined. No permanent complications related to SVC isolation with PFA have been documented in the published literature to date. In the future, lower or adapted pulse waveforms may allow for easier application of PFA in the SVC while further minimizing the risk of phrenic nerve and sinus node injury.

Additional PWI

Additional PWI has been rapidly adopted in clinical practice among PFA users. Due to the broader lesion geometry associated with PFA, incidental or unintended PWI or a very small space between PVI lines (which is potentially proarrhythmic) has been reported, supporting the rationale for intentionally targeting the posterior wall following PVI[124,125]. The feasibility and safety of adjunctive PWI—particularly regarding esophageal safety—have been demonstrated in both pre-clinical studies and small clinical cohorts[126-130]. These findings are further supported by safety data from large-scale registries such as MANIFEST 17K[86]. Reported studies have shown arrhythmia-free survival rates ranging from 53% to 83.5% following the addition of PWI[75,82,86,126,131,132], including a success rate of 73.8% for dual-energy approaches, as exemplified by the randomized SPHERE-Per-AF study, where 93.4% of patients underwent PWI. In the multicenter ADVANTAGE AF phase 2 study investigating PVI combined PWI with an implanted loop recorder for persistent AF, an atrial arrhythmia burden of <0.1% and atrial arrhythmia episodes lasting less than 1 hour were achieved in approximately 72% of patients and were associated with the lowest levels of health care utilization[74]. The additional ablation may not be totally benign, however, as the stroke rate in the ADVANTAGE AF phase 2 study was 1.2%.

Published studies comparing PFA-based PVI alone to PVI with adjunctive PWI have not demonstrated a significant improvement in arrhythmia-free survival[133,134]. Considering the lack of evidence, the decision to add PWI should therefore be individualized, considering patient-specific substrate characteristics and procedural goals[135].

CTI ablation

CTI ablation using PFA has primarily been demonstrated in case series and clinical studies[111,136,137]. When applying PFA at the CTI, larger lesion dimensions than those seen with thermal ablation should be anticipated and transient conduction disturbances may occur[138,139]. While the achievement of acute isthmus block is frequent, especially due to the associated stunning effects of PFA, the long-term efficacy is not well known. A systematic review and meta-analysis of 11 studies (155 patients) found that PFA achieved acute CTI block in 100% of cases, with a mean of 7.78 (95% CI, 6.53-9.48) applications per procedure[93]. While acute success was observed in 100% of cases, evidence regarding the durability of block is limited. One study observed an 8% reconnection rate at a 3-month remapping procedure in 12 patients, while another showed about 50% reconnection in 15 patients undergoing repeat ablations[111,140]. In the ADVANTAGE AF phase 2 trial, acute bidirectional block of the CTI using a single-tip PFA catheter was achieved in 98.6% patients[74]. At 1 year, freedom from recurrent atrial flutter was observed in 96.4% of patients, but no remapping was performed. In a large U.S.-based cohort of 311 patients undergoing PFA-based CTI or MVI ablation for atrial flutter, atrial flutter recurrence was 3.9% over a median follow-up of 175 days (interquartile range, 132–244 days)[141].

Coronary spasm is the main risk associated with CTI ablation, since the ventricular aspect of the CTI is close to the right coronary artery[93,142] (Supplemental Figure 1). The incidence and pathogenesis of coronary spasms is discussed in detail in the safety section of this document. Subclinical moderate-to-severe coronary spasm has been reported in 80%–100% of patients undergoing CTI ablation with PFA without nitroglycerin pretreatment, while clinically apparent spasms—characterized by ST-segment elevations and potentially life-threatening arrhythmias—are less common[143-145]. One proposed nitroglycerin dosing regimen involves administering an intravenous/intra-atrial bolus of 3 mg 1 minute prior to the first PFA application, followed by an additional 2 mg every 2 minutes of ablation (Table 3)[146]. In this study, a total dose of 4 ± 2 mg of nitroglycerin was typically sufficient during 8 ± 13 minutes of CTI ablation, and no clinically apparent coronary spasm was observed. In other smaller studies, lower doses of 0.4 mg intravenous nitroglycerin were also used effectively[40], but more extensive safety data for lower doses are not available. Nitroglycerin administration will lead to hypotension, which should be promptly recognized and managed accordingly with vasopressors. The safety of repeated cycles of vasodilators followed by vasopressors is not known and may be more feasible in a general anesthesia setting.

Despite prophylactic nitroglycerin, vasospasms may still occur. Spasms may also occur several hours or even days following pulsed field energy delivery[147], which is described in the safety section. In the event of coronary spasm, administration of intracoronary nitroglycerin and timely management of ischemic complications—such as ST-segment elevations on electrocardiogram, heart block, or ventricular fibrillation (VF)—may be necessary[148]. Immediate and effective treatment is important.

MVI line ablation

MVI line ablation has also been shown to be feasible with PFA, achieving high acute success rates for acute conduction block. The addition of MVI ablation using PFA resulted in arrhythmia-free survival rates of 80%-90%[89,141]. A current limitation in interpreting these outcomes is the significant heterogeneity in ablation strategies used across studies—for example, the frequent combination of PWI and mitral ablation—which complicates the scientific evaluation and comparison of standardized procedural protocols. Additionally, the long-term durability of PFA-guided mitral ablation lesions is not well known and may be quite poor with large catheters designed for PVI[90,145]. In one study, acute MVI block was obtained in all patients with a pentaspline catheter, but at the time of remapping (second procedure for left atrial appendage [LAA] occlusion), durable block was seen in only 5.5%[149].

Coronary spasm is also a risk with PFA application on the posterior mitral isthmus since it is near the circumflex coronary artery (Supplemental Figure 1). Clinically apparent spasm occurred in 9.7% of

patients receiving MVI ablation without prior nitroglycerin administration[144]. Anatomical positioning of the ablation line appears to influence this risk. In one study, coronary spasm was observed in 41.2% (7 of 17) of patients undergoing posterior MVI ablation with PFA[150]. Notably, spasm occurred in 77.8% (7 of 9) of patients in whom the MVI ablation line was placed superiorly—closer to the left circumflex artery—while no coronary spasm was observed in patients with inferior line placement. In contrast, none of the patients undergoing MVI ablation with RF energy experienced coronary vasospasm[150]. Use of an anterior mitral line from the anterior mitral isthmus to the left superior vein or a roof line may be less likely to cause coronary spasm, but ablation close to the LAA with a large catheter could risk partial isolation of the LAA. The safety of prophylactic nitroglycerin (as for the CTI) is less known in the mitral location, although it is likely to have the same effects—good, but not complete protection.

In weighing the benefit-risk ratio for CTI or MVI flutter line ablation with PFA, operators should consider using RF energy at these locations, either by utilizing a dual-platform PFA/RF device or by introducing an additional ablation catheter, although this approach will increase procedural costs (Figure 8). As the use of PFA near the coronary arteries advances, protocols for prophylaxis and management of potential vasospasm could be further refined and standardized based on emerging evidence.

Other linear ablations with PFA are also feasible. Even though studies have reported high acute success rate in creating linear lesions using PFA, data on the long-term durability of the lesions are lacking. To assess the persistence of block in the lines created by the pentaspline PFA catheter ablation system, a recent study conducted a 3-month remapping in 236 consecutive long-standing persistent AF patients receiving isolation of coronary sinus, LAA, or MVI ablation[149]. Acute LAA isolation and MVI block was achieved in all (100%), whereas acute coronary sinus isolation was documented in 62.2% of patients. Remapping revealed persistent coronary sinus isolation in 1.3%, MVI block in 5.5%, and LAA isolation in 4.6%. With LAA, delayed conduction was observed in 80% and complete reconnection was noted in 15.6%. Based on these and previous findings, it seems obvious that acute success does not directly translate to chronic success for all linear lesions[90,145].

An earlier first-in-human study reported the acute as well as long-term efficacy of the hybrid dual-energy (PFA/RF) ablation systems in creating durable linear lesions. The lattice-tip PFA/RF catheter was used to create linear lesion sets (left atrial roof line, MVI line, and CTI line) using either PFA or RF[111]. Acute success was achieved in all (100%). Invasive remapping revealed overall PVI durability of 75% and that of linear lesions at 82%, 68%, and 87% for the LA roof, MVI, and CTI lines, respectively. In the randomized SPHERE-Per-AF study, a substantial proportion of linear lesion sets were performed by the operators using the lattice-tip PFA/RF catheter, yielding encouraging procedural and clinical outcomes[82]. However, as different combinations of RF and PF energy were used to create these lesions, it is difficult to assess the exact contribution of PFA to lesion durability. RF may have been used alone and in combination with PFA, which could enhance long-term durability[151].

It should be noted that randomized clinical trials have not demonstrated the additional benefit of empirical ablation in addition to PVI using PFA[82,152]. Furthermore, lack of durability of linear lesions could be device-specific and should be assessed in other PFA systems in future studies.

Three-dimensional mapping with PFA

Three-dimensional (3D) electroanatomical mapping plays a central role in contemporary AF ablation, particularly when using catheter platforms with focal (small- or large-tip) ablation catheters. In the era of PFA, both fully integrated 3D navigation systems and open-platform, impedance-based visualization tools are available to support procedures [30,111,153-156]. The relevance of 3D electroanatomical mapping may vary depending on the ablation strategy: while it may appear less critical in single-shot,

anatomically guided PVI procedures, it becomes increasingly important when additional ablation beyond PVI is performed. One rationale for integrating 3D mapping is the currently suboptimal durability of PVI achieved with fluoroscopy-guided PFA. In the EU-PORIA registry, PV reconnections were observed in 29% of PVs during repeat ablation procedures, highlighting the need for improvement[157].

In general, mapping systems may offer several procedural advantages in guiding PFA energy delivery. These include visualization of the estimated electric field and ablation targets, assessment of lesion overlap, catheter-tissue contact, and dynamic representation of lesion sets. Present-day field estimates provided by mapping systems are just illustrations and are not based on computational field modeling. Additional benefits include support for individualized ablation strategies, possibility to perform pre- and post-ablation voltage and activation maps, improved workflow efficiency, and reduction of fluoroscopy exposure[158-160]. However, these benefits must be balanced against increased procedural costs and improved outcome. Another consideration is whether to perform mapping using the PFA catheter itself or to introduce a separate high-density mapping catheter, which further increases cost and procedural duration. Whether the routine use of 3D mapping in single-shot PFA procedures translates into improved clinical outcomes remains to be determined[161,162].

Today, some mapping systems are offering impedance-based contact assessment that can be applied to any PFA catheter. Since contact is so important to optimal lesion delivery, use of such a tool may favor the use of a mapping system.

Mapping with reversible PFA pulses

Mapping with reversible electroporation pulses may offer a novel electrophysiological tool. When applied to myocardial tissue, they have the ability to only transiently block electrical conduction, thereby aiding in the identification of critical isthmuses within tachycardia circuits[163]. This approach may lead to more precise lesion sets and reduce the risk of ablating viable and non-arrhythmogenic myocardium[164].

Contact assessment

Regardless of PFA waveform and catheter form factor, contact of catheter/electrode with tissue is an acknowledged and accepted requirement for successful ablation[19,23,165-168] (Figure 9). Prior studies have shown that while distances of 2-4 mm may still achieve a partial lesion, the lesion quality is sub-standard. Beyond a 2-4 mm distance, almost no PFA lesion is formed[57,169-172]. Evidence suggests that, in the context of PFA, the catheter-tissue contact may be more critical than the magnitude of contact force[168,173]. Pre-clinical PFA data indicate that lesion size does not increase with contact force beyond a certain threshold (about 10 g); however, this threshold may vary depending on the specific catheter form factor[19]. Nevertheless, adequate catheter-tissue contact remains essential in PFA to ensure effective lesion formation [19,23,169,171,172]. Furthermore, tissue contact was shown in pre-clinical/in vitro setting to attenuate the risk of hemolysis[174,175].

The method of contact assessment varies between systems and may be indirect—such as impedance-based monitoring, direct contact force measurement, visualization via endoscopy, visualization on ICE, or thermal measurements based on cooling or heating rate [21,166,176-178]. In a feasibility study of a balloon-type PFA device, the catheter is equipped with an impedance-based tissue proximity indicator that provides real-time feedback on electrode-tissue proximity, displaying proximity values through a dynamic real-time display[69]. The display shows not only binary contact or no contact but also real-time variances in the impedance and how close it is to the contact threshold. Real-time contact visualization using impedance is superior to just binary displays. In a spherical catheter PFA

system, small tissue temperature rises are used to assess tissue contact, since incidental heating occurs when PFA is delivered. However, this does not provide information prior to ablation. In the first-in-human PULSE-EU trial[28], a globe-shaped catheter was tested. The catheter incorporates contact sensing through a blood flow map, assessing for cooler electrodes with less contact. It also heats electrodes to assess if tissue is contacting the electrode surface to allow for optimal contact prior to delivery. In the first-in-human PULSE-EU trial, PFA using this device was associated with persistent isolation of 93.5% of the PVs at the 3-month invasive remapping procedure[28].

Some technologies have proposed indices in which contact force and number of pulse deliveries are combined in a formula. However, it would appear that the main driver of such indices is really the number of deliveries and their overlap rather than the absolute value of contact force[11,21,22]. Such an index will most likely be PFA system specific. The contact force and its role and importance on lesion formation may also depend on catheter form factor, in that it may be less important for larger-profile catheters and more so for single-point catheters.

Use of ICE

ICE is one of the most direct assessments of tissue-catheter contact and is widely used in electrophysiology procedures to visualize anatomical landmarks and navigate catheters. While at least one multicenter study found no advantages with the addition to ICE to PFA in reduction of procedural times, fluoroscopy time, or time to isolation, it is important to recognize that this study did not assess long-term durability of PVI or long-term recurrence[179]. ICE can be used to provide far-field imaging from the right atrium, or it can be placed transseptally for near-field visualization. While left atrial ICE is safe and provides superior imaging[180], for the purpose of ensuring tissue contact, ICE imaging from the right atrium and SVC usually is sufficient.

A recently published consecutive prospective series showed that ICE-guided PFA ablation was associated with significantly lower arrhythmia recurrence and PV reconnection rate compared with fluoroscopy-guided PFA ablation[181]. Additionally, isolation of SVC using PFA guided by ICE has been documented to be safe and effective without permanent damage to phrenic nerve or sinus node[120]. ICE may be even more helpful in transseptal transit with the larger diameter sheaths that many PFA systems require. ICE is also integral to zero-fluoroscopy approaches to PFA, which have benefits to patients and those who perform the procedures[182]. Finally, given the recent evidence implicating PFA in coronary lumen loss following coronary spasm[92], ICE may also be beneficial in providing direct visualization of coronary arteries and left ventricular wall motion.

Although ICE guidance offers benefits, a fluoroscopy-only approach with or without mapping approach remains a practical option, particularly in geographies where ICE costs are not sustainable. Notably, approximately three-quarters of the data from the EU-PORIA registry were derived from fluoroscopy-only procedures[96]. The implementation of the 5-S strategy has led to significant improvements in outcomes—all without the use of additional imaging modalities[98,114].

Acute endpoints in PFA procedures

In thermal ablation procedures, dormant conduction or reconnection across ablation lines can be assessed after a 20–30-minute waiting period, with or without intravenous adenosine or isoproterenol. While clear evidence of overall benefit is lacking[183,184], adenosine and isoproterenol have shown complementary effects in detecting dormant PV conduction for thermal ablation[185,186].

However, due to myocardial stunning of the tissue post-PFA, the use of such strategies remains unclear. Regarding the post-ablation waiting time, it is known from pre-clinical studies that lesions may

take 7-14 days to mature[15]. Therefore, waiting 20-30 minutes to reassess PVI may be of little use, although the method has been used in several PFA studies based on US Food and Drug Administration requirements[52,69,71,72,82]. There is also no evidence that additional isoproterenol or adenosine to assess for non-PV triggers or concealed conduction provides any benefit post-PFA procedures, again due to the combination of ablation and tissue stunning. Recovery of conduction from adenosine in thermal ablation is due to stimulation of Ik-ach-ado, leading to hyperpolarization of the cell membrane and restoration of membrane excitability[187]—an effect unlikely to be relevant in reversibly or irreversibly electroporated cell membranes.

Safety issues related to PFA

PFA has shown improved safety of adjacent tissue compared with thermal approaches to cardiac ablation, but new or more pronounced safety considerations related to PFA have emerged (Figure 10 and Table 5). Many considerations related to safety and efficacy are directly related to the design of both the catheter and the waveform.

Hemolysis

Pulsed electric fields can cause red blood cell membrane poration and rupture (hemolysis) due to multiple biophysical and electrochemical stresses on circulating red blood cells[188]. The rupture (lysis) of red blood cells leads to the release of their contents (cytoplasm) into the blood[189]. Disruption of red blood cells is more pronounced with PFA than with thermal ablation[174,190]. Severe hemolysis can cause acute kidney injury (AKI) and may even require temporary hemodialysis[191,192]. The reason for this is that the release of free hemoglobin, heme, and iron trigger inflammatory and oxidative pathways. The body's scavenger proteins (haptoglobin, hemopexin) bind these byproducts, but excessive hemolysis overwhelms these defenses, resulting in complement and platelet activation that causes a coagulopathy[193] and could increase risk of stroke. Further, free hemoglobin scavenges nitric oxide, which can lead to vasoconstriction that potentiates end-organ damage and vasospasm (immediate or delayed)[189] and may be a mechanism for delayed vasospasm occurring after ablation. Hemoglobinuria is a hallmark of significant hemolysis and can injure renal tubules, resulting in tubular cast nephropathy[194].

Although hemolysis is mostly observed within seconds after electroporation, it can progress over several hours and the nitric oxide effects could persist for days[195]. The level of hemolysis can be determined clinically by measuring biomarkers, namely, plasma free hemoglobin. Plasma free hemoglobin is the most sensitive for indicating any degree of hemolysis, and a level >0.5 g/L (50 g/dL or 500 mg/L) typically indicates severe hemolysis. Haptoglobin depletion, elevation of bilirubin, and presence of urinary myoglobin and hemoglobin are indicators of clinically significant hemolysis, only change hours after ablation, and may persist for days. Plasma free hemoglobin elevates immediately after ablation and may be an initial good marker for severity of hemolysis[195].

The amount of hemolysis is dependent on catheter design, number of electrodes, and their exposure to the bloodstream. Catheter designs that minimize the number of active electrodes during delivery or that incorporate a balloon or other material to partly cover electrodes and prevent contact of blood with electrodes on the catheter cause less extensive hemolysis[69,175]. The hemolysis profile for various devices is summarized in Figure 11. The level of hemolysis correlates with an increased number of PFA applications and tissue contact, as good contact means less blood is exposed to the high electric field in immediate vicinity of the catheter[175,190,196]. The effect of hemolysis on renal function can be limited by pre-hydration of patients (2 L normal saline has been described[192]) and not delivering an excessive number of PFA applications[192]. Although some degree of hemolysis always occurs with PFA, the incidence of AKI requiring hemodialysis after a PFA ablation is quite low (0.03%)[86] and pre-hydration is

not always required, as it is dependent on the device and number of lesions. Avoiding unnecessary lesions, optimizing catheter contact, and limiting the total energy delivered are practical steps to mitigate risk[197]. Pre-hydration does not, however, mitigate the platelet-mediated coagulopathy, the depletion of nitric oxide causing vasospasm, and subclinical kidney injury associated with hemolysis, so minimization of hemolysis is always important.

Some patients may be more prone to AKI (for example those with pre-existing renal insufficiency), and identifying these patients and providing prophylactic measures to mitigate renal injury may be warranted. Patients with mechanical valves who have some underlying hemolysis may also have higher risk of renal dysfunction after PFA[198].

Coronary spasm

PFA's effects on coronary arteries were initially thought to be benign, given that electroporation spares acellular collagen scaffolds[199]. However, exposure of coronary smooth muscle to high voltage electric pulses can provoke intense vasospasm[94,148,200]. The mechanism of this vasospasm is unclear but may reflect (1) stimulation of vascular smooth muscle cells by electric pulses, (2) the release of vasoconstrictive substances such as serotonin, histamine, or endothelin, (3) (reversible) electroporation of the cell membrane leading to static coronary artery contraction[201], or (4) free hemoglobin from hemolysis scavenging nitric oxide, which may lead to vasoconstriction that potentiates vasospasm[189].

Coronary vasospasm can be proximity-related when PFA is applied near the coronary arteries or generalized when delivered remotely. The first reported case of coronary artery spasm during PFA was in 2021 during an off-label MVI ablation[94]. In pre-clinical studies, direct application over the left anterior descending coronary artery led to reproducible spasm with about 50% coronary artery narrowing that gradually resolved over 30 minutes without intervention[202]. Clinically, PFA applied near the atrioventricular groove such as the MVI and CTI or septum has led to spasm (circumflex, right coronary, and left anterior descending, respectively)[94,142]. In the MANIFEST-PF multicenter registry[86], PFA confined to PVI had an extremely low incidence of clinical coronary vasospasm (only 1 case out of ~17,000 PVI patients, ~0.06%).

Prophylaxis and treatment of intra-procedural coronary spasm are described in the workflow section. Coronary spasm may also cause chronic coronary changes. In one study, routine angiography and optical coherence tomography (OCT) 3 months after CTI PFA (including nitroglycerine prophylaxis) using a pentaspline catheter revealed a mean 10.1% arterial narrowing[92]. However, another study performed coronary angiography with no apparent coronary stenoses[142]. Mild coronary artery injury and even severe stenosis has also been described with RF, although rarely [92,143]. Whether coronary artery injury with PFA is different from RF is unclear[203-205].

The best way to avoid coronary vasospasm is to not apply PFA directly over or close to a coronary artery, ie, within 6.5 mm of the electrode[206]; the distance will be specific to each PFA system/waveform. In regions close to coronaries, RF may be preferred, particularly when using a dual-energy catheter. If CTI PFA ablation is indicated, one needs to carefully weigh the risks and benefits of using PFA, consider nitroglycerin prophylaxis, and be prepared to treat clinical spasm. Certainly, in patients with known multivessel coronary artery disease, PFA near a CA should be avoided.

Delayed coronary vasospasm and risk of serious ventricular arrhythmias

The prior section described proximity-related coronary spasm. However, isolated case reports have described sudden cardiac death or delayed vasospasm following PFA[207,208]. A new publication has compiled a systematic literature review and several cases of delayed complications following PFA,

including ST-segment elevations associated with suspected or confirmed coronary vasospasm, myocardial ischemia, chest pain, prolonged bradycardias, malignant ventricular arrhythmias, and sudden cardiac death occurring minutes to days after the index procedure[209]. These rare life-threatening complications (incidence 0.16%) have been reported across different available PFA systems. A consistent feature across cases is a high number of PFA applications, often in the context of PWI. Not all these patients had proximity-related spasm during the initial procedure. The underlying mechanism remains unclear but may involve hemolysis-induced nitric oxide depletion, predisposition to vasospasm (eg, Prinzmetal's angina), subclinical coronary artery disease, or microvascular dysfunction. Notably, coronary angiography frequently failed to reveal obstructive lesions. Identification of high-risk patients and prevention strategies—such as limiting energy delivery or using PFA systems with reduced hemolytic potential—are essential to better characterize and mitigate this rare but life-threatening phenomena.

Vagal reactions

PVI using any energy is associated with a risk of vagal reaction, especially on the anterior aspect of the left superior PV ridge[2]. PFA creates more potent vagal reactions due to wide spread of electric field (sublethal) leading to greater stimulation of the atrial ganglionated plexi. This does not necessarily indicate ablation of these plexi. These responses typically manifest as bradycardia, atrioventricular block, or transient pauses[108].

In a multicenter study of 80 PFA procedures, when left superior PVI was performed first, 78% of patients exhibited vagal responses—compared with only 13% when the right superior PV was approached first[108]. These vagal reflexes are generally transient and reversible and do not result in lasting autonomic dysfunction[210-212].

Pretreatment with anticholinergic agents and changing order of vein isolation to prevent vagal reactions are discussed in the workflow section.

PFA and device interaction

PFA in the presence of metallic implants such as pacemakers, implantable cardioverter-defibrillators (ICDs) (with their metallic casing or leads), mechanical valves, appendage occluders, and stents can modify the electric field distribution and current flow[213,214]. Since electroporation depends on electric field distribution, the presence of metallic implants may cause ablation to be suboptimal. Metallic implants could also draw excessive current that can heat adjacent cardiac tissue. Bipolar PFA deliveries within proximity of implants can also cause arcing and short circuiting, which represent a hazard to the PFA catheter and devices[215]. Whether an energy delivery will be automatically aborted upon detection of arcing or a sudden change in current depends on the specific shut-off mechanisms built into the PFA generators, and they differ between manufacturers.

High voltage electric pulses may also interfere with implanted cardiac device functioning and integrity; therefore, until recently, patients with pacemakers and ICDs have been excluded from PFA studies[216]. The effect of PFA on implantable electronic devices has been studied ex vivo, and PFA was found to be safe for implanted cardiac devices or leads[215]. The function and integrity were further assessed in the clinical setting; it was confirmed that devices were not compromised by PFA, although transient ventricular pacing inhibition was observed[217,218]. Appropriate peri-procedural programming, as for any ablation, may mitigate any adverse consequences[216], but further data on PFA effects on implanted devices are required.

Finally, the high voltage electric pulse may damage other computers or equipment attached to the patient during an electrophysiologic procedure, particularly if protection circuitry is not present.

Some electroanatomic mapping systems that use magnetic fields for catheter location may require deactivation of the magnet during PFA energy delivery. Other sensitive equipment may need to be disconnected from the patient before applying PFA.

Phrenic nerve palsy: acute and chronic

Direct phrenic nerve injury is less likely with PFA compared with thermal energy modalities [62,219,220]. In human studies, permanent phrenic injury is uncommon. Acute phrenic nerve palsy has been reported as high as 1.3% in the ADVENT study[83], but all patients recovered by 1 year and most stunning recovers within 12-24 hours[221]. Only isolated reports of persistent damage have been published[221]. However, a recent study reported phrenic stunning in 19% of patients at the end of the procedure, with 1 patient (4%) having palsy beyond 3 months[63].

Pre-clinical work exploring dynamics of nerve damage and recovery due to electroporation has shown that nerve damage due to electroporation may need a few days to manifest histologically[222,223] and may normalize weeks later[224]. Increased nerve injury can occur with direct application over nerve bundles; therefore, use of PFA during epicardial ablation adjacent to the phrenic nerve should be avoided[223,225].

Esophageal risk

While early pre-clinical and clinical studies suggested the esophagus was not affected by PFA[42,118,226,227] later studies have shown that small luminal esophageal temperature rises may be detected[54,228] and that specific devices such as the variable loop, pentaspline, and small spherical catheters may cause short but significant increases. In some cases, the esophageal muscularis externa layer may be injured acutely[59,229]. The absence of atrioesophageal fistula is, at least in part, due to non-transmural injury to esophageal muscularis externa and preservation of the extracellular matrix, which allows repopulation with progenitor cells[230], which then heals within 2 to 4 weeks without leading to atrioesophageal fistula[230]. Results from a recent clinical study where procedure-related complications were monitored and esophagogastroduodenoscopy was performed the day after PFA (comprising PVI and PWI) showed no thermal damage to the mucosal layer and are thus consistent with the lack of a transmural lesion being formed[130]. In another study, magnetic resonance imaging (MRI) of the esophagus done post-AF ablation performed with PFA showed preservation of the esophagus[227]. In multiple clinical studies, there have been zero incidences of atrioesophageal fistula after AF ablation with PFA[70,72,82,83].

PV narrowing/stenosis:

To date, there has been no signal of PV stenosis caused by PFA. In the ADVENT trial, the change in aggregate PV cross-sectional area from baseline to day 90 was negligible in PFA subjects (−0.18 cm^2 or 0.9%) compared with a more noticeable reduction in thermal subjects (−1.18 cm^2 or 12.0%)[83].

General ablation complications highlighted in the PFA era

General ablation complications that have found renewed attention in the PFA era are listed in Table 5.

Vascular access

PFA systems are introduced into the left atrium via a long vascular sheath. While some PFA systems may use sheaths with diameters similar to those used for RF catheters (8.5 Fr inner and 10 Fr outer), other systems use larger sheaths to permit a larger multielectrode catheter design (13 Fr inner to 17 Fr outer). Large vascular sheaths are more likely to cause vascular injury, so use of ultrasound for access is recommended to reduce vascular complications[231]. Use of larger catheters and sheaths also increases the likelihood of entraining air bubbles during catheter introduction or exchange, which could lead to air embolism. One should therefore be careful to withdraw from the sheath side-arm whenever withdrawing catheters and withdraw and flush with saline whenever a new catheter or device is introduced. If ST elevation or neurological sequelae are noted after a catheter exchange (usually due to air embolism to the right coronary artery), time will often lead to resolution, but coronary angiography and use of a wire to break up air bubbles may be required. One should also ensure that the ST elevation is not due to coronary vasospasm. For strokes or seizures that are felt to be related to cerebral air emboli, hyperbaric oxygen may be helpful[232].

Stroke

Cerebral embolism (stroke) is one of the most feared complications of catheter ablation. Cerebral MRI after catheter ablation using RF or cryoablation can detect asymptomatic cerebral emboli in up to 35% of cases[233], but the incidence of clinical transient ischemic attack/stroke is much lower at 0.15% to 0.5%[234-236]. Stroke and transient ischemic attack have been reported for different PFA systems. Currently available literature suggests there are no large differences in stroke rate among different PFA systems, and these are comparable to those observed with thermal ablation[70,86,96].

With most PFA systems we can see microbubble formation on ICE during delivery of pulses[70,83]. These bubbles have been suggested to be of largely thermal origin when using biphasic pulses, although hydrolysis, degassing of nitrogen, and blood warming can also be causes[34]. In theory these microbubbles could lead to acute silent cerebral emboli, but they are unlikely to cause stroke. Although PFA is often described as “non-thermal,” several degrees of temperature rise in response to PFA may occur[52]. Very small fluid volumes in vicinity of sharp edges on the catheter can also experience significant temperature increases—even to the level of boiling[237]. These temperatures may lead to denaturation of proteins and coagulum depending on the catheter and waveform design, and this has already been shown to cause stroke with one catheter[55]. Catheter irrigation is used for cooling in some PFA platforms[53], but good catheter and waveform design can obviate a lot of these thermal risks[17]. Hemolysis may also cause a cascade of coagulation; electroporation of platelets/thrombocytes has led to activation of the coagulation cascade in vitro using nanosecond electric pulses[189,193,238], and standard anticoagulation may not protect against platelet-mediated clot. In addition, prolonged inflammation perpetuated by cardiac tissue injury and remodeling/healing by fibrosis can cause thrombosis[239].

To minimize the risk of stroke, PFA ablation procedures should follow current guidance and be done with uninterrupted anticoagulation, with a direct oral anticoagulant and unfractionated heparin intra-procedurally to maintain an ACT >300. Avoidance of excessive PFA lesions, hemolysis, and shorter procedures also should reduce stroke risk.

Excessive ablation, tissue destruction, and impaired left atrial function

Given the ease, efficiency, and apparent safety of PFA ablation, there is a potential risk of overablation by operators, which may compromise patient safety by impairing left atrial function and increasing the risk of hemolysis and cerebral embolism. The troponin level rises seen post-PFA appear to be much higher than those associated with RF[190,240,241]. This concern may be particularly relevant when PFA is applied outside the atria[242]. The higher elevations in cardiac markers could represent (1) more

ablations being performed by operators because of the ease of PFA, (2) more tissue being destroyed because of larger footprint catheters, or (3) a combination of stunned and ablated myocardium that will both release troponin (but the stunned tissue will recover). Unlike thermal ablation, PFA spares the extracellular matrix of the tissue, allowing replacement fibrosis[243,244], which seems to mitigate structural and functional atrial impairment compared with thermal ablation[245]. Studies have demonstrated superior recovery of left atrial strain—a sensitive marker of myocardial integrity and performance—following PVI with PFA, suggesting reduced chronic fibrosis and a more favorable reparative response[244]. This preservation of myocardial structure may contribute to maintained tissue compliance and left atrial reservoir function[243]. In addition, significant improvements in left atrial reservoir strain and evidence of reverse remodeling, improved left atrial compliance, and enhanced left ventricular systolic function have been reported following extensive ablation beyond PVI using PFA[246]. However, this does not mean that stiff left atrial syndrome could not develop years later, and long-term study is required.

PFA for non-AF arrhythmias

Rationale for PFA in ventricular arrhythmia

Getting adequate tissue depth from PFA lesions suitable for ventricular tachycardia (VT) ablation remains a challenge. Repetition of pulse trains and contact force can increase lesion depth and width, but not substantially, and there is a plateau effect[15,118]. Use of bipolar delivery between two ablation catheters has been shown pre-clinically to create transmural lesions across the intraventricular septum[247]. However, this is unlikely to be a routine clinical application, given the need and expense of more than one PFA catheter. For unipolar PFA, modifying the return to an intravascular or intracardiac multielectrode catheter (in the inferior vena cava or coronary sinus) may be capable of achieving deeper lesions up to 11 mm[44]. Finally, deliveries of PFA between various bipolar configurations on a single-point catheter, coupled with high voltages, can also achieve large tissue depths. One such system has been developed, and although the system alternates between microseconds and nanoseconds to offset muscle stimulation, the stimulation remains severe and requires general anesthesia and paralysis[248-250]. Delivering deep lesions also requires very wide lesions, which can increase myocardial damage[248,249]. Optimizing pulse parameters and catheter design to achieve deep lesions that can have a constrained width remains an important challenge for future development. There are systems in development, like a multielectrode grid[251], that are attempting to solve these issues.

Combining thermal and PFA energies may have the potential to create deeper lesions. By delivering short durations of RF followed by PFA, the tissue impedance is reduced, and edema is increased, potentially allowing deeper PFA lesions[151]. While this has been demonstrated pre-clinically, ongoing studies will determine if this is effective (DUAL-VT, NCT06816368).

The main advantage of PFA in the ventricle is its ability to penetrate and homogenize scarred myocardium, which is a challenge for RF[15,252]. Scar tissue is heterogeneous with fibrosis, fat, collagen, and myocytes with different electrical and thermal properties[253]. Both fat and collagen have high resistivity and thermally insulate cardiomyocytes, which limits RF penetration[15,254]. PFA, however, demonstrates improved penetration of scarred ventricular tissue in multiple pre-clinical studies[15,252]. Electroporation seems to be more efficient in achieving scar homogenization[15]. Other advantages are that PFA can also more easily target challenging substrates for focal sources where catheter stability may be limited. Through a combination of a high friction coefficient spherical catheter and unipolar PFA deliveries in a pre-clinical model, mobile structures such as the moderator band, papillary muscles, and intraventricular septum were targeted effectively[247]. The same catheter is being evaluated in an early feasibility trial for VT ablation (SPHERE-9 VT, NCT06703489). PFA may also be able to selectively target

Purkinje fibers without causing other myocardial damage[255]. Finally, the short delivery times of PFA lesions have the potential to dramatically shorten VT procedures[256].

Delivery of PFA using monophasic pulses has been shown to trigger VT or VF in pre-clinical models, requiring R wave gating to prevent delivery in the vulnerable repolarization zone[257]. However, with biphasic, short-duration deliveries, the risk of ventricular arrhythmia is low and may not require gating[36]. The safety of epicardial delivery is also not well known. Prior pre-clinical study and one case report suggested that it was safe and there was no clinical coronary spasm[258]. However, another pre-clinical study demonstrated consistent moderate spasm and appearance of mild chronic coronary changes[202]. In the AVAAR registry (126 patients), epicardial access was performed in 21 patients (17%) using the lattice-tip PFA/RF catheter[256]. Coronary injury or ST changes may occur following epicardial PFA.

Early clinical experience of PFA and ventricular arrhythmia

Data on clinical applications of PFA for ventricular arrhythmia are currently limited. A recent meta-analysis summarized some of the early case reports where pentaspline PFA was used for different underlying cardiomyopathies (n = 9)[259]. Since the pentaspline catheter was not designed for ventricular ablation, there were challenges with catheter manipulation. Studies reported excellent acute results, but long-term results were not consistently reported. PFA has also demonstrated excellent acute results with extra-corporeal membrane oxygenation and an implanted left ventricular assist device (Impella)[260], premature ventricular contractions (PVCs) from the papillary muscles[261], and epicardial ablation [258]. A two-center experience reported PFA ablation in 44 patients for premature ventricular beats or VT ablation[262]; acute non-inducibility or PVC elimination was about 80%, but long-term freedom from VT was only 50%. With stunning of the myocardium, the utility of acute non-inducibility of VT may not be as useful. Conduction block was also reported during ablation away from the septum due to proximal electrode current leak[262]. The AVAAR registry evaluated a spherical catheter for VT, PVCs, and VF in 126 patients[256]. Major complications were observed in 5.9%. After a mean follow-up of 5.6 ± 3.7 months, absence of recurrence was 78% for PVC, 70% for VT, and 100% for VF. Finally, in a first-in-human study of a nanosecond-microsecond, monophasic, long pulse duration (<200 ms), high voltage (>10 kV), synchronized catheter, 6-month follow-up revealed 81.8% freedom from recurrent VT/VF or ICD therapy[263].

Supraventricular tachycardia

PFA has been proposed as an advantageous ablation modality for the treatment of supraventricular tachycardia (SVT). The Multicenter Study of Pulsed Field Ablation for Paroxysmal Supraventricular Tachycardia enrolled 40 patients with typical atrioventricular nodal reentrant tachycardia (AVNRT) undergoing slow pathway modification.[242] Ablation was performed using a 1-pulse train delivery for 1–3 sinus cycles. Once junctional or sustained junctional rhythm was induced, a consecutive 3-pulse train delivery was delivered until cessation of junctional rhythm. The acute procedural success was 100%, and no patient experienced recurrence within 6 months. However, 7 patients (17.5%) experienced transient complete heart block and 8 (20%) experienced mild skeletal muscle contraction.

The FASTPFA (Safety and Efficacy of Pulsed Field Ablation and Radiofrequency Ablation for Paroxysmal Supraventricular Tachycardia) study was a prospective, multicenter, single-arm study performed at 8 centers in China[264]. The study used an 8-F focal pressure-sensing PFA catheter to treat SVT in 158 patients (77 with AVNRT, 63 with atrioventricular reentrant tachycardia [AVRT], 16 with Wolff-Parkinson-White [WPW] syndrome, and 2 with AVNRT and AVRT). PFA ablation used 800-1500 V (His

region: AVNRT or peri-Hisian accessory pathway) or 1000-1800 V (non-His region) followed by consolidation ablation with PFA (His region) or RF (non-His region). Acute ablation was successful in 99.4%. During 180 days of follow-up, the freedom from recurrent SVT was 100% for AVNRT, 94% for AVRT or WPW (PFA alone), and 94% for AVRT or WPW receiving combination PFA and RF. One patient experienced transient complete heart block.

Future directions for PFA

Several challenges remain for the clinical application of PFA[24]. As mentioned earlier in this document, achieving deeper lesions for addressing ventricular arrhythmias has not yet been fully addressed.

The increased cost of PFA devices remains a barrier for many geographies to widely adopt the technology. Even if the technology is adopted, foregoing electrophysiological staples, such as mapping and peri-procedural imaging, may be required to contain cost efficiency. However, with such rapid development of newer PFA technologies, we anticipate that the extinction cycle will be equally rapid, and costs of older PFA technologies will hopefully drop rapidly in the upcoming months and years.

Assessing creation of durable lesions with PFA is particularly challenging, as classical acute markers of lesion formation, such as the disappearance of bipolar signals commonly used to estimate lesion completeness, are unreliable indicators for PFA. Even subtherapeutic pulses can lead to signal attenuation due to effects of cellular stunning. In one study assessing local electrogram amplitudes, ablation electrodes exhibited an amplitude reduction to <0.5 mV after 67.5% of PFA deliveries as compared with 27% with RF[265]. Furthermore, PFA resulted in 100% bipolar capture loss, whereas RF achieved 92% capture loss[24]. Currently, no tools are available to distinguish what proportion of this signal loss is attributable to irreversible damage versus cellular stunning. The stunned cells or the penumbra area refers to cells in the region surrounding the lethally affected tissue that are damaged but not killed, with potential for recovery over time[15]. Understanding which areas will result in complete ablation and which will remain in a “penumbra reversible zone” is a field of growing interest.

Several studies have explored novel ways to assess acute lesion completeness (Figure 12). One study demonstrated the presence of acute, dynamic unipolar electrogram changes (ST elevation and R/S ratio) that differed between reversible and irreversible areas, allowing for the prediction of areas achieving durable lesions[266]. Frequency analysis of low frequency changes (like ST elevation) can further enhance the unipolar electrogram’s ability to predict lesion formation[267]. Optical signals may be useful; a pre-clinical porcine study using polarization-sensitive optical coherence reflectometry (PS-OCR) to directly visualize tissue and tissue changes with PFA showed that a >20% loss of tissue birefringence predicted chronic tissue fibrosis with excellent sensitivity and specificity[268]. Early first-in-human results of PS-OCR were very promising, with PV gaps correlating to inadequate reduction of tissue birefringence <20%[269]. A High Frequency Dielectric Sensing Lesion Assessment System (HFDS-LAS) has also been proposed to assess intra-operative lesion formation confirmation by redesigning sensor electrodes on ablation catheters and adding a high-fidelity antenna[270]. The antenna measures the electrical properties (specifically the impedance) of the tissue at MHz-GHz frequencies in real time. In experimental models, HFDS-LAS has been shown to predict tissue lesion depth[270]. Finally, preliminary work is being done with cardiac MRI to see if differential gadolinium uptake at different times post-ablation can help to distinguish between reversibly and irreversibly electroporated cardiac tissue[15].

The authors of this document also emphasize the need for ongoing clinical registries to build knowledge of both the efficacy and safety of PFA and to compare the ablation performed by various

systems. There is an urgent need to develop dynamic, multimodal clinical registries that leverage modern artificial intelligence (AI) and machine learning capabilities. These new registries must be capable of ingesting and interpreting diverse data streams—ranging from surface electrocardiograms, intracardiac electrograms, 3D mapping data, wearable device outputs, and imaging modalities like MRI and ICE—automatically and in real time. Integrating these modalities will enable a far deeper understanding of the underlying clinical substrate and the procedural effect on it.

The Heart Rhythm Society's PFA Registry exemplifies this vision. Designed as a flexible, AI-powered platform, it will support high-fidelity data capture and continuous longitudinal tracking, reduce manual data entry, and facilitate cross-institutional benchmarking. Critically, it will serve as a foundational tool for post-US Food and Drug Administration approval device surveillance, safety monitoring, and efficacy analysis. Furthermore, the data captured will empower the development of generative AI tools and Software as a Medical Device (SaMD), transforming intra-procedural decision-making and long-term care strategies.

Finally, the authors of this document stress the importance of the release of technical information pertinent to specific PFA waveforms and parameters by manufacturers. Catheters, waveforms, and procedural workflow continue to evolve while remaining blind to evolving PFA specifications. Even catheters from the same manufacturer have ongoing modification and changes of waveforms that could substantially affect procedural workflow, efficacy, and safety. For this reason, we do not know if the patients treated by a specific PFA system in 2020 and 2025 have been treated by the same waveform, which may further limit the broad applicability of registry data. There are profound differences between PFA systems, and knowledge of the specific waveforms would help us better understand the specific desirable and undesirable effects using theoretical approaches and mechanistic reasoning.

Therefore, this committee calls for at least a minimal disclosure and reporting in published manuscripts for all PFA technologies:

1. Pulse amplitude (current or voltage)
2. Vectoring (bipolar or monopolar); vectoring between electrodes and splines
3. Total on time of a single train; number of trains delivered and pause between trains
4. Total energy (of a single train or application)
5. Duty cycle (eg, % of on-time during train delivery)

Standardized bench-top tests should be developed and studies reporting hemolysis and thermal profile made available.

This would allow for comparison and calculations of thermal footprints but still allow manufacturers to keep their specific/proprietary waveforms undisclosed. The version of waveforms and catheters should also be available and included in registry data. Not only will this facilitate a greater understanding of the technology among electrophysiologists, it will also facilitate our ability to better choose between technologies. Ultimately, shared information will improve patient safety and long-term outcomes of PFA treatments.

Recommendations

Although this is not a formal guideline, the writing committee decided to make some recommendations based on the text of this document (Table 6). For transparency and to help the reader interpret the strength of consensus, the committee vote count is provided, as are points of discussion when there was a split vote.

Acknowledgments

The authors would like to acknowledge the contributions of Dr. Sanghamitra Mohanty, Director of Research at the Texas Cardiac Arrhythmia Institute, Austin, Texas, for helping to complete this document. The authors thank Amin Al-Ahman, MD, FHRS, CCDS, Bradley Knight, MD, FHRS, and Arian Sultan, MD for serving as peer reviewers for this document.

Tables

TABLE 1 – Terminology for pulsed field ablation

Term	Definition	Options in PFA systems	Clinical considerations
Electrode configuration	Electric pulses delivered between electrodes on the catheter (bipolar) or between electrode(s) on the catheter and the grounding patch (unipolar).	Bipolar configurations (larger-size pulmonary vein catheters). Unipolar configuration (large or small footprint point-by-point catheters). Some systems use combinations.	Unipolar ablation is associated with deeper lesions and lower blood pool delivery but higher likelihood of skeletal muscle contraction. Bipolar ablation is associated with a more focused electric field, less penetration into tissue, and enhanced local heating and electrode edge effects.
Pulse(s)	An individual pulse is defined by an amplitude, duration, rise-time, shape, etc.	Many commercial systems use about 10-40 pulses per train.	Higher number of pulses increases electroporation efficacy but also tissue heating. Shorter pulses require greater amplitudes.
Phase	PFA with only positive electric pulses (monophasic) or with positive and negative voltage pulses (biphasic).	Nearly all commercially available PFA systems use biphasic pulses.	Monophasic pulses are more efficient for electroporation but also result in more neuromuscular capture and electrolysis. Biphasic pulses require higher amplitudes and greater number of pulses for the same effectiveness. There are less electrochemical reactions but more heating.
Pulse shape	The shape of the pulse.	Most commercial systems use symmetrical biphasic rectangular waveform.	Rectangular or exponentially decaying. Some systems utilize a sine wave.
Amplitude	Voltage or current for a given pulse (baseline to peak). Peak-to-peak amplitude measures from maximum negative to positive excursion.	Range from 500 V to 3000 V; this refers to baseline to peak only. Peak-to-peak may thus be double the value.	Amplitude is an important value in determining tissue lesion depth. It is difficult if not impossible to compare systems by their amplitude alone, as there can be countless differences in the other parameters that heavily impact the field strength and lesion parameters.
Pulse width	The duration of a pulse.	Nanoseconds to microseconds. Most commercial systems are using pulse widths of several hundred nanoseconds (a single decimal place of a microsecond) to the low microseconds (1-10).	Pulse width is an important value to help determine lesion depth. At a given amplitude, shorter pulse widths are less likely to recruit skeletal muscle but may create shallower lesions.

Term	Definition	Options in PFA systems	Clinical considerations
Interphase delay	The time between the positive and negative phases in a biphasic pulse.	Usual duration is in microseconds (0-5).	Shorter interphase delays reduce skeletal muscle contraction.
Train (or burst)	A group of pulses followed in a sequence with delay between them (usually equally spaced).	Many commercial systems use 1 to 10 trains in an application. Inter-train delays help avoid tissue heating.	Longer trains create a larger field cloud and deeper lesion depth; they are limited by the R-T interval if gated; and they are associated with greater tissue heating.
Interpulse delay	Time between individual pulses within a train.	May range from 5 to several thousand microseconds.	Long interpulse delays optimally reduce tissue heating and musculoskeletal contraction.
Duty cycle	Percentage or proportion of the on-time or active time during the cycle.	Duty cycle is the fraction of time during which electric field is delivered, often expressed as a percentage (a measure of the "on" time).	Determines how heavily tissue and the catheter will be heated.
Synchronization	Pulse delivery is timed or synchronized to the R-wave or the S-wave or a brief interval after the R or S wave.	Some commercial systems are gated to the ECG, and some are not.	Synchronization may help avoid risk of ventricular arrhythmias triggered by activity on the T-wave. Gating may be less an issue for atrial and biphasic pulse deliveries, which are less prone to cause ventricular arrhythmias.
Irrigation	Fluid delivered at the catheter tip/electrodes.	None to several milliliters per minute.	A certain amount of tissue heating can be mitigated with irrigation. Excessive irrigation needs may indicate excessive catheter heating effects.
Application	A group of trains that is considered to represent one application (or “single press of the ablation button”).	Many commercial systems call for 1 to 8 applications per pulmonary vein. Commercial systems insert pauses to avoid excessive heating and to allow recharging of the generator.	Increasing applications typically result in greater lesion depth and width but with a plateau effect. If delivered in rapid succession, they can lead to heat stacking.

ECG = electrocardiogram; PFA = pulsed field ablation.

TABLE 2 – Reported efficacy and complications from single-arm and randomized studies

Study name	Monitoring	Endpoint	Efficacy	Safety	FDA or CE mark
Single-arm studies					
PULSED AF (PulseSelect Pulsed Field Ablation System; Medtronic, Inc)[70]	**TTM**: weekly and when symptomatic (3–12 months) **ECG**: 3, 6, and 12 months **Holter**: 24 hours at 6 and 12 months	**Primary effectiveness endpoint:** freedom from a composite of acute procedural failure, arrhythmia recurrence, or antiarrhythmic escalation through 12 months **Primary safety endpoint:** freedom from a composite of serious procedure- and device-related adverse events	Paroxysmal AF: 66.2%; Persistent AF: 55.1%	Primary safety endpoint occurred in 1 patient (0.7%; 95% CI, 0.1–4.6) in both paroxysmal and persistent AF cohorts	FDA
INSPIRE (Varipulse with Trupulse PFA generator; Biosense Webster, Inc)[72]	**Remote monitoring**: weekly between month 3 and 5; monthly between 6 and 12 months **ECG:** 1,3, 6, and 12 months	**Primary effectiveness endpoint:** freedom from arrhythmia of ≥30 s duration after 3-month blanking period **Primary safety endpoint**: incidence of primary adverse events within 7 days of initial ablation, including pericarditis, myocardial infarction, cardiac tamponade/perforation, thromboembolism, stroke, TIA or cerebrovascular accident, phrenic nerve paralysis, or major vascular access complication/bleeding, as well as death, PV stenosis, and atrioesophageal fistula that occurred later than 7 days post-procedure	**WAVE II:** 12-month freedom from arrhythmia recurrence: 78.9%	No primary adverse events	FDA
AdmIRE (Varipulse with Trupulse PFA generator; Biosense Webster, Inc)[71]	**Remote monitoring:** weekly between 3 and 5 months; monthly between 6 and 12 months **ECG:** 1,3, 6, and 12 months **Holter:** 24 hours at 3 6, and 12 months	**Primary effectiveness endpoint:** composite endpoint: 12-month freedom from documented atrial tachyarrhythmia episodes, failure to achieve PVI, use of a non-study catheter for PVI, repeat procedure (except for one repeat during blanking), taking a new AAD or dose escalation of previously failed class I or III antiarrhythmic or direct current cardioversion after blanking **Primary safety endpoint:** primary adverse event within 7 days of ablation	12-month primary effectiveness endpoint: 74.6% 1-year freedom from arrhythmia: 75.4%	2.9% (8 of 272), with the most common complication being pericardial tamponade	FDA

Study name	Monitoring	Endpoint	Efficacy	Safety	FDA or CE mark
ADVANTAGE AF (FARAWAVE; Boston Scientific, Inc)[75]	24-hour Holter monitoring at 6 and 12 months + twice monthly and symptomatic TTM	**Primary effectiveness endpoint:** acute success and post-blanking 1-year freedom from atrial tachyarrhythmia recurrence (>30 s), repeat ablation, cardioversion, or antiarrhythmic drug escalation **Primary safety endpoint:** incidence of predefined adverse events	**Primary effectiveness**: 63.5% at 1 year Freedom from symptomatic AF: 85.3% **Success rate varied by operator experience:** Less experience: 52.5% More experience: 73.8%	Primary safety endpoint was 2.3%, including 1 pericarditis, 1 myocardial infarction, and 4 pulmonary edema	FDA
ADVANTAGE AF phase 2 (FARAWAVE; Boston Scientific, Inc)[74] Reddy et al[61]	Continuous rhythm monitoring after ablation with insertable cardiac monitors	**Primary composite effectiveness endpoint:** (1) acute success of PVI and PWI, both using only the investigational catheter for ablation; (2) post–3-month blanking freedom from recurrence of AF/AFL/AT; (3) freedom from re-ablation for AF/AFL/AT; (4) freedom from any DCCV for AF/AFL/AT; and (5) freedom from use of new or escalated doses of class I/III AADs or any post-blanking amiodarone. **Primary safety endpoint:** Rate of predefined safety events	Freedom from atrial arrhythmia (AA): 73.4% Freedom from atrial arrhythmia of ≥30 s: 52.0% No episode exceeded 24 hours in 94.0% Atrial arrhythmia burden >0.1% and longest episode duration >1 h were predictive of increased health care use	Primary safety event rate was 2.4% (3 stroke , 1 cardiac tamponade and 1 death)	FDA
PULSAR (Globe PF System; Kardium, Inc)[271] Reddy et al, JACC 2025 (in press)	TTM weekly + symptoms, and 24-hour Holter monitoring at 6 and 12 months	**Primary effectiveness endpoint:** freedom from treatment failure at 12 months **Primary safety endpoint:** safety events to 6 months post-PFA	Primary effectiveness endpoint at 12 months: 80.8%	Primary safety event rate: 0.6% (1 stroke)	
VOLT CE (Abbott Laboratories)[30]	Follow-up ongoing 12-lead ECG: 3 months	**Primary effectiveness endpoint:** Composite of AF/AFL/AT episodes >30 s in duration	Freedom from documented arrhythmias was 88.2% in paroxysmal AF	4 (2.7%; 4/146) primary serious adverse events	

Study name	Monitoring	Endpoint	Efficacy	Safety	FDA or CE mark
Interim analysis at 6 months Tilz et al[60]	TTM: Every 14-day period between the 3- and 6- month visits 24-h Holter: 6 months	documented by protocol-specified 12-lead ECG, TTM, or Holter monitor after the 90-day blanking period **Primary safety endpoint:** rate of experiencing a pre-defined device and/or procedure-related serious adverse event within 7-days of any ablation procedure	patients and 76.7% in persistent AF patients		
VOLT IDE (Abbott Laboratories)[69]		**Acute effectiveness:** confirmation of PV isolation via entrance block after a 20-min wait period. **Primary safety endpoint:** device and/or procedure-related serious adverse event with onset within 7 days of the ablation procedure	Paroxysmal AF: 99.4% of veins (666/670) in 98.2% of patients Persistent AF: 99.8% of veins (633/634) in 99.4% of patients	1.9% (2 cardiac tamponade, 1 pericarditis, 1 stroke, 1 vascular access complication, and 1 prolonged hospitalization)	
FOCALFLEX CE Mark Trial (Abbott Laboratories)	Estimated study completion date: 3/30/2026				
FlexPulse IDE Trial (Abbott Laboratories)	Estimated study completion date: 4/30/2026				
Sphere-360 (Medtronic, Inc)[249]	In person or virtual visits: 10 days, 75 days, 6 months, 12 months TTM: Weekly through 21 weeks and monthly thereafter + when symptomatic 48-hour Holter: 6 and 12 months	**Primary effectiveness endpoint:** acute electrical isolation of all PVs **Primary safety endpoint:** Device-related serious adverse events within 7 days, including death, myocardial infarction, persistent phrenic nerve palsy, TIA, stroke, thromboembolism, major vascular complications/bleeding, heart block, gastroparesis, severe pericarditis, hospitalization (initial and prolonged) due to cardiovascular or pulmonary adverse events, cardiac	The Kaplan–Meier estimate of 1-year freedom from atrial arrhythmias was 81.8% (95% CI, 70.2–89.2) for the total and 100% (95% CI, 80.6–100) for the PULSE3 cohort PVI durability was 90% and 99% on a per-vein basis for the total and PULSE3 cohort, respectively	No predefined primary safety events	

Study name	Monitoring	Endpoint	Efficacy	Safety	FDA or CE mark
		tamponade/perforation (up to 30 days), PV stenosis (up to 180 days), and atrioesophageal fistula (up to 180 days)			
ECLIPSE AF (Cardiofocus CENTAURI system)[26]	Follow-up was scheduled at 7-day, 30-day, 90-day, 6-month, and 12-month post-index procedure Cardiac CT and invasive high-density remapping of PVs at 90 days	**Primary effectiveness endpoints:** (1) **acute success**, defined as PVI achieved with the CENTAURI System during the index procedure assessed by entrance and exit block after a 20-min waiting period and (2) **chronic success**, defined as the per-patient and per-PV isolation rate at 90 (±15) days, assessed by high-density remapping and confirmation of entrance and exit block. **Primary safety endpoint:** incidence of predefined system-related and procedure-related serious adverse events of interest within 30 days post-ablation	Acute procedural success was achieved in all 82 (100%) treated patients and 322 (100%) treated PVs, with first-pass isolation in 92.2% of PVs Chronic success: Development cohort 1 and 2: per-patient isolation rates of 38% and 26% and a per-PV isolation rates of 47% and 53% Optimized cohorts 3-5: per-patient isolation rates of 60%, 73%, and 81% and per-PV isolation rates of 84%, 90%, and 92%	Primary safety events in 4 (4.9%); all procedure-related Vascular access complications: 3 Exacerbated cardiac tamponade secondary to perforation leading to non-embolic stroke: 1 Other complications: Catheter perforation: 2 Esophageal injury: 2	
SmartfIRE (Biosense Webster, Inc)[76]	**12-lead ECG:** pre-procedure, pre-discharge, and at 1-, 3-, 6-, and 12-month visits and unscheduled visits (if any) **24-h Holter monitoring:** 3, 6, and 12 months **TTM:** Weekly: 1- 5 months	**Effectiveness endpoint:** Acute procedural failures; freedom from symptomatic and asymptomatic arrhythmia episodes of ≥30 s during days 91-365 on or off AAD **Safety endpoint:** Device or procedure-related serious adverse events (ie, death, life-threatening illness or injury, permanent impairment of a body structure or a body function, in-patient hospitalization or prolongation of patient hospitalization, medical	Freedom from arrhythmia at 12 months: 71.5% (84.2% when using standard-of-care monitoring only) Clinical success rate (freedom from symptomatic arrhythmia): 86.4%	Device/procedure-related serious adverse events: 5 (3.6%) Cardiac tamponade: 2 PV stenosis: 2 Anaphylactic shock: 1	

Study name	Monitoring	Endpoint	Efficacy	Safety	FDA or CE mark
	Monthly: 6-12 months, and following any symptomatic episodes, recorded for 1 min	or surgical intervention to prevent life-threatening illness or injury or permanent impairment to body structure or a body function, chronic disease, fetal distress, fetal death, or a congenital physical or mental impairment or birth defect	Single procedural success: 81.0% Use of class I/III AAD decreased from 60.3% at baseline to 23.9% at 6–12 months post-ablation	Cardiovascular hospitalization rate reduced from 20.1% to 11.9% during the 12 months before vs after ablation, respectively	
The first-in-human VCAS trial (Field Medical, Inc)[263]	Follow-up for 180 days with visits at pre-discharge, 30 days, 90 days, and 180 days post-ablation. During these visits, blood labs, ECGs, ICD interrogations, adverse events, and physical exams were performed	**Primary endpoint**: to assess the incidence of device- or procedure-related complications within 180 days of the procedure **Secondary endpoints:** procedural efficiency, arrhythmia burden, and arrhythmia recurrence	Freedom from recurrent VT/VF or ICD shock: 81.8% [95% CI, 67.1–99.8] VT/VF burden: significantly decreased from baseline to post-PFA by 98% vs 0%; p < 0.001	Primary safety endpoints within 180 days occurred in 3 of 26 (11.5%) patients: Cardiogenic shock followed by death Heart failure hospitalization Retroperitoneal bleed	
Randomized studies					
ADVENT (FARAPULSE; Boston Scientific, Inc)[83]	TTM: weekly (3–12 months) + when symptomatic ECG: 3, 6, and 12 months Holter: 72 hours at 6 and 12 months	**Primary efficacy endpoint**: freedom from a composite of initial procedural failure, documented atrial tachyarrhythmia after a 3-month blanking period, AAD use, cardioversion, or repeat ablation Primary safety endpoint: acute and chronic device- and procedure-related serious adverse events	Primary endpoint (success rate): PFA 73.3% vs thermal ablation 71.3%	PFA: 6 (2.1%) Thermal: 4 (1.5%) Mean change in the cross-sectional area of the PVs: −0.18 cm^2 (0.9%) with PFA and −1.18 cm^2 (12.0%) with thermal ablation	FDA
CHAMPION SINGLE SHOT (FARAPULSE;	Continuous rhythm monitoring after ablation with implantable cardiac monitors	**Primary endpoint:** recurrence of atrial tachyarrhythmia between day 91 and day 365 after ablation	Recurrence rate: PFA 37.1% vs cryoballoon 50.7%	1 patient in the PFA vs 2 patients in the cryoballoon	

Study name	Monitoring	Endpoint	Efficacy	Safety	FDA or CE mark
Boston Scientific, Inc)[84]		**Safety endpoint:** composite of procedure-related complications		group met the safety endpoint	
SPHERE PER-AF (Affera; Medtronic, Inc)[82]	Office visits: 1, 3, 6, and 12 months 24-hour Holter: 6 and 12 months 12-lead ECG: 3, 6, and 12 months	**Primary effectiveness composite endpoint:** failure to acutely isolate all targeted PVs and complete all left atrial ablation with the assigned study device; repeat ablation at any time after the index procedure; and, after a 3-month blanking period, documented occurrence of atrial tachyarrhythmia, escalation or initiation of class I or class III anti-arrhythmic drugs, or cardioversion **Primary safety endpoint:** composite of prespecified device-related or procedure-related serious adverse events	Success rate: Dual energy SPHERE-9 arm 73.8% vs traditional RFA arm (control) 65.8%	Primary safety events occurred in 3 (1.4%) patients in the investigational arm and in 2 (1.0%) patients in the control arm	FDA
BEAT-PAROX AF (FARAPULSE; Boston Scientific, Inc)[272]	Telephone follow-up at 1 month, in-person follow-up at 2, 6, and 12 months. Weekly self-recorded single-lead ECGs with hand-held ECG (AliveCor Kardia) and symptom-driven recordings	**Superiority trial** Primary endpoint: single-procedure success rate after 12 months defined as the absence of ≥30 s atrial arrhythmia recurrence, class I/III antiarrhythmic drug resumption after a 2-month blanking period, or any repeat ablation Secondary effectiveness endpoints: 1) Multiple procedure success 2) Quality of life 3) Proportion of participants with death, strokes, or embolic events from arrhythmia up to 12 months after the index ablation procedure Secondary safety endpoint: composite of prespecified device- and procedure-related serious adverse events within 7 days after the procedure	PFA arm: 112/145 (7 7.2%) RFA arm: 111/143 (77.6%) Adjusted risk difference 0.9% (95% CI, -8.2 to 10.1; p = 0.84)	Composite safety endpoint of at least one adverse event per patient: PFA arm: 7 (4.8%) including 1 TIA, 1 pericarditis, 6 hospitalisations, 1 vascular access complications RFA arm: 11 (7.6%), including 2 cardiac tamponade, 1 pericarditis, 9	CE and FDA approved

Study name	Monitoring	Endpoint	Efficacy	Safety	FDA or CE mark
				hospitalisations, 4 vascular access complications, 2 pulmonary vein stenosis >70%	

AAD = antiarrhythmic drug; AF = atrial fibrillation; AFL = atrial flutter; AT = atrial tachycardia; ECG = electrocardiogram; CT = computed tomography; DCCV= direct current cardioversion; FDA = US Food and Drug Administration; ICD = implantable cardioverter-defibrillator; IDE = ; PV = pulmonary vein; PVI = pulmonary vein isolation; PWI= posterior wall isolation; RFA = radiofrequency ablation; TIA = transient ischemic attack; TTM = transtelephonic monitoring

Heart Rhythm Society SM

TABLE 3 – Characteristics of PFA catheters

Brand name	Catheter	Descriptive name	Ablation energy	Diameter (mm)/size (F)	Irrigation/flow (mL/min)	Number of applications recommended	Ablation mode/configuration	Nominal amplitude	Integration in mapping/mapping system	Waveform description	Vectoring/activation pattern	Pulse duration	Number of trains/application	Contact sensing/type
Farawave Boston Scientific		Pentaspline 20 electrodes (4 electrodes on each of 5 splines)	PFA	31 & 35 mm/12F	Saline drip	8 applications per vein (nominal)	Bipolar	1800-2000 V	Yes	Biphasic	Between spline pairs	Microseconds	5	Local impedance
OptiShot Cardiofocus		Compliant PFA balloon	PFA	Up to 40 mm/12F	No	1 per position/1 per vein	Bipolar	Up to 2 kV	Not required	Biphasic	Simultaneous delivery to non-adjacent splines	Microseconds	Not provided	Direct visual confirmation
Farapoint Boston Scientific		Focal	PFA	8F	No	3-5 mm between lesions	Bipolar	1400-2000 V	Yes	Biphasic	Between electrode pairs	Microseconds	5	Local impedance (future)
PulseSelect Medtronic		Circular: 9 electrodes	PFA	25 mm/9F	Not irrigated	Minimum of 8 per vein	Bipolar	1500 V	Yes (compatible with all mapping systems)	Biphasic	Dual field: odd and even electrodes activated separately during pulse train	Microseconds	4	In development/impedance based
Varipulse Biosense Webster		Variable loop: 10 electrodes	PFA	25-35 variable/8.5F	Yes	>=12 per vein	Bipolar	1800 V	Yes	Biphasic	Between adjacent electrodes	Microseconds	Not provided	Impedance
Sphere-9 Medtronic		Large-tip focal	PFA & RFA	9 mm/8F	Yes/15 mL/min (PF); 30 mL/min (RF)	5-6 mm between lesions, user configurable	Monopolar	Up to 2000 V	Yes/Affera Prism	Biphasic	Lattice to return patches	microseconds	12	Impedance and temperature change after starting ablation
Centauri Cardiofocus (Galaxy)		Focal	PFA	3.5-4 mm/8F	4 mL/min	4-5 mm between lesions	Monopolar	19 A, 22 A, 25 A, up to 3.5 kV	Yes	Biphasic	Unipolar to patch	Microseconds	Not provided	Contact force
Globe System Kardium		122 electrode spherical array	PFA RFA (investigational)	30 mm/16F	Yes/100 mL/h (yes/1.67 mL/min) Heparin coated	1 application per vein /target area	Bipolar	1700 V	Yes/Globe System	Biphasic	2 to 64 electrodes simultaneously	Microseconds	2 to 6	Thermal contact mapping
STSF dual energy Biosense Webster		Focal	PFA & RFA	3.5 mm/8F	Saline drip	Up to 24 applications, 28 s max, duration varies according to PF	Bipolar	1.0-1.5 kV	Yes	Biphasic	Unipolar to patch	Microseconds	Not provided	Contact force with direction vector
OMNY pulse Biosense Webster		Large-tip focal	PFA	12 mm/7.5F	Saline drip	Up to 12 applications, 14.5 s max, duration varies according to PF	Bipolar	1.0-1.5 kV	Yes	Biphasic	Bipolar 3 splines vs 3 splines	Microseconds	Not provided	Contact force with direction vector
Abbott Volt		Balloon in splined basket	PFA	28 mm/12.5F	None	Nominal waveform: minimum 2, average of 4 Low waveform: minimum of 3	Bipolar	Nominal: 1700 V Low: 1345 V	Yes	Biphasic	Spline to neighboring spline in sequence around the 8 splines	Microseconds	10	Yes: complex impedance (LivePoint)
Abbott Tactiflex Duo		Focal	PFA & RFA	4 mm tip/8F	2 mL/min baseline 13 mL/min on PF and RF	1 application per location for atrial locations	Monopolar	Nominal: 2232 V Low: 1950 V	Yes	Biphasic	Unipolar to patch	Microseconds	Nominal: 5 trains Low: 10 trains	Yes: Light-interferometry contact force
Sphere-360		Very large array	PFA	34 mm/8F	Not irrigated	3-4 per vein	Monopolar	Not provided	Yes/Affera Prism	Biphasic	6 panels activated individually to return patch	Microseconds	Not provided	Impedance
nsPFA, PusIseBiosciences		Very large array	PFA	30 mm/11F	No	1 ostial and 1 antral application per vein	Bipolar	Not provided	Feasibility clinical integration with EnSite and CARTO	Monophasic	Between rings	Nanoseconds	Not provided	No
ElectroPulse, CathRx		Variable loop: 10 electrodes	PFA	2.33 mm/8F	No	1 per location	Bipolar	2800 V	Yes	Biphasic	Between adjacent electrodes	Microseconds	7	Yes
LotosPFA Insight Medtech		Interconnected spline in spindle and lotus configurations	PFA	28 or 31 mm/11F	Saline drip	8 applications per vein	Bipolar	2100 V	No	Biphasic	Between adjacent electrodes	Nanoseconds	5 trains per site	No
Adagio		Very large array	PFA	20-25 mm/8.5F	Not irrigated	Not provided	Bipolar	1100 V	Feasibility with Ensite	Biphasic	Between adjacent electrodes	Not provided	1	Not provided
Faraflex Boston Scientific		Large focal	PFA	10 mm/8F	2 mL/min	5-6 mm between lesions	Monopolar/bipolar	2000 V	Yes	Biphasic	Monopolar: distal electrode-patch; bipolar: distal - proximal	Microseconds	5	Local impedance
QuickShot Cardiofocus		Map & ablate mini basket	PFA	10 mm/8.5F	2 mL/min	1 per position	Monopolar	33 A, 40 A up to 5 kV	Yes	Biphasic	Unipolar to patch	Microseconds	Not provided	Yes: impedance algorithm
Field Medical		Focal	PFA	8.5F	Irrigated	Not provided	Monopolar	>10 kV	Feasibility with CARTO	Monophasic	Not provided	Nano/microseconds	Not provided	Yes
Arga Medtech SA		Circular, linear, focal	PFA	25 mm/7F	No	5-7 applications per PV	Bipolar, monopolar, and combination	2250-3250 V	No	Biphasic, coherent sine wave	Not provided	Microseconds	Not provided	Yes: impedance

Data were retrieved from public sources and compiled. The table was sent to companies to confirm, modify, and provide more information. Fields that are not populated indicate data that are either not available or were not disclosed by the companies. PFA = pulsed field ablation; PV = pulmonary vein; RFA = radiofrequency ablation. See an expanded version of the table in Supplemental Materials.

TABLE 4 – Adjuvant medications for PFA procedures

Drug	Indication in PFA procedure	Contraindications (most common/relevant)	Side effects (most common/relevant)	Timing of application	Application route	Dose
Nitroglycerin	Prevention of coronary spasm	Severe hypotension, hypertrophic obstructive cardiomyopathy, concomitant use of PDE5 inhibitors, increased intracranial pressure, severe anemia	Hypotension, headache, dizziness, syncope, flushing, tachycardia, nausea	1-2 min before PFA delivery, and repeated every 2-3 mins	Intravenous, intra-atrial, intra-coronary	3 mg initial bolus, followed by + 2 mg every 2 min until ablation is stopped Pressor support (eg, phenylephrine) often needed
Atropine (crosses blood-brain barrier)	Prevention of vagal responses	Glaucoma, urinary tract obstruction, pyloric stenosis, ileus, thyrotoxicosis, myasthenia gravis, ulcerative colitis	Visual disturbances, gastrointestinal disorders (nausea and constipation), urinary retention, delirium	Before start of PFA delivery	Intravenous	0.5-1 mg
Glycopyrrolate (does not cross blood-brain barrier)	Prevention of vagal responses	Hypersensitivity, glaucoma, urinary tract obstruction, pyloric stenosis, ileus, thyrotoxicosis, myasthenia gravis, ulcerative colitis	Visual disturbances, gastrointestinal disorders (nausea and constipation), urinary retention, delirium (less than with atropine)	Before start of PFA delivery	Intravenous	0.2 mg
Lidocaine	Prevention of coughing	Hypersensitivity, severe sinoatrial, atrioventricular, or intraventricular block, porphyria, severe hepatic impairment Relative contraindications: seizure disorder, heart failure, renal dysfunction	Perioral numbness or tingling, metallic taste, light-headedness or dizziness, nausea, tinnitus, blurred or double vision, tremor	Before start of PFA delivery	Intravenous	0.5-1.0 mg/kg

PFA = pulsed field ablation.

TABLE 5 – Safety of PFA versus RFA and CBA

Complication	Radiofrequency (RFA)	Cryoballoon (CBA)	Pulsed field (PFA)
Coronary spasm			0–0.14%[70,75,83,84,86]{Jais, 2025 #603}
Pericarditis	0.3–0.7%[70,83,86,273-275]{Jais, 2025 #603}	0.3–0.7%[70,83,86,273-276]	0.4–0.7%[70,75,83,84,86]{Jais, 2025 #603}
Pericardial tamponade	0–1.3%[234,273,275,277]	0–1.9%[84,234,273-276]	0–0.7%[70,75,83,86]
Pulmonary vein stenosis	0–1.4%[4,75,83,273,275,277]{Jais, 2025 #603}	0%[4,75,83,273-276]	0%[70,75,83,84,86]{Jais, 2025 #603}
Phrenic nerve injury	Transient: 0–0.6% Permanent: 0–0.16%[4,75,83,234,273,275,277,278]	Transient: 0–4.4% Permanent: 0–2.7%[4,75,83,234,273-276]	Transient: 0–1.3% Permanent: 0–0.4%[70,75,83,84,86]
Atrioesophageal fistula	0–0.04%[4,75,83,273,275,277,279]{Jais, 2025 #603}	0–0.01%[4,75,83,273-276,279]	0%[70,75,83,84,86]{Jais, 2025 #603}
Major vascular complications	0–4.3%[4,75,83,234,273,275,277]	0–1.9%[4,75,83,234,273-276]	0–0.3%[70,75,83,84,86]{Jais, 2025 #603}
Stroke/TIA	0–0.5%[4,75,83,234,273,275,277]	0–0.9%[4,75,83,234,273-276]	0–0.95%[70,75,83,84,86]{Jais, 2025 #603}
Delayed coronary spasm/malignant arrhythmias			0.16%[209]
Death (≤30 days post-ablation)	0–0.1%[83,234,273,274,277]	0–0.5%[84,192,234,273-275]	0–0.3%[70,75,83,84,86]{Jais, 2025 #603}
Hemolysis/hemoglobinuria		Rare case reports[192]	0.03–0.4%[70,75,83,86,280]

*Pulmonary vein stenosis has been reported rarely in small cryoballoon series but was not observed in large, randomized trials or registries used for this table. See Ref 17.

TABLE 6 – Committee recommendations

Domain	Survey question	Vote (Yes)	Active discussion points during vote
Procedural workflow			
	We recommend that pulsed field ablation is the preferred initial energy source for patients undergoing pulmonary vein isolation.	8/11 (73%)	Radiofrequency and cryoablation have been used for years and still have a role to play.
	We recommend that operators be well versed in the safety profile (eg, hemolysis, coronary artery spasm, thermal profile) of the pulsed field ablation system they are using.	11/11 (100%)	
	We recommend that pulsed field ablation procedures be preferentially performed under general anesthesia, with deep sedation being a reasonable alternative.	9/11 (82%)	Disagreement from operators in regions where general anesthesia is not readily available.
	We recommend vascular ultrasound guidance for vascular access during pulsed field ablation procedures to reduce the risk of vascular complications.	11/11 (100%)	
	We recommend heparin should be administered during pulsed field ablation procedure and titrated to achieve and maintain an activated clotting time of at least 300 s.	11/11 (100%)	
	We recommend heparin should be administered following vascular access (before transseptal access) in order to ensure activated clotting time is therapeutic prior to pulsed field ablation energy delivery.	11/11 (100%)	
	We recommend meticulous sheath management (flushing, heparin lock) to minimize the risk of adverse event.	11/11 (100%)	
	We suggest that intravenous lidocaine (0.5-1 mg/kg) may be prophylactically administered to reduce cough reflexes when using deep sedation.	8/11 (73%)	While commonly used, use of lidocaine has not been extensively studied.
	We suggest that an anticholinergic agent (atropine 0.5 mg or glycopyrrolate 0.2-0.4 mg) may be prophylactically administered to avoid vagal reactions.	8/11 (73%)	Atrial pacing may be useful and avoid pauses. High doses of anticholinergics can produce side effects like urinary retention.
	We suggest that operators start with ablation of the right pulmonary veins prior to the left pulmonary veins to minimize vagal reactions, especially when deep sedation is being used.	5/11 (45%)	While some published evidence supports this, it was not accepted by the majority of the panel.
	We recommend that ablation catheter-to-tissue contact be optimized prior to energy delivery.	11/11 (100%)	

Domain	Survey question	Vote (Yes)	Active discussion points during vote
	We suggest that intracardiac echocardiography be used, where available, to facilitate lesion formation by ensuring adequate tissue contact	8/11 (73%)	Disagreement from operators in regions where intracardiac echocardiography is not readily available.
	We recommend adequate overlap of pulsed field ablation lesions (eg, ~50%) to optimize durability and procedural success.	11/11 (100%)	
	We recommend that the total number of pulsed field ablation lesions delivered should be kept as low as reasonably achievable to obtain procedural success while minimizing adverse events (eg, hemolysis).	10/11 (91%)	Hemolysis and thermal profiles are system specific, so this may apply to some systems more than others.
	We suggest that a post-isolation intraprocedural waiting period is not necessary after pulsed field ablation.	8/11 (73%)	There is active investigation on whether other electrogram metrics (such as unipolar signals) can predict completeness of lesions.
	We suggest that a post-isolation pharmacological challenge (eg, adenosine) is not necessary after pulsed field ablation.	9/11 (82%)	There was wide agreement on lack of utility for adenosine, but isoproterenol may be useful for inducing non-pulmonary vein triggers.
Technology development			
	We recommend that first-in-human studies of novel pulsed field ablation devices include protocol-mandated pulmonary vein remapping studies to guide optimal dosing parameters.	8/11 (73%)	There is limited ability to perform such studies outside of specific geographies (eg, Eastern Europe).
	We recommend that pulmonary vein remapping studies are independently adjudicated by blinded investigators not involved in the initial procedure.	8/11 (73%)	There may be logistical challenges in implementation but was generally accepted.
	We recommend harmonized benchtop pre-clinical testing for all new pulsed field ablation systems to quantify thermal profile, hemolysis risk, musculoskeletal stimulation, and tissue depth.	11/11 (100%)	
Safety			
Coronary protection	We suggest that radiofrequency energy may be preferred to pulsed field energy when performing ablation at the cavotricuspid isthmus or along the posterior mitral isthmus line because of the risk of coronary spasm in these areas.	9/11 (82%)	This may be more relevant for dual-energy catheters that can deliver both radiofrequency and pulsed field.
	We recommend that if pulsed field ablation is administered to areas in proximity to coronary	10/11 (91%)	The optimal dose of nitroglycerin is unclear, and

Domain	Survey question	Vote (Yes)	Active discussion points during vote
	arteries (cavotricuspid isthmus or posterior mitral isthmus), intravenous nitroglycerin (3 mg IV followed by 2 mg IV every 5 min) be administered.		it may not prevent all spasm. There is a cost to perfusion pressure during the procedure.
	We recommend hemodynamic and continuous electrocardiogram ST-segment monitoring with a 12-lead electrocardiogram used when pulsed field ablation is performed in proximity to the coronary arteries (cavotricuspid isthmus or posterior mitral isthmus).	11/11 (100%)	
	We recommend urgent access to coronary angiography be available when performing pulsed field ablation in close proximity to the coronary arteries.	11/11 (100%)	
	We suggest that long-term follow-up is recommended for patients who experience severe clinical manifestations of coronary artery spasm to exclude delayed coronary injury.	9/11 (82%)	Exact testing and evaluation to be done during follow-up is unknown at this time.
Renal protection	We recommend choosing a pulsed field ablation system that minimizes hemolysis since significant hemolysis not only increases the risk of renal injury but may also increase platelet activation, vasospasm, and delayed vasospasm events.	8/11 (73%)	Systems that are prone to more hemolysis are in active use.
	We suggest that intravenous fluid (1-2 L) be administered to patients at elevated risk of pulsed field ablation-associated renal injury when a large number of pulsed field ablation lesions are delivered.	8/11 (73%)	Hemolysis and thermal profiles are system specific, so this may apply to some systems more than others. Fluid overload of patients may prolong hospitalization and/or intervention.
	We suggest that biochemical markers of hemolysis be evaluated immediately post-procedure (plasma free hemoglobin) and again within 5 days (creatinine, hemoglobin, haptoglobin, and bilirubin) in patients who receive a large number of pulsed field ablation lesions.	8/11 (73%)	Evaluating such markers may not change management plan.
Device interaction	We suggest that pulsed field ablation may be used in patients with intracardiac metallic implants; however, care should be taken to avoid close proximity or contact during application.	10/11 (91%)	Arcing may be more likely when in close proximity versus in contact. Being in contact will often cause some generators to shut down to avoid energy delivery.
	We recommend that cardiac implantable electronic devices be interrogated prior to and following a pulsed field ablation procedure.	10/11 (91%)	

Domain	Survey question	Vote (Yes)	Active discussion points during vote
	We recommend that patients at risk of harm (eg, dependent patients or those with a defibrillator) have their cardiac implantable electronic devices reprogrammed prior to and following the pulsed field ablation procedure.	11/11 (100%)	
Phrenic nerve	We suggest that routine monitoring of phrenic nerve function is not necessary during endocardial ablation using pulsed field ablation.	10/11 (91%)	It is unknown if application close to the phrenic nerve epicardially is safe. Excessive lesion stacking near the phrenic nerve may cause persisting damage.
Esophageal	We suggest that esophageal temperature monitoring, cooling, or deviation are not necessary during pulsed field ablation procedures.	11/11 (100%)	
	We recommend against rapid stacking of pulsed field ablation lesions in anatomic locations in close proximity to the esophagus or phrenic nerve.	10/11 (91%)	While most pulsed field systems have demonstrated esophageal and phrenic safety, varying systems have major differences in thermal profiles, which could cause risk if stacking occurs.

Figures

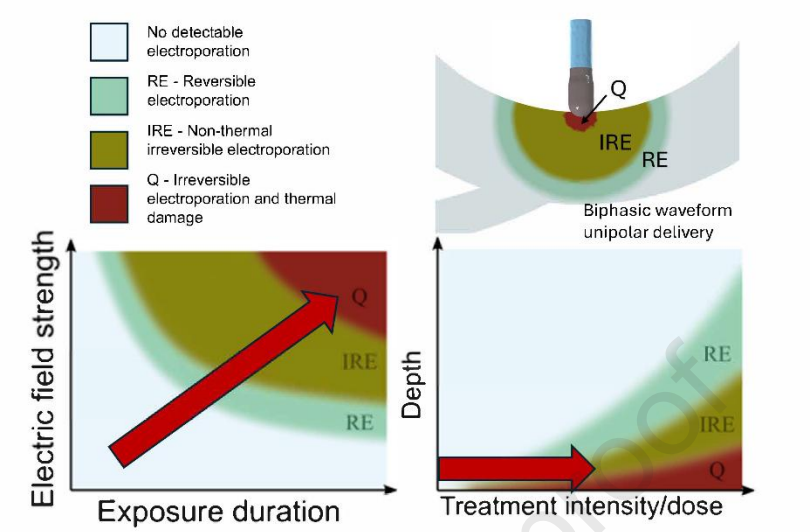


Figure 1 – Catheter proximity, field, and resulting lesion. Driving lesion depth/size with increasing treatment intensity/dose (by amplitude, pulse duration, number of pulses or trains, and repetitive treatment applications) will inevitably lead to tissue thermal damage and (prohibitively) high temperatures at the catheter and its immediate vicinity.

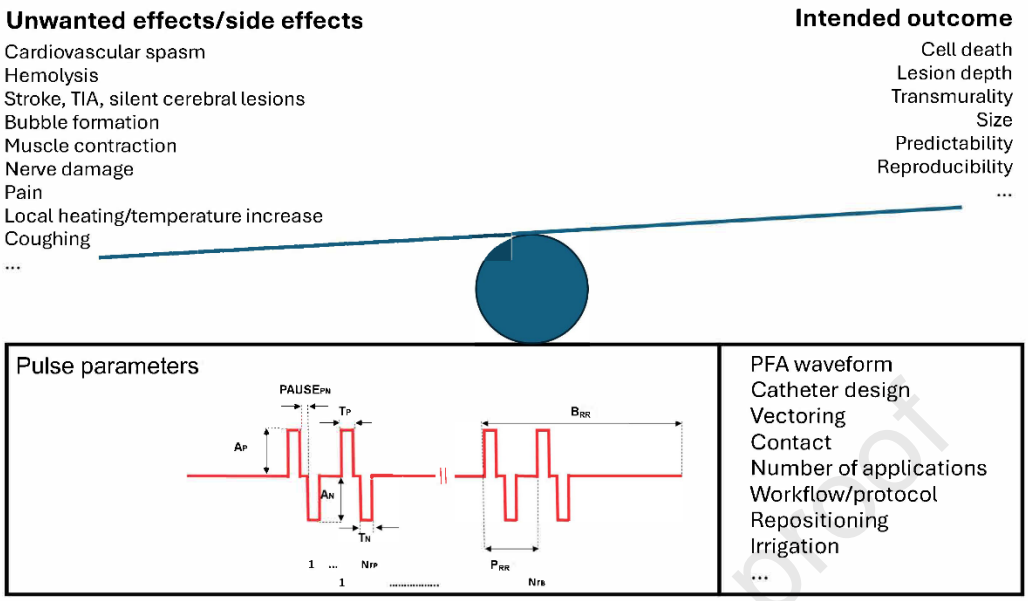


Figure 2 – Pulse parameters and balancing desired and undesired effects. The choice of pulsed field ablation waveform, pulse parameters, catheter design, and vectoring will affect not only lesion size (the primary target) but also thermal footprint, neuromuscular capture, hemolysis, and other effects. A_p = amplitude of the positive phase; A_N = amplitude of the negative phase; T_p = duration of the positive phase; T_n = duration of the negative phase; $PAUSE_{PN}$ = interphase delay; P_{RR} = pulse repetition rate; B_{RR} = burst repetition rate; N_{rP} = number of pulses in burst; N_{rB} = number of bursts; PFA = pulsed field ablation; TIA = transient ischemic attack.

	Lesion depth	Stunning	Heating	Electro-chemistry	Pain	Neuromuscular stimulation	Arrhythmogenic
Pulse amplitude	↑↑	↑	↑↑	↑	↑	↑	↑
Pulse width	↑	↑	↑	↑↑	↑↑	↑↑	↑↑
Number of pulses	↑	↑	↑	↑↑	↑	↑	↑
Monophasic pulse	↑	↑	—	↑↑	↑	↑	↑
Biphasic pulse	↓	↓	—	↓↓	↓	↓	↓
Interphase delay	?	↑	↓	—	↑	↑	↑
Interpulse delay	↑	?	↓	—	↑↑	↑↑	↑↑
Intertrain delay	—	—	↓↓	—	—	—	—

Figure 3 – The effects of changing pulse parameters and their impact on clinical and adverse effects.

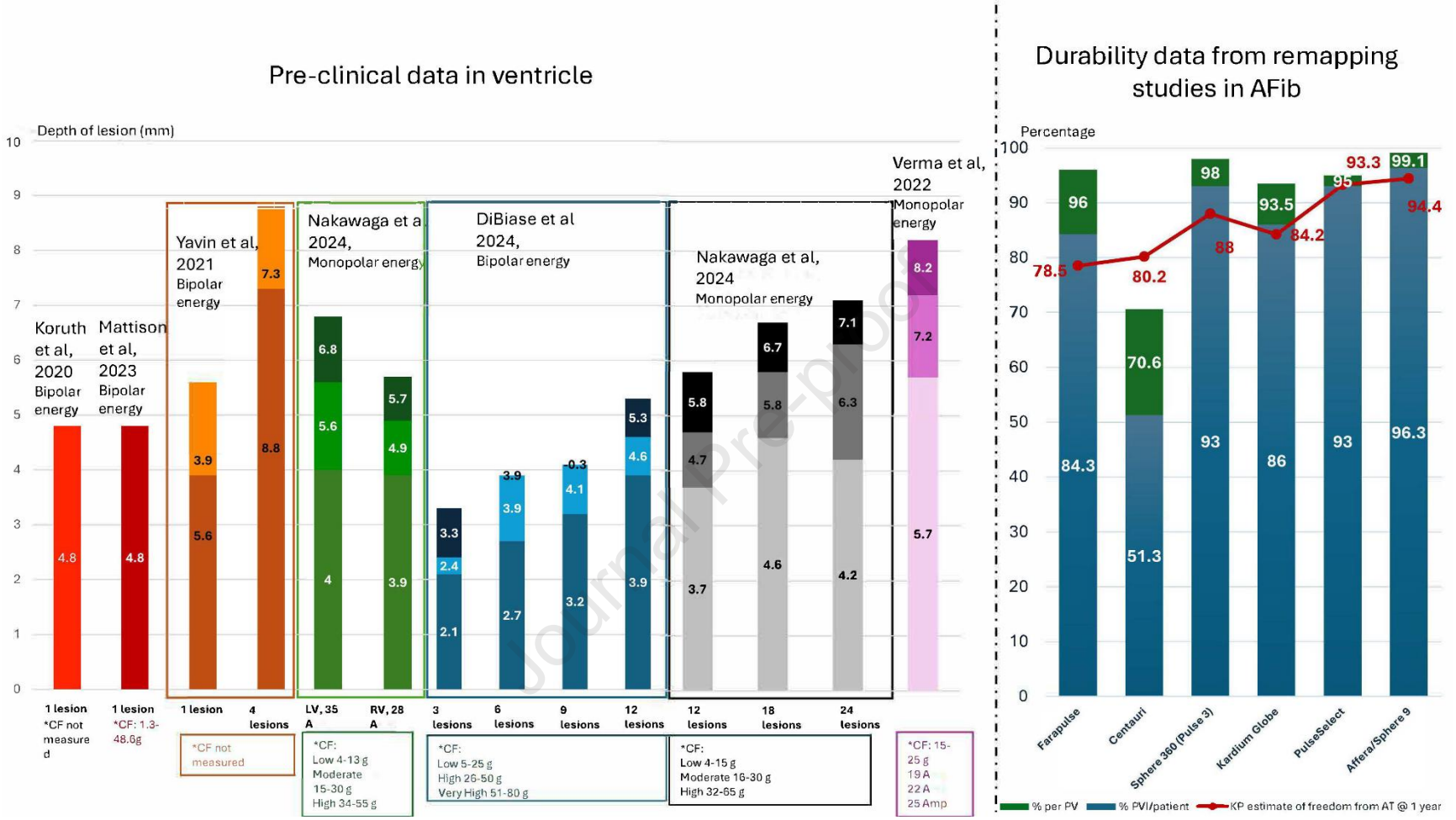


Figure 4 – Lesion depths associated with various pulsed field ablation technologies are shown in the left panel. In the right panel, the percentage of durable pulmonary vein isolation at remapping is shown by patient (blue bars) and by pulmonary vein (green bars). The red lines describe one-year freedom from atrial arrhythmia reported by the same studies. Afib = atrial fibrillation; AT = atrial arrhythmia/tachycardia; CF = contact force; KP = Kaplan Meier plot; LV = left ventricle; PV = pulmonary vein; PVI = pulmonary vein isolation; RV = right ventricle.

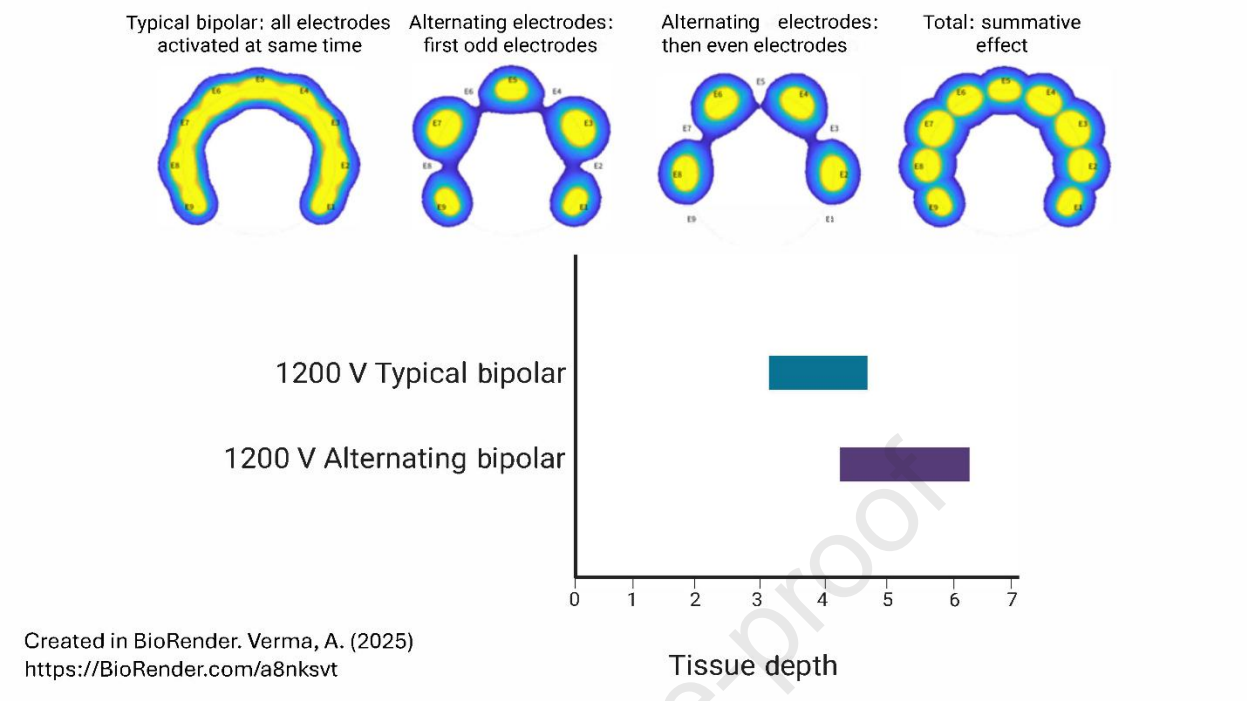


Figure 5 – The effect of alternating skipped electrode pulsed field ablation delivery on tissue depth while keeping voltage constant.

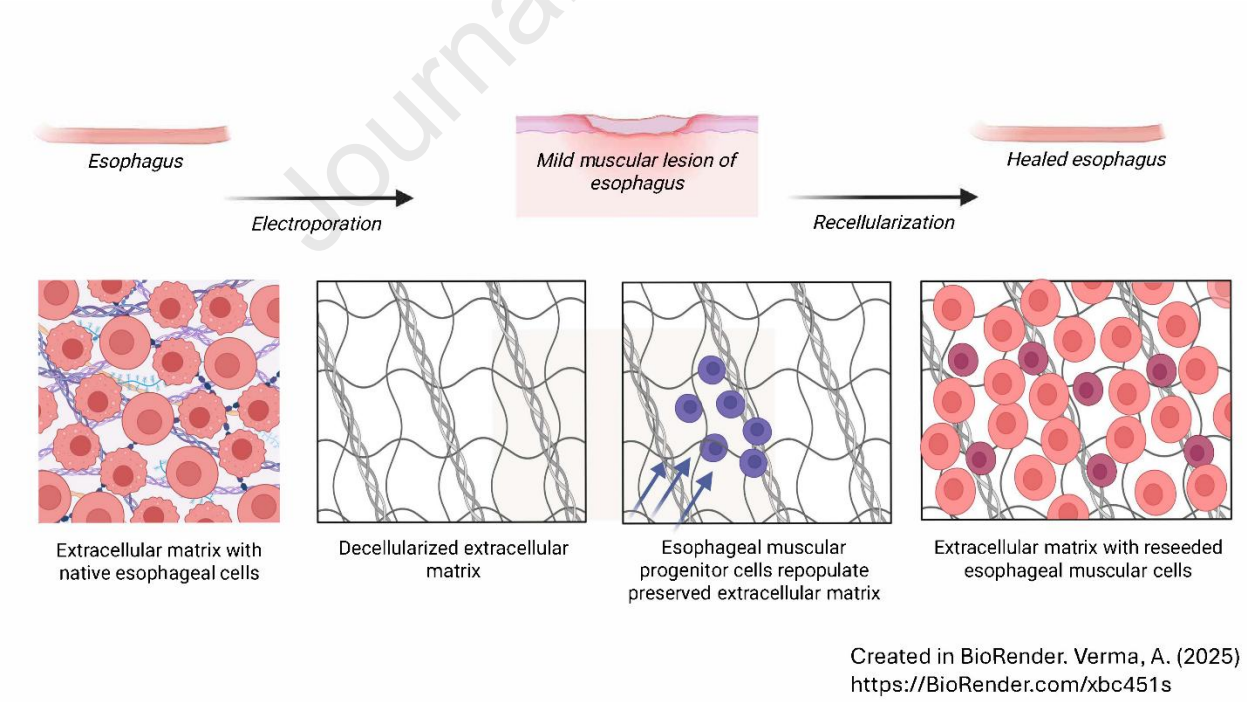


Figure 6 – The ability of collateral tissue damage (in this case, esophagus), to heal after pulsed field ablation delivery because of preservation of extracellular matrix.

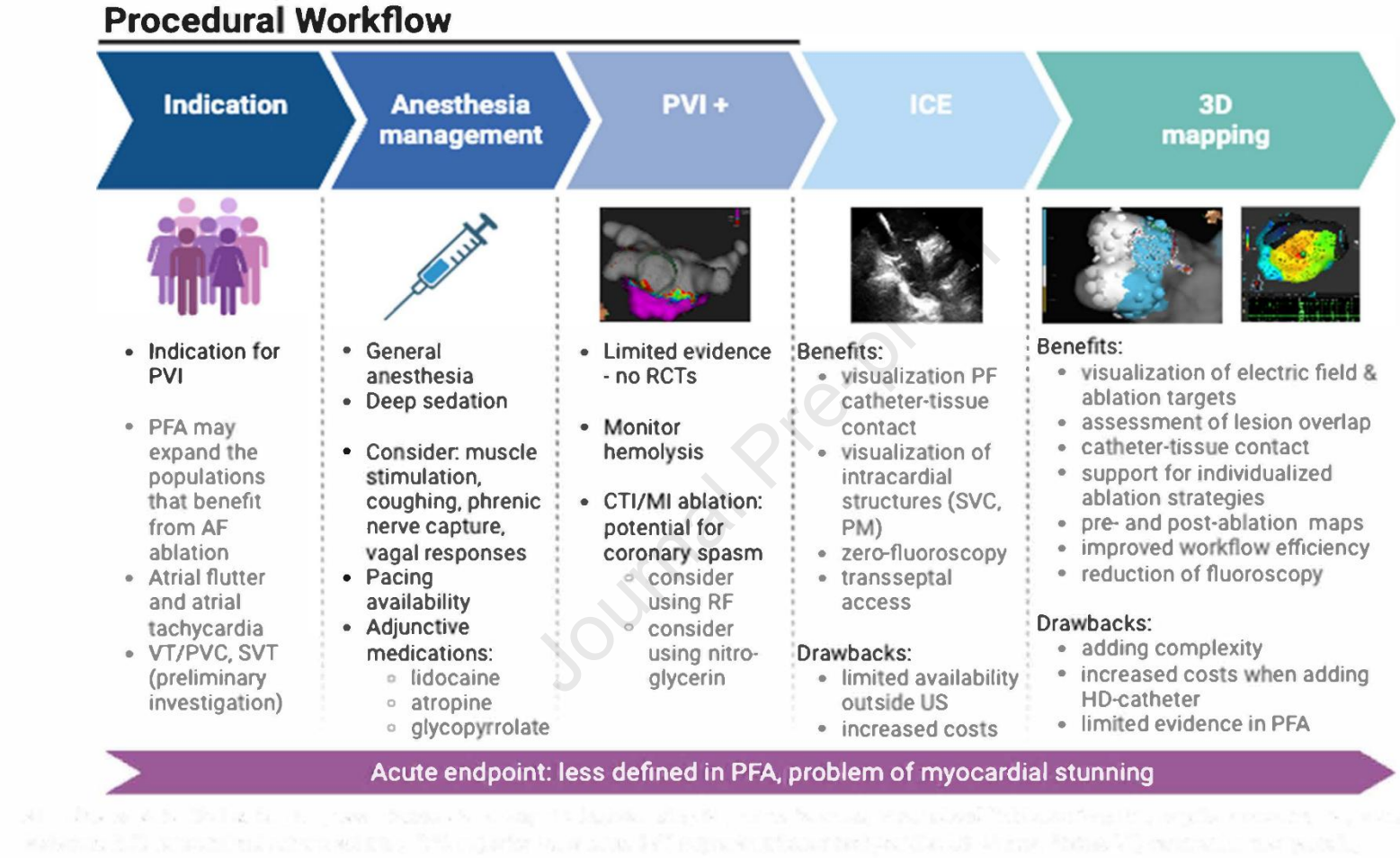


Figure 7 – Workflow illustration. 3D = three-dimensional; AF = atrial fibrillation; CTI = cavotricuspid isthmus; HD = high-density; ICE = intracardiac echocardiography; MI = mitral isthmus; PFA = pulsed field ablation; PM = papillary muscle; PVI = pulmonary vein isolation; RCT = randomized controlled trial; RF = radiofrequency; SVC = superior vena cava; SVT = supraventricular tachycardia; VT = ventricular tachycardia.

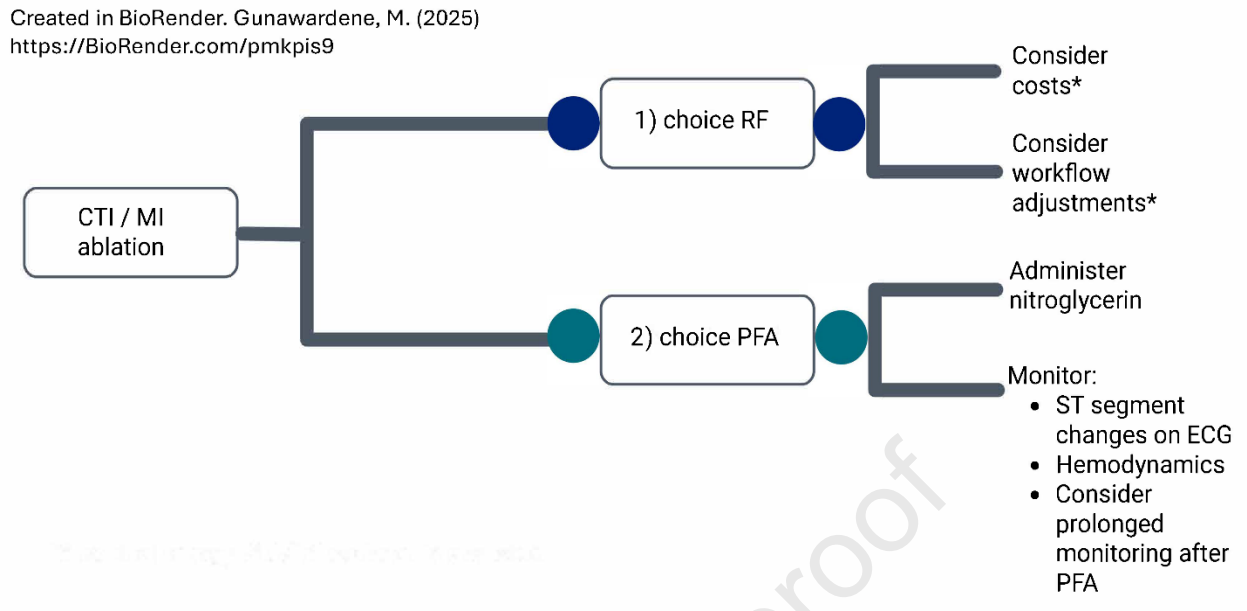


Figure 8 – Pulsed field ablation versus radiofrequency ablation on critical isthmuses. *If no dual-energy pulsed field ablation/radiofrequency catheter is available. CTI = cavotricuspid isthmus; ECG = electrocardiogram; HD = high-density; MI = mitral isthmus; PFA = pulsed field ablation; RF = radiofrequency.

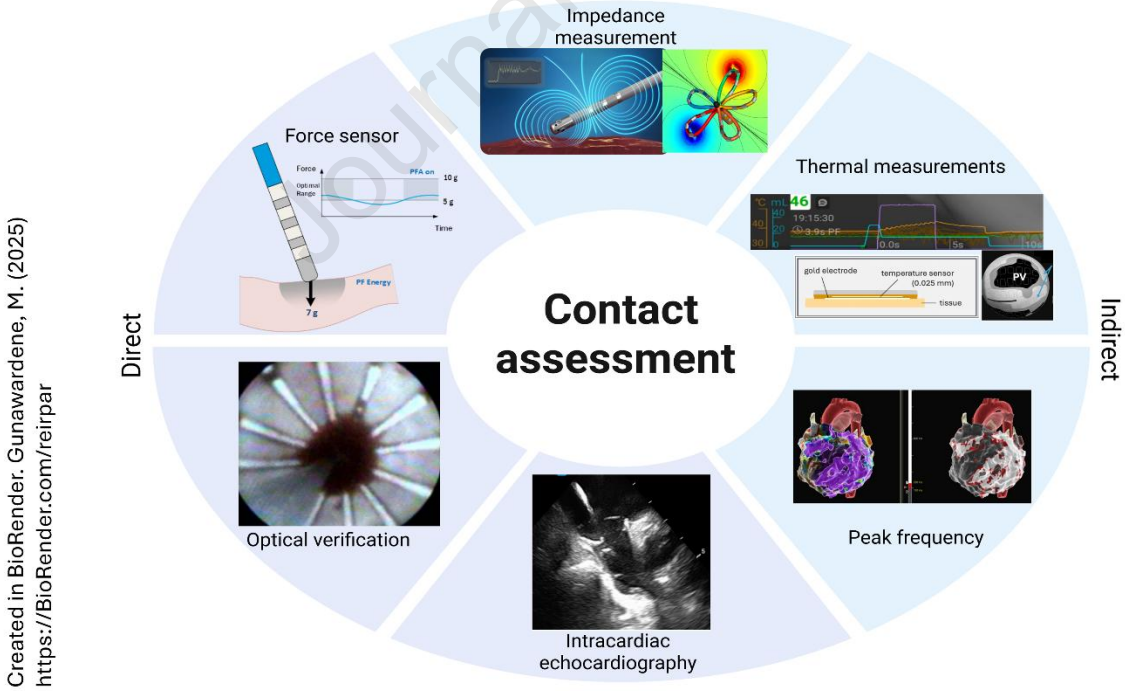


Figure 9 – How to assess catheter-tissue contact for pulsed field ablation. PFA = pulsed field ablation; PV = pulmonary vein.

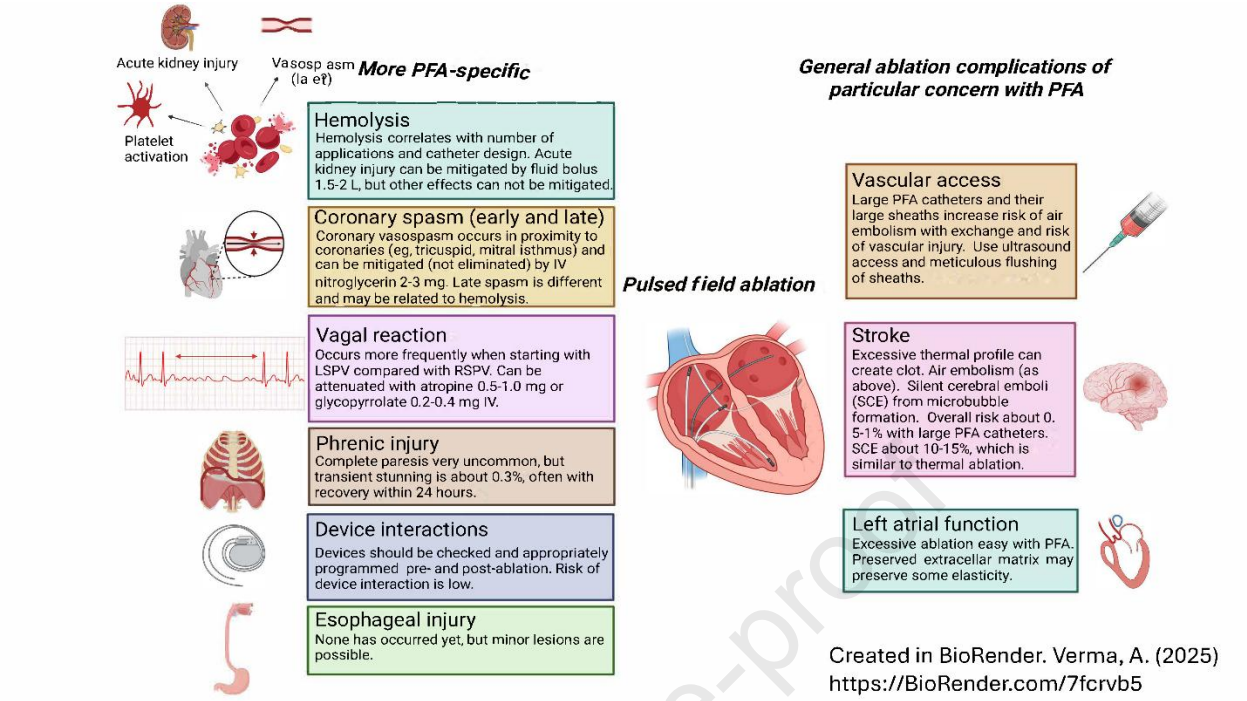


Figure 10 – Safety considerations related to pulsed field ablation, both specific and non-specific for pulsed field ablation. LSPV = left superior pulmonary vein; PFA = pulsed field ablation; RSPV = right superior pulmonary vein.

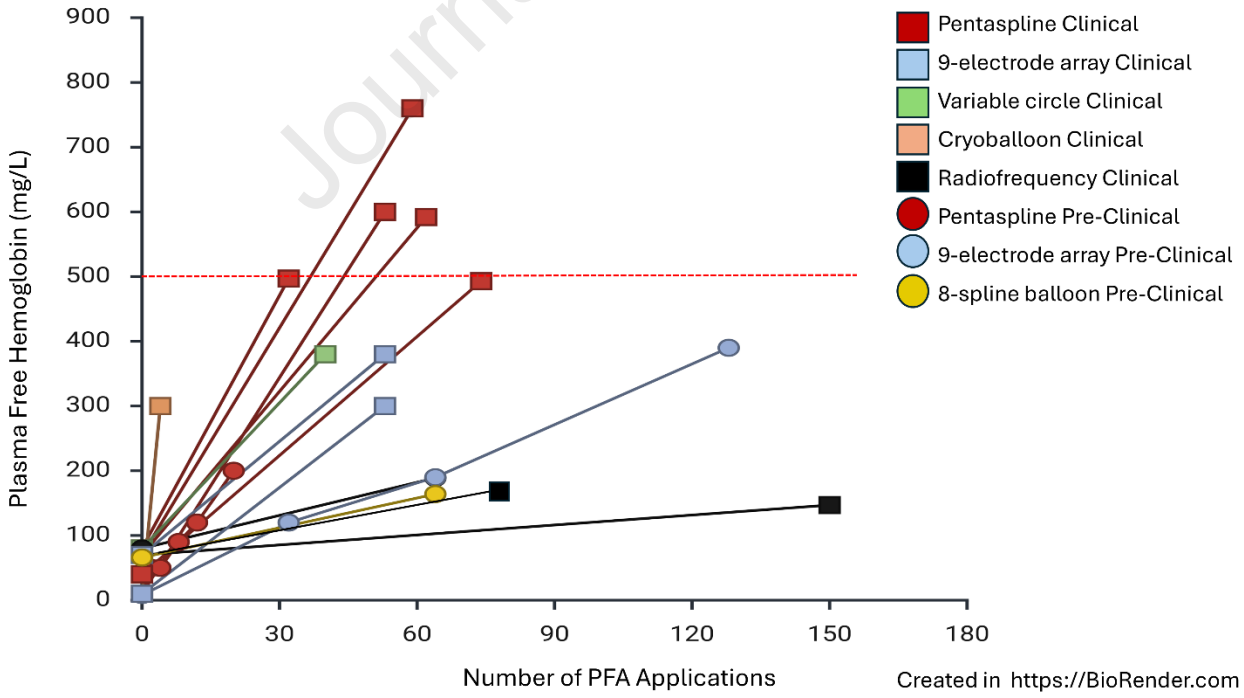


Figure 11 – Hemolysis profile for various pulsed field ablation devices. Devices have differences in their hemolytic potential. PFA = pulsed field ablation.

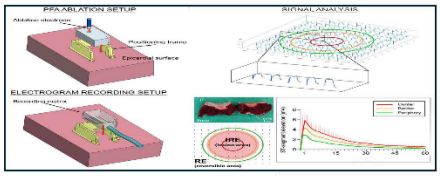
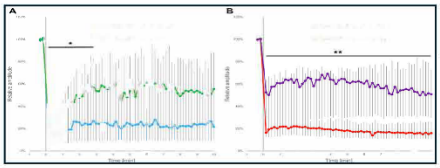
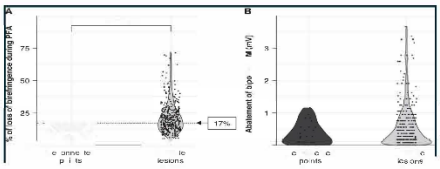
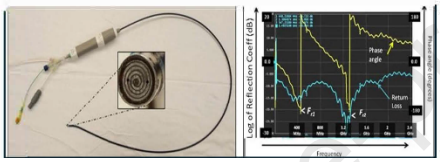
Changes in unipolar electrogram morphology		Changes in ST elevation and R/S ratio differentiate irreversible vs reversible electroporation but discriminatory power may disappear after 30 min
Changes in unipolar electrograms by frequency analysis		Changes in ST elevation measured as low frequency components of the signal may differentiate transmural vs non-transmural lesions
Changes in tissue optical birefringence		Pre-clinical and early human analysis show drops in tissue birefringence (an optical property) can differentiate between complete histological lesions and durable PV isolation
Changes in high frequency electrical properties (resonant frequencies)		Changes in resonant frequencies at the tip of an antenna electrode can detect tissue property changes indicative of complete lesions

Figure 12 – Techniques for assessing durability for pulsed field ablation lesions. Reprinted with permission from Amorós-Figueras G et al[266], Stublar J et al[267], Martins RP et al[269], and Parag K et al[270]. EGM = electrogram; IRE = non-thermal irreversible electroporation; PV = pulmonary vein; RE = reversible electroporation; RFA = radiofrequency ablation.

REFERENCES

1. Scheinman MM, Morady F, Hess DS, Gonzalez R. Catheter-induced ablation of the atrioventricular junction to control refractory supraventricular arrhythmias. JAMA 1982;248(7):851-855.
2. Verma A, Asivatham SJ, Deneke T, Castellvi Q, Neal RE, 2nd. Primer on Pulsed Electrical Field Ablation: Understanding the Benefits and Limitations. Circ Arrhythm Electrophysiol 2021;14(9):e010086. doi:10.1161/CIRCEP.121.010086.
3. Bardy GH, Coltorti F, Stewart RB, Greene HL, Ivey TD. Catheter-mediated electrical ablation: the relation between current and pulse width on voltage breakdown and shock-wave generation. Circ Res 1988;63(2):409-414. doi:10.1161/01.res.63.2.409.
4. Tzeis S, Gerstenfeld EP, Kalman J, et al. 2024 European Heart Rhythm Association/Heart Rhythm Society/Asia Pacific Heart Rhythm Society/Latin American Heart Rhythm Society expert consensus statement on catheter and surgical ablation of atrial fibrillation. Europace 2024;26(4). doi:10.1093/europace/euae043.
5. Chun KJ, Miklavcic D, Vlachos K, et al. State-of-the-art pulsed field ablation for cardiac arrhythmias: ongoing evolution and future perspective. Europace 2024;26(6). doi:10.1093/europace/euae134.
6. Kotnik T, Rems L, Tarek M, Miklavcic D. Membrane Electroporation and Electropermeabilization: Mechanisms and Models. Annu Rev Biophys 2019;48:63-91. doi:10.1146/annurev-biophys-052118-115451.
7. Yarmush ML, Golberg A, Sersa G, Kotnik T, Miklavcic D. Electroporation-based technologies for medicine: principles, applications, and challenges. Annu Rev Biomed Eng 2014;16:295-320. doi:10.1146/annurev-bioeng-071813-104622.
8. Aycock KN, Davalos RV. Irreversible Electroporation: Background, Theory, and Review of Recent Developments in Clinical Oncology. Bioelectricity 2019;1(4):214-234. doi:10.1089/bioe.2019.0029.
9. Breton M, Mir LM. Microsecond and nanosecond electric pulses in cancer treatments. Bioelectromagnetics 2012;33(2):106-123. doi:10.1002/bem.20692.
10. Miklavcic D, Semrov D, Mekid H, Mir LM. A validated model of in vivo electric field distribution in tissues for electrochemotherapy and for DNA electrotransfer for gene therapy. Biochim Biophys Acta 2000;1523(1):73-83. doi:10.1016/s0304-4165(00)00101-x.
11. Kos B, Mattison L, Ramirez D, et al. Determination of lethal electric field threshold for pulsed field ablation in ex vivo perfused porcine and human hearts. Front Cardiovasc Med 2023;10:1160231. doi:10.3389/fcvm.2023.1160231.
12. Neal RE, 2nd, Garcia PA, Kavnoudias H, et al. In vivo irreversible electroporation kidney ablation: experimentally correlated numerical models. IEEE Trans Biomed Eng 2015;62(2):561-569. doi:10.1109/TBME.2014.2360374.
13. Geboers B, Scheffer HJ, Graybill PM, et al. High-Voltage Electrical Pulses in Oncology: Irreversible Electroporation, Electrochemotherapy, Gene Electrotransfer, Electrofusion, and Electroimmunotherapy. Radiology 2020;295(2):254-272. doi:10.1148/radiol.2020192190.

14. Corovic S, Zupanic A, Kranjc S, et al. The influence of skeletal muscle anisotropy on electroporation: in vivo study and numerical modeling. Med Biol Eng Comput 2010;48(7):637-648. doi:10.1007/s11517-010-0614-1.
15. Miklavcic D, Verma A, Krahn PRP, et al. Biophysics and electrophysiology of pulsed field ablation in normal and infarcted porcine cardiac ventricular tissue. Sci Rep 2024;14(1):32063. doi:10.1038/s41598-024-83683-y.
16. Smerc R, Ramirez DA, Mahnic-Kalamiza S, et al. A Multiscale Computational Model of Skeletal Muscle Electroporation Validated Using In Situ Porcine Experiments. IEEE Trans Biomed Eng 2023;70(6):1826-1837. doi:10.1109/TBME.2022.3229560.
17. Koop B. Fundamentals of System Design for Cardiac Pulsed Field Ablation: Optimization of Safety, Efficacy, and Usability. Pacing Clin Electrophysiol 2025. doi:10.1111/pace.15120.
18. Koruth JS, Kuroki K, Iwasawa J, et al. Endocardial ventricular pulsed field ablation: a proof-of-concept preclinical evaluation. EP Europace 2019;22(3):434-439. doi:10.1093/europace/euz341.
19. Mattison L, Verma A, Tarakji KG, et al. Effect of contact force on pulsed field ablation lesions in porcine cardiac tissue. J Cardiovasc Electrophysiol 2023;34(3):693-699. doi:10.1111/jce.15813.
20. Yavin HD, Higuchi K, Sroubek J, Younis A, Zilberman I, Anter E. Pulsed-Field Ablation in Ventricular Myocardium Using a Focal Catheter: The Impact of Application Repetition on Lesion Dimensions. Circ Arrhythm Electrophysiol 2021;14(9):e010375. doi:10.1161/circep.121.010375.
21. Nakagawa H, Castellvi Q, Neal R, et al. Effects of Contact Force on Lesion Size During Pulsed Field Catheter Ablation: Histochemical Characterization of Ventricular Lesion Boundaries. Circ Arrhythm Electrophysiol 2024;17(1):e012026. doi:10.1161/CIRCEP.123.012026.
22. Di Biase L, Marazzato J, Govari A, et al. Pulsed Field Ablation Index-Guided Ablation for Lesion Formation: Impact of Contact Force and Number of Applications in the Ventricular Model. Circ Arrhythm Electrophysiol 2024;17(4):e012717. doi:10.1161/CIRCEP.123.012717.
23. Nakagawa H, Farshchi-Heydari S, Maffre J, et al. Evaluation of Ablation Parameters to Predict Irreversible Lesion Size During Pulsed Field Ablation. Circ Arrhythm Electrophysiol 2024;17(8):e012814. doi:10.1161/CIRCEP.124.012814.
24. Verma A, Neal R, Evans J, et al. Characteristics of pulsed electric field cardiac ablation porcine treatment zones with a focal catheter. J Cardiovasc Electrophysiol 2023;34(1):99-107. doi:10.1111/jce.15734.
25. Reddy VY, Dukkipati SR, Neuzil P, et al. Pulsed Field Ablation of Paroxysmal Atrial Fibrillation: 1-Year Outcomes of IMPULSE, PEFCAT, and PEFCAT II. JACC Clin Electrophysiol 2021;7(5):614-627. doi:10.1016/j.jacep.2021.02.014.
26. Anić A, Phlips T, Brešković T, et al. Pulsed Field Ablation Using Focal Contact Force–Sensing Catheters for Treatment of Atrial Fibrillation: 1-Year Outcomes of the ECLIPSE AF Study. Circulation: Arrhythmia and Electrophysiology 2025;18(1):e012794. doi:doi:10.1161/CIRCEP.124.012794.

27. Reddy VY, Peichl P, Kautzner J, et al. One-year outcomes of a conformable single-shot pulsed-field ablation catheter for the treatment of paroxysmal atrial fibrillation. Heart Rhythm 2025;22(10):2551-2561. doi:10.1016/j.hrthm.2025.04.031.

28. Turagam MK, Neuzil P, Petru J, et al. AF ablation using a novel "single-shot" map-and-ablate spherical array pulsed field ablation catheter: 1-Year outcomes of the first-in-human PULSE-EU trial. Heart rhythm 2024;21(8):1218-1226. doi:10.1016/j.hrthm.2024.04.102.

29. Verma A, Al-Ahmad A, Račkauskas G, et al. Lesion Durability Using a Circular Pulsed Field Ablation Catheter and Novel Mapping-Navigation System. Circulation: Arrhythmia and Electrophysiology 2025;18(12):e014102. doi:doi:10.1161/CIRCEP.125.014102.

30. Tilz RR, Chierchia GB, Gunawardene M, et al. Safety and Effectiveness of the First Balloon-in-Basket Pulsed Field Ablation System for the Treatment of Atrial Fibrillation: VOLT CE Mark Study 6-Month Results. Europace 2025. doi:10.1093/europace/euaf072.

31. Reddy VY, Neužil P, Peichl P, et al. A Lattice-Tip Temperature-Controlled Radiofrequency Ablation Catheter. JACC: Clinical Electrophysiology 2020;6(6):623-635. doi:doi:10.1016/j.jacep.2020.01.002.

32. Sweeney DC, Rebersek M, Dermol J, Rems L, Miklavcic D, Davalos RV. Quantification of cell membrane permeability induced by monopolar and high-frequency bipolar bursts of electrical pulses. Biochim Biophys Acta 2016;1858(11):2689-2698. doi:10.1016/j.bbamem.2016.06.024.

33. Cvetkoska A, Macek-Lebar A, Trdina P, Miklavcic D, Rebersek M. Muscle contractions and pain sensation accompanying high-frequency electroporation pulses. Sci Rep 2022;12(1):8019. doi:10.1038/s41598-022-12112-9.

34. Mahnič-Kalamiza S, Miklavčič D, Lombergar P, et al. Elucidating the mechanisms of microbubble formation in intracardiac pulsed field ablation. Electrochimica Acta 2024;497:144550. doi:https://doi.org/10.1016/j.electacta.2024.144550.

35. Meininger GR, Neal RE, 2nd, Hunter DW, Krimsky WS. Absence of Arrhythmogenicity with Biphasic Pulsed Electric Fields Delivered to Porcine Airways. Ann Biomed Eng 2024;52(1):1-11. doi:10.1007/s10439-023-03190-5.

36. Kumru HT, Mattison L, Tarakji KG, Verma A, Sigg DC. Arrhythmogenicity of monophasic and biphasic PFA waveforms in a porcine model. J Cardiovasc Electrophysiol 2024;35(12):2487-2490. doi:10.1111/jce.16480.

37. Bi S, Jia F, Lv C, et al. Preclinical Study of Biphasic Asymmetric Pulsed Field Ablation. Front Cardiovasc Med 2022;9:859480. doi:10.3389/fcvm.2022.859480.

38. Sano MB, Fan RE, Xing L. Asymmetric Waveforms Decrease Lethal Thresholds in High Frequency Irreversible Electroporation Therapies. Sci Rep 2017;7:40747. doi:10.1038/srep40747.

39. Chen B, Lv C, Cui Y, et al. A pilot clinical assessment of biphasic asymmetric pulsed field ablation catheter for pulmonary vein isolation. Front Cardiovasc Med 2024;11:1266195. doi:10.3389/fcvm.2024.1266195.

40. Anic A, Velagic V, Papiashvili G, et al. Sine wave electroporation in patients with atrial fibrillation: Initial results of the BURST-AF study. Heart Rhythm 2025;22:1946-1956. doi:10.1016/j.hrthm.2025.04.042.

41. Garcia-Sanchez T, Merla C, Fontaine J, Muscat A, Mir LM. Sine wave electropermeabilization reveals the frequency-dependent response of the biological membranes. Biochim Biophys Acta Biomembr 2018;1860(5):1022-1034. doi:10.1016/j.bbamem.2018.01.018.
42. Stewart MT, Haines DE, Miklavcic D, et al. Safety and chronic lesion characterization of pulsed field ablation in a Porcine model. J Cardiovasc Electrophysiol 2021;32(4):958-969. doi:10.1111/jce.14980.
43. Belalcazar A, Heist EK. Comparison of efficiency of PFA catheter designs by computer modeling. J Cardiovasc Electrophysiol 2024;35(12):2382-2393. doi:10.1111/jce.16459.
44. Terricabras M, Lombergar P, Escartin T, et al. Modified Unipolar Return Pulsed Field Ablation in Ventricular Myocardium. Circulation: Arrhythmia and Electrophysiology;0(0):e014006. doi:10.1161/CIRCEP.125.014006.
45. Kim SH, Kang JM, Park Y, Kim Y, Lim B, Park J-H. Effects of bipolar irreversible electroporation with different pulse durations in a prostate cancer mouse model.
46. Pucihar G, Krmelj J, Rebersek M, Napotnik TB, Miklavcic D. Equivalent pulse parameters for electroporation. IEEE Trans Biomed Eng 2011;58(11):3279-3288. doi:10.1109/TBME.2011.2167232.
47. Garcia-Sanchez T, Amoros-Figueras G, Jorge E, et al. Parametric Study of Pulsed Field Ablation With Biphasic Waveforms in an In Vivo Heart Model: The Role of Frequency. Circ Arrhythm Electrophysiol 2022;15(10):e010992. doi:10.1161/CIRCEP.122.010992.
48. Ding L, Zhang A, Sun Y, et al. Nanosecond vs Microsecond Pulsed Field Ablation: Lesion Durability and Muscle Contraction in a Canine Model. JACC Clin Electrophysiol 2025;11(6):1218-1230. doi:10.1016/j.jacep.2025.01.017.
49. Cvetkoska A, Macek-Lebar A, Polajzer T, et al. The Effects of Interphase and Interpulse Delays and Pulse Widths on Induced Muscle Contractions, Pain and Therapeutic Efficacy in Electroporation-Based Therapies. J Cardiovasc Dev Dis 2023;10(12):490. doi:10.3390/jcdd10120490.
50. Sano MB, Arena CB, DeWitt MR, Saur D, Davalos RV. In-vitro bipolar nano- and microsecond electro-pulse bursts for irreversible electroporation therapies. Bioelectrochemistry 2014;100:69-79. doi:10.1016/j.bioelechem.2014.07.010.
51. Garcia-Sanchez T, Leray I, Ronchetti M, Cadossi R, Mir LM. Impact of the number of electric pulses on cell electrochemotherapy in vitro: Limits of linearity and saturation. Bioelectrochemistry 2019;129:218-227. doi:10.1016/j.bioelechem.2019.05.021.
52. Verma A, Zhong P, Castellvi Q, Girouard S, Mediratta V, Neal RE, 2nd. Thermal Profiles for Focal Pulsed Electric Field Ablation. JACC Clin Electrophysiol 2023;9(9):1854-1863. doi:10.1016/j.jacep.2023.05.005.
53. Sauer WH, Campos-Villarreal D, Steiger NA. Irrigation of Pulsed Field Ablation Electrodes Mitigates Joule Heating and the Heat Stacking Phenomena. JACC Clin Electrophysiol 2025;11:1866-1868. doi:10.1016/j.jacep.2025.04.018.
54. Kocharian AA, Murthy MK, Patel A, et al. Luminal Esophageal Temperature Rises With Pulsed Field Ablation. JACC: Clinical Electrophysiology 2025;11(5):1033-1035. doi:doi:10.1016/j.jacep.2025.02.037.
55. Database. M. MAUDE Report ID: D141201. Device: PERCUTANEOUS CARDIAC ABL CATH FOR TREATMT OF AFIB W IRREVERSIBLE ELECTROPORATION. Manufacturer: Biosense

Webster.
https://wwwaccessdatafdagov/scripts/cdrh/cfdocs/cfmaude/detailcfm?mdrfoi__id=21453840&pc=QZI 2025.

56. Zaineb J, Ali M, Majek I. Insights and Applications: Evaluating Edge Effects in Planar Capacitors with Advanced Modeling. Vol 72024.

57. Howard B, Verma A, Tzou WS, et al. Effects of Electrode-Tissue Proximity on Cardiac Lesion Formation Using Pulsed Field Ablation. Circ Arrhythm Electrophysiol 2022;15(10):e011110. doi:10.1161/CIRCEP.122.011110.

58. Younis A, Santangeli P, Garrott K, et al. Impact of Contact Force on Pulsed Field Ablation Outcomes Using Focal Point Catheter. Circ Arrhythm Electrophysiol 2024;17(6):e012723. doi:10.1161/CIRCEP.123.012723.

59. Nies M, Koruth JS, Mlcek M, et al. Is the esophagus spared during pulsed field ablation? Early histopathology and in vivo esophageal retraction. Heart Rhythm 2025. doi:10.1016/j.hrthm.2025.06.033.

60. Pansera F, Bordignon S, Bologna F, et al. Catheter ablation induced phrenic nerve palsy by pulsed field ablation-completely impossible? A case series. Eur Heart J Case Rep 2022;6(9):ytac361. doi:10.1093/ehjcr/ytac361.

61. Franceschi F, Koutbi L, Maille B, Deharo JC. First electromyographic monitoring of a progressive phrenic nerve palsy in a pulsed field ablation procedure. HeartRhythm Case Rep 2024;10(7):447-450. doi:10.1016/j.hrcr.2024.04.004.

62. Howard B, Haines DE, Verma A, et al. Characterization of Phrenic Nerve Response to Pulsed Field Ablation. Circ Arrhythm Electrophysiol 2022;15(6):e010127. doi:10.1161/CIRCEP.121.010127.

63. Chéhirlian L, Koutbi L, Mancini J, et al. High incidence of phrenic nerve injury in patients undergoing pulsed field ablation for atrial fibrillation. Heart Rhythm 2025:e1206-e1213. doi:10.1016/j.hrthm.2025.08.010.

64. Li W, Fan Q, Ji Z, Qiu X, Li Z. The effects of irreversible electroporation (IRE) on nerves. PLoS One 2011;6(4):e18831. doi:10.1371/journal.pone.0018831.

65. Gerstenfeld EP, Mansour M, Whang W, et al. Autonomic Effects of Pulsed Field vs Thermal Ablation for Treating Atrial Fibrillation: Subanalysis of ADVENT. JACC Clin Electrophysiol 2024;10(7 Pt 2):1634-1644. doi:10.1016/j.jacep.2024.05.005.

66. Kumar A, Shariff M, Pachon JC, et al. A comparative meta-analysis of addition of ganglionic plexus ablation versus no ganglionic plexus ablation to pulmonary vein isolation for atrial fibrillation. J Interv Card Electrophysiol 2025;68(2):347-350. doi:10.1007/s10840-024-01945-1.

67. Hertel JN, Nissen SD, Lindberg LA, et al. Targeted epicardial pulsed field ablation of atrial ganglionated plexi: Electrophysiological and histologic analysis in pigs. Heart Rhythm 2025;22:3289-3299. doi:10.1016/j.hrthm.2025.06.016.

68. Musikantow DR, Reddy VY, Shaburishvili T, et al. Epicardial Pulsed Field Ablation for the Treatment of Paroxysmal Atrial Fibrillation During Cardiac Surgery. JACC Clin Electrophysiol 2024;10(9):2097-2099. doi:10.1016/j.jacep.2024.06.012.

69. Lo M, Gambhir A, Sundaram S, et al. Safety and effectiveness of a novel balloon-in-basket pulsed-field ablation catheter for the treatment of paroxysmal and persistent AF:

Volt-AF IDE trial acute results. Heart Rhythm 2025;22:2524-2533. doi:10.1016/j.hrthm.2025.04.037.

70. Verma A, Haines DE, Boersma LV, et al. Pulsed Field Ablation for the Treatment of Atrial Fibrillation: PULSED AF Pivotal Trial. Circulation 2023;147(19):1422-1432. doi:10.1161/CIRCULATIONAHA.123.063988.

71. Reddy VY, Calkins H, Mansour M, et al. Pulsed Field Ablation to Treat Paroxysmal Atrial Fibrillation: Safety and Effectiveness in the AdmIRE Pivotal Trial. Circulation 2024;150(15):1174-1186. doi:10.1161/CIRCULATIONAHA.124.070333.

72. Duytschaever M, De Potter T, Grimaldi M, et al. Paroxysmal Atrial Fibrillation Ablation Using a Novel Variable-Loop Biphasic Pulsed Field Ablation Catheter Integrated With a 3-Dimensional Mapping System: 1-Year Outcomes of the Multicenter inspIRE Study. Circ Arrhythm Electrophysiol 2023;16(3):e011780. doi:10.1161/CIRCEP.122.011780.

73. Anić A, Phlips T, Brešković T, et al. Pulsed field ablation using focal contact force-sensing catheters for treatment of atrial fibrillation: acute and 90-day invasive remapping results. Europace 2023;25(6):euad147. doi:10.1093/europace/euad147.

74. Reddy VY, Gerstenfeld EP, Schmidt B, et al. Pulsed Field Ablation of Persistent Atrial Fibrillation With Continuous Electrocardiographic Monitoring Follow-Up: ADVANTAGE AF Phase 2. Circulation 2025;152(1):27-40. doi:10.1161/CIRCULATIONAHA.125.074485.

75. Reddy VY, Gerstenfeld EP, Schmidt B, et al. Pulsed Field Ablation for Persistent Atrial Fibrillation: 1-Year Results of ADVANTAGE AF. JACC 2025;85(17):1664-1678. doi:10.1016/j.jacc.2025.03.515.

76. De Potter T, Scherr D, Purerfellner H, et al. Dual energy for pulmonary vein isolation using focal ablation technology integrated with a three-dimensional mapping system: SmartfIRE 12-month results. Europace 2025;27(9). doi:10.1093/europace/euaf174.

77. Isenegger C, Arnet R, Jordan F, et al. Pulsed-field ablation versus cryoballoon ablation in patients with persistent atrial fibrillation. Int J Cardiol Heart Vasc 2025;59:101684-101684. doi:10.1016/j.ijcha.2025.101684.

78. Urbanek L, Bordignon S, Schaack D, et al. Pulsed Field Versus Cryoballoon Pulmonary Vein Isolation for Atrial Fibrillation: Efficacy, Safety, and Long-Term Follow-Up in a 400-Patient Cohort. Circ Arrhythm Electrophysiol 2023;16(7):389-398. doi:10.1161/CIRCEP.123.011920.

79. Schipper JH, Steven D, Luker J, et al. Comparison of pulsed field ablation and cryoballoon ablation for pulmonary vein isolation. J Cardiovasc Electrophysiol 2023;34(10):2019-2026. doi:10.1111/jce.16056.

80. Badertscher P, Weidlich S, Knecht S, et al. Efficacy and safety of pulmonary vein isolation with pulsed field ablation vs. novel cryoballoon ablation system for atrial fibrillation. Europace 2023;25(12):euad329. doi:10.1093/europace/euad329.

81. Chaumont C, Hayoun C, Savoure A, et al. Pentaspline Pulsed Field Ablation Catheter Versus Cryoballoon for Atrial Fibrillation Ablation: Results From a Prospective Comparative Study. J Am Heart Assoc 2024;13(6):e033146. doi:10.1161/JAHA.123.033146.

82. Anter E, Mansour M, Nair DG, et al. Dual-energy lattice-tip ablation system for persistent atrial fibrillation: a randomized trial. Nat Med 2024;30:2303-2310. doi:10.1038/s41591-024-03022-6.

83. Reddy VY, Gerstenfeld EP, Natale A, et al. Pulsed Field or Conventional Thermal Ablation for Paroxysmal Atrial Fibrillation. New Engl J Med 2023;389(18):1660-1671.

84. Reichlin T, Kueffer T, Badertscher P, et al. Pulsed Field or Cryoballoon Ablation for Paroxysmal Atrial Fibrillation. New Engl J Med 2025;392(15):1497-1507. doi:10.1056/NEJMoa2502280.

85. Cho MS, Lee S-R, Black-Maier E, et al. Complications associated with pulsed field ablation vs radiofrequency catheter ablation of atrial fibrillation. Heart Rhythm 2024;22:2194-2200. doi:10.1016/j.hrthm.2024.10.063.

86. Ekanem E, Neuzil P, Reichlin T, et al. Safety of pulsed field ablation in more than 17,000 patients with atrial fibrillation in the MANIFEST-17K study. Nat Med 2024;30(7):2020-2029. doi:10.1038/s41591-024-03114-3.

87. Castellucci G, D'angelo L, Cipolletta L, et al. Pulsed-field ablation of atrial fibrillation in elderly and frail patients: procedural efficacy and safety from a single-center experience. EP Europace 2024;26(Supplement_1):euae102.760. doi:10.1093/europace/euae102.760.

88. Turagam MK, Neuzil P, Schmidt B, et al. Safety and Effectiveness of Pulsed Field Ablation for Atrial Fibrillation in Patients With Heart Failure. JACC Clin Electrophysiol 2024. doi:10.1016/j.jacep.2024.05.002.

89. Davong B, Adeliño R, Delasnerie H, et al. Pulsed-Field Ablation on Mitral Isthmus in Persistent Atrial Fibrillation: Preliminary Data on Efficacy and Safety. JACC Clin Electrophysiol 2023;9(7 Pt 2):1070-1081. doi:10.1016/j.jacep.2023.03.021.

90. Gunawardene MA, Harloff T, Jularic M, et al. Contemporary catheter ablation of complex atrial tachycardias after prior atrial fibrillation ablation: pulsed field vs. radiofrequency current energy ablation guided by high-density mapping. Europace 2024;26(4):euae072. doi:10.1093/europace/euae072.

91. Weyand S, Adam V, Biehler P, et al. One-year outcomes of focal pulsed-field ablation for redo procedures in atrial fibrillation and atypical flutter. J Interv Card Electrophysiol 2025;68:1625-1636. doi:10.1007/s10840-025-02079-8.

92. Tam MTK, Chan JYS, Chan CP, et al. Effect of Pulsed-Field Ablation on Human Coronary Arteries: A Longitudinal Study With Intracoronary Imaging. JACC Clin Electrophysiol 2025. doi:10.1016/j.jacep.2025.03.014.

93. Rodriguez-Riascos JF, Vemulapalli HS, Muthu P, et al. Safety and Efficacy of Pulsed Field Ablation for Cavotricuspid Isthmus-Dependent Flutter: A Systematic Literature Review. J Cardiovasc Electrophysiol 2025;35:2013-2024. doi:10.1111/jce.16719.

94. Gunawardene MA, Schaeffer BN, Jularic M, et al. Coronary Spasm During Pulsed Field Ablation of the Mitral Isthmus Line. JACC Clin Electrophysiol 2021;7:1618-1620. doi:10.1016/j.jacep.2021.08.016.

95. Reddy VY, Neuzil P, Koruth JS, et al. Pulsed Field Ablation for Pulmonary Vein Isolation in Atrial Fibrillation. J Am Coll Cardiol 2019;74(3):315-326. doi:10.1016/j.jacc.2019.04.021.

96. Schmidt B, Bordignon S, Neven K, et al. EUropean real-world outcomes with Pulsed field ablatiOn in patients with symptomatic atRIAl fibrillation : lessons from the multi-centre EU-PORIA registry. Europace 2023;25(7):1-11. doi:10.1093/europace/euad185.

97. Ekanem E, Reddy VY, Schmidt B, et al. Multi-national survey on the methods, efficacy , and safety on the post-approval clinical use of pulsed field ablation (MANIFEST-PF). Europace 2022;24:1256-1266.

98. Schmidt B, Bordignon S, Tohoku S, Chen S, Bologna F. 5S Study : Safe and Simple Single Shot Pulmonary Vein Isolation With Pulsed Field Ablation Using Sedation. Circ Arrhythm Electrophysiol 2022:15:e010817. doi:10.1161/CIRCEP.121.010817.

99. Rillig A, Hirokami J, Moser F, et al. General anaesthesia and deep sedation for monopolar pulsed field ablation using a lattice-tip catheter combined with a novel three-dimensional mapping system. Europace 2024;26(11):euae270. doi:10.1093/europace/euae270.

100. Wahedi R, Willems S, Feldhege J, et al. Pulsed-field versus cryoballoon ablation for atrial fibrillation-Impact of energy source on sedation and analgesia requirement. J Cardiovasc Electrophysiol 2024;35(1):162-170. doi:10.1111/jce.16141.

101. Grimaldi M, Quadrini F, Caporusso N, et al. Deep sedation protocol during atrial fibrillation ablation using a novel variable-loop biphasic pulsed field ablation catheter. Aug. doi:10.1093/europace/euad222

102. Iacopino S, Colella J, Dini D, et al. Sedation strategies for pulsed-field ablation of atrial fibrillation: focus on deep sedation with intravenous ketamine in spontaneous respiration. doi:10.1093/europace/euad230

103. Sochorová V, Kunštátová V, OsmanČík P, et al. COnventional vs. Optimized PERiprocedural Analgosedation vs. Total IntraVEnous Anesthesia for Pulsed-Field Ablation: a Three-Arm Randomized Controlled Trial (COOPERATIVE-PFA). Circulation 2025. doi:10.1161/CIRCULATIONAHA.125.074427.

104. Wang Z, Jia L, Shi T, Liu C. General anesthesia is not superior to sedation in clinical outcome and cost-effectiveness for ablation of persistent atrial fibrillation. Clin Cardiol 2021;44(2):218-221. doi:10.1002/clc.23528.

105. Lee L-Y. Respiratory sensations evoked by activation of bronchopulmonary C-fibers. May. doi:10.1016/j.resp.2008.05.006

106. Anand A. Low activation threshold of juxtapulmonary capillary (J) receptors of the lung. Respir Physiol Neurobiol 2019;266:66-72. doi:10.1016/j.resp.2019.05.003.

107. Vetta G, Della Rocca DG, Magnocavallo M, et al. Efficacy and Drug-Related Complications of Anticholinergic Drugs for Vagal Reaction Prevention During Pulsed Field Ablation. JACC Clin Electrophysiol 2025;11:1757-1768. doi:10.1016/j.jacep.2025.04.015.

108. Del Monte A, Della Rocca DG, Pannone L, et al. Pulsed field ablation of the right superior pulmonary vein prevents vagal responses via anterior right ganglionated plexus modulation. Heart Rhythm 2024;21(6):780-787. doi:10.1016/j.hrthm.2024.01.040.

109. Silberbauer J, Bulava A, Sanders P, et al. AB-514135-003 INITIAL CLINICAL EXPERIENCE WITH THE TACTIFLEX DUO SYSTEM: SAFETY AND ACUTE RESULTS OF THE FOCALFLEX STUDY. Heart Rhythm 2025;22(4, Supplement):S810-S811. doi:https://doi.org/10.1016/j.hrthm.2025.03.1931.

110. Tilz RR, Wenzel J-P, Eitel C, et al. "Awake and ablated": first experience with a balloon-in-basket PFA system without propofol. Heart Rhythm O2 2025. doi:10.1016/j.hroo.2025.11.011.

111. Reddy VY, Peichl P, Anter E, et al. A Focal Ablation Catheter Toggling Between Radiofrequency and Pulsed Field Energy to Treat Atrial Fibrillation. JACC Clin Electrophysiol 2023;9(8 Pt 3):1786-1801. doi:10.1016/j.jacep.2023.04.002.

112. Verma A, Al-Ahmad A, Rackauskas G, et al. Lesion durability using a circular pulsed field ablation catheter and novel mapping-navigation system. Circ Arrhythm Electrophysiol 2025 (in press):16:e014102.

113. Scherr D, Turagam MK, Maury P, et al. Repeat Procedures After Pulsed Field Ablation for Atrial Fibrillation: MANIFEST-REDO Study. Europace 2025;27:euaf012. doi:10.1093/europace/euaf012.

114. Schaack D, Urbanek L, Bordignon S, et al. The Olive Strategy: Improved Pulmonary Vein Isolation Durability With the Pentaspline Pulsed Field Catheter. JACC Clin Electrophysiol 2025;11:1555-1568. doi:10.1016/j.jacep.2025.02.026.

115. Gunawardene MA, Hartmann J, Dickow J, et al. Pulsed field ablation using a circular electrode array catheter in patients with atrial fibrillation: A workflow optimization study evaluating the role of mapping. Int J Cardiol Heart Vasc 2025;58:101674-101674. doi:10.1016/j.ijcha.2025.101674.

116. De Potter T, Grimaldi M, Duytschaever M, et al. Predictors of Success for Pulmonary Vein Isolation With Pulsed-Field Ablation Using a Variable-Loop Catheter With 3D Mapping Integration: Complete 12-Month Outcomes From inspIRE. Circ Arrhythm Electrophysiol 2024;17:e012667-e012667. doi:10.1161/CIRCEP.123.012667.

117. Reddy VY, Anter E, Peichl P, et al. First-in-human clinical series of a novel conformable large-lattice pulsed field ablation catheter for pulmonary vein isolation. Europace 2024;26(4). doi:10.1093/europace/euae090.

118. Yavin H, Shapira-Daniels A, Barkagan M, et al. Pulsed Field Ablation Using a Lattice Electrode for Focal Energy Delivery: Biophysical Characterization, Lesion Durability, and Safety Evaluation. Circ Arrhythm Electrophysiol 2020;13(6):e008580. doi:10.1161/CIRCEP.120.008580.

119. Ollitrault P, Chaumont C, Font J, et al. Superior vena cava isolation using a pentaspline pulsed-field ablation catheter: feasibility and safety in patients undergoing atrial fibrillation catheter ablation. Europace 2024;26(7):euae160. doi:10.1093/europace/euae160.

120. Pierucci N, La Fazia VM, Mohanty S, et al. Results of ICE-Guided Isolation of the Superior Vena Cava With Pulsed Field Ablation. JACC Clin Electrophysiol 2025;11(4):752-760. doi:10.1016/j.jacep.2024.11.009.

121. Chen S, Schaack D, Hirokami J, Schmidt B, Chun JKR. Pulsed field ablation of incessant superior vena cava-triggered atrial fibrillation: watch out for the sinoatrial node. J Interv Card Electrophysiol 2023;66(7):1759-1763. doi:10.1007/s10840-023-01624-7.

122. Ellejmi MA, Sorgente A, Della Rocca DG, et al. Superior vena cava isolation using a multielectrode pulsed field ablation catheter. Journal of interventional cardiac electrophysiology : an international journal of arrhythmias and pacing 2023;66(6):1323-1324. doi:10.1007/s10840-023-01565-1.

123. Tsiachris D, Doundoulakis I, Kordalis A, Antoniou C-K, Tsioufis K. Superior vena cava isolation with pulsed field ablation in the presence of defibrillator leads. J Arrhythm 2023;39(3):483-485. doi:10.1002/joa3.12848.

124. Tohoku S, Chun KRJ, Bordignon S, et al. Findings from repeat ablation using high-density mapping after pulmonary vein isolation with pulsed fi eld ablation. Europace 2022;00:1-8.

125. Bohnen M, Weber R, Minners J, et al. Characterization of circumferential antral pulmonary vein isolation areas resulting from pulsed-field catheter ablation. Europace 2023;25(1):65-73. doi:10.1093/europace/euac111.

126. Gunawardene MA, Frommeyer G, Ellermann C, et al. Left Atrial Posterior Wall Isolation with Pulsed Field Ablation in Persistent Atrial Fibrillation. J Clin Med 2023;12(19):6304-6304. doi:10.3390/jcm12196304.

127. Koruth JS, Kuroki K, Kawamura I, et al. Pulsed Field Ablation Versus Radiofrequency Ablation: Esophageal Injury in a Novel Porcine Model. Circ Arrhythm Electrophysiol 2020(March):13(13):e008303-008313(008303):e008303. doi:10.1161/CIRCEP.119.008303.

128. Cochet H, Nakatani Y, Sridi-Cheniti S, et al. Pulsed field ablation selectively spares the oesophagus during pulmonary vein isolation for atrial fibrillation. EP Europace 2021;23(9):1391-1399. doi:10.1093/europace/euab090.

129. Reddy VY, Anic A, Koruth J, et al. Pulsed Field Ablation in Patients With Persistent Atrial Fibrillation. JACC 2020;76(9):1068-1080. doi:10.1016/j.jacc.2020.07.007.

130. Gunawardene MA, Middeldorp M, Pape UF, et al. Esophageal endoscopic findings after pulmonary vein and posterior wall isolation using pulsed field ablation - Results from the Eso-PFA study. Europace 2025;27:euaf133. doi:10.1093/europace/euaf133.

131. Kueffer T, Tanner H, Madaffari A, et al. Posterior wall ablation by pulsed-field ablation: procedural safety, efficacy, and findings on redo procedures. Europace 2023;26(1). doi:10.1093/europace/euae006.

132. Schiavone M, Solimene F, Moltrasio M, et al. Pulsed field ablation technology for pulmonary vein and left atrial posterior wall isolation in patients with persistent atrial fibrillation. J Cardiovasc Electrophysiol 2024;35(6):1101-1111. doi:10.1111/jce.16246.

133. Pranata R, Kamarullah W, Karwiky G, Achmad C, Iqbal M. Left atrial posterior wall isolation in addition to pulmonary vein isolation using a pentaspline catheter in pulsed-field ablation for atrial fibrillation: A systematic review and meta-analysis. Heart Rhythm O2 2024;5(10):720-727. doi:10.1016/j.hroo.2024.08.006.

134. Hirokami J, Chun KRJ, Bordignon S, et al. Pulsed-Field Ablation for Persistent Atrial Fibrillation in EU-PORIA Registry. J Cardiovasc Electrophysiol 2025;36:1710-1720. doi:10.1111/jce.16583.

135. Kistler PM, Chieng D, Sugumar H, et al. Effect of Catheter Ablation Using Pulmonary Vein Isolation With vs Without Posterior Left Atrial Wall Isolation on Atrial Arrhythmia Recurrence in Patients With Persistent Atrial Fibrillation: The CAPLA Randomized Clinical Trial. JAMA 2023;329(2):127-135. doi:10.1001/jama.2022.23722.

136. Ruwald MH, Johannessen A, Hansen ML, Worck R, Hansen J. Pulsed field ablation of the cavotricuspid isthmus using a multispline-electrode pulsed field ablation catheter. HeartRhythm Case Reports 2022;8(3):147-150. doi:10.1016/j.hrcr.2021.12.009.

137. Chaumont C, Ollitrault P, Savoure A, et al. Cavotricuspid isthmus ablation using a pentaspline pulsed field ablation catheter: feasibility and acute results. Europace 2024;26(10). doi:10.1093/europace/euae262.

138. Farnir FIP, Chaldoupi S-M, Hermans B, et al. Ablation of cavo-tricuspid isthmus dependent atrial flutter using a focal monopolar pulsed-field ablation catheter: Feasibility, periprocedural coronary spasms and conduction disorders. Heart Rhythm 2026;23:105-113. doi:10.1016/j.hrthm.2025.07.001.

139. Andrikopoulos G, Tampakis K, Sykiotis A, Pastromas S. Transient conduction disturbances acutely after pulsed-field cavotricuspid isthmus ablation: a case report. Eur Heart J Case Rep 2023;7(8):ytad370-ytad370. doi:10.1093/ehjcr/ytad370.

140. Saleem M, Oates CP, Banai A, et al. PO-04-003 DURABILITY OF CAVOTRICUSPID ISTHMUS ABLATION WITH PULSE FIELD ABLATION USING THE PENTASPLINE CATHETER. Heart Rhythm 2025;22(4):S440. doi:10.1016/j.hrthm.2025.03.1138.

141. Demian J, Younis A, Wazni OM, et al. Pulsed-Field Ablation of Atrial Flutter: Insights From a Large Volume U.S. Center. JACC Clin Electrophysiol 2025:11L2394-2403. doi:10.1016/j.jacep.2025.06.036.

142. Reddy VY. Coronary Arterial Spasm During Pulsed Field Ablation to Treat Atrial Fibrillation. Circulation 2022;146:1808-1819. doi:10.1161/CIRCULATIONAHA.122.061497.

143. Malyshev Y, Neuzil P, Petru J, et al. Does Acute Coronary Spasm From Pulsed Field Ablation Translate Into Chronic Coronary Arterial Lesions? JACC Clin Electrophysiol 2024;10(5):970-972.

144. Menè R, Boveda S, Della Rocca DG, et al. Efficacy of Intravenous Nitrates for the Prevention of Coronary Artery Spasm During Pulsed Field Ablation of the Mitral Isthmus. Circ Arrhythm Electrophysiol 2024;17(1):e012426. doi:10.1161/CIRCEP.123.012426.

145. Kueffer T, Seiler J, Madaffari A, et al. Pulsed-field ablation for the treatment of left atrial reentry tachycardia. J Interv Card Electrophysiol 2023;66(6):1431-1440. doi:10.1007/s10840-022-01436-1.

146. Malyshev Y, Neuzil P, Petru J, et al. Nitroglycerin to Ameliorate Coronary Artery Spasm During Focal Pulsed-Field Ablation for Atrial Fibrillation. JACC Clin Electrophysiol 2024;10(5):885-896. doi:10.1016/j.jacep.2023.12.015.

147. Gunawardene MA, Hartmann J, Tigges E, Jezuit J, Willems S. Word of caution: clinically apparent coronary spasm following pulsed field cavotricuspid isthmus ablation despite nitroglycerin prophylaxis - a case report. Eur Heart J Case Rep 2024;8(11):ytae553. doi:10.1093/ehjcr/ytae553.

148. Reddy VY, Petru J, Funasako M, et al. Coronary Arterial Spasm During Pulsed Field Ablation to Treat Atrial Fibrillation. Circulation 2022;146(24):1808-1819. doi:10.1161/CIRCULATIONAHA.122.061497.

149. La Fazia VM, Mohanty S, Gianni C, et al. Feasibility and Safety of Pulsed Field Ablation for Coronary Sinus and Left Atrial Appendage Isolation and Mitral Isthmus Ablation: Acute and Chronic Findings. Circ Arrhythm Electrophysiol 2025:e014026. doi:10.1161/CIRCEP.125.014026.

150. Zhang C, Neuzil P, Petru J, et al. Coronary Artery Spasm During Pulsed Field vs Radiofrequency Catheter Ablation of the Mitral Isthmus. JAMA Cardiology 2024;9(1):72-77. doi:10.1001/jamacardio.2023.4405.

151. Verma A, Maffre J, Sharma T, Farshchi-Heydari S. Effect of Sequential, Colocalized Radiofrequency and Pulsed Field Ablation on Cardiac Lesion Size and Histology. Circ Arrhythm Electrophysiol 2025;18(2):e013143. doi:10.1161/CIRCEP.124.013143.

152. Turagam MK, Neuzil P, Schmidt B, et al. Impact of Left Atrial Posterior Wall Ablation During Pulsed-Field Ablation for Persistent Atrial Fibrillation. JACC Clin Electrophysiol 2024;10(5):900-912. doi:10.1016/j.jacep.2024.01.017.

153. Mills MT, Calvert P, Phenton C, et al. An approach to electroanatomical mapping with a pentaspline pulsed field catheter to guide atrial fibrillation ablation. J Interv Card Electrophysiol 2025;68:921-931. doi:10.1007/s10840-025-01980-6.

154. Sanders P, Healy S, Emami M, Kotschet E, Miller A, Kalman JM. Initial Clinical Experience with the Balloon-in-Basket Pulsed Field Ablation System: Acute Results of the VOLT CE Mark Feasibility Study. Europace 2024;26:euae118. doi:10.1093/europace/euae118.

155. Badertscher P, Serban T, Isenegger C, et al. Role of 3D electro-anatomical mapping on procedural characteristics and outcomes in pulsed-field ablation for atrial fibrillation. EP Europace 2024;26(4):euae075. doi:10.1093/europace/euae075.

156. Gunawardene MA, Schaeffer BN, Jularic M, et al. Pulsed - field ablation combined with ultrahigh - density mapping in patients undergoing catheter ablation for atrial fibrillation : Practical and electrophysiological considerations. J Cardiovasc Electrophysiol 2022;33(3):345-356. doi:10.1111/jce.15349.

157. Kueffer T, Bordignon S, Neven K, et al. Durability of Pulmonary Vein Isolation Using Pulsed-Field Ablation: Results From the Multicenter EU-PORIA Registry. JACC Clin Electrophysiol 2024;10(4):698-708. doi:10.1016/j.jacep.2023.11.026.

158. Huo Y, Christoph M, Forkmann M, et al. Reduction of radiation exposure during atrial fibrillation ablation using a novel fluoroscopy image integrated 3-dimensional electroanatomic mapping system: A prospective, randomized, single-blind, and controlled study. Heart rhythm 2015;12(9):1945-1955. doi:10.1016/j.hrthm.2015.05.018.

159. Sommer P, Bertagnolli L, Kircher S, et al. Safety profile of near-zero fluoroscopy atrial fibrillation ablation with non-fluoroscopic catheter visualization: experience from 1000 consecutive procedures. Europace 2018;20(12):1952-1958. doi:10.1093/europace/eux378.

160. Voskoboinik A, Kalman ES, Savicky Y, et al. Reduction in radiation dose for atrial fibrillation ablation over time: A 12-year single-center experience of 2344 patients. Heart rhythm 2017;14(6):810-816. doi:10.1016/j.hrthm.2017.02.014.

161. Kueffer T, King R, Maurhofer J, et al. Beyond the learning curve: How operator experience affects pulsed-field ablation outcomes. Heart Rhythm 2025. doi:10.1016/j.hrthm.2025.08.045.

162. Mills MT, Sommer P, Day J, et al. Characterization of acute residual pulmonary vein connections using electroanatomic mapping during pulsed-field ablation of atrial fibrillation. Heart Rhythm 2025. doi:10.1016/j.hrthm.2025.06.037.

163. Koruth JS, Neuzil P, Kawamura I, et al. Reversible Pulsed Electrical Fields as an In Vivo Tool to Study Cardiac Electrophysiology: The Advent of Pulsed Field Mapping. Circ Arrhythm Electrophysiol 2023;16(10):e012018. doi:10.1161/CIRCEP.123.012018.

164. Cespon-Fernandez M, Pannone L, Sieira J, et al. Feasibility of reversible electroporation mapping in human atrial flutter. Heart Rhythm 2025. doi:10.1016/j.hrthm.2025.04.021.

165. Gunawardene M, Münkler P, Eickholt C, et al. A novel assessment of local impedance during catheter ablation: Initial experience in humans comparing local and generator measurements. Europace 2019;21:I34-I42. doi:10.1093/europace/euy273.

166. Tonko JB, Silberbauer J, Lambiase PD. Peak frequency analysis for epicardial contact mapping: How (in)frequent is epicardial adipose tissue? Heart rhythm 2024;21(10):1898-1899. doi:10.1016/j.hrthm.2024.04.095.

167. Zheng X, Walcott GP, Hall JA, et al. Electrode impedance: An indicator of electrode-tissue contact and lesion dimensions during linear ablation. J Interv Card Electrophysiol 2000;4(4):645-654. doi:10.1023/A:1026586119600.

168. Ikeda A, Nakagawa H, Lambert H, et al. Relationship between catheter contact force and radiofrequency lesion size and incidence of steam pop in the beating canine heart: Electrogram amplitude, impedance, and electrode temperature are poor predictors of electrode-tissue contact force and lesion. Circ Arrhythm Electrophysiol 2014;7(6):1174-1180. doi:10.1161/CIRCEP.113.001094.

169. Groen MHA, Fish JM, Loh P, van Es R. Impact of electrode-tissue proximity on formation of pulsed field ablation lesions: Using multi-electrode impedance measurements. Heart Rhythm O2 2025;6. doi:10.1016/j.hroo.2025.05.026.

170. Doshi SK, Flaherty MC, Laughner J, Quan M, Anic A. Catheter-tissue contact optimizes pulsed electric field ablation with a large area focal catheter. J Cardiovasc Electrophysiol 2024;35(4):765-774. doi:10.1111/jce.16208.

171. Okumura Y, Watanabe R, Nagashima K, et al. In vivo assessment of catheter-tissue contact using tissue proximity indication and its impact on cardiac lesion formation in pulsed field ablation. Heart Rhythm 2025;22(4):952-960. doi:10.1016/j.hrthm.2024.09.061.

172. Saito Y, Nagashima K, Watanabe R, et al. Clinical importance of tissue proximity indication during pulsed field ablation for atrial fibrillation: Insights from initial experience. Heart Rhythm 2025;22(7):e51-e59. doi:https://doi.org/10.1016/j.hrthm.2025.01.022.

173. Kuck K-H, Reddy VY, Schmidt B, et al. A novel radiofrequency ablation catheter using contact force sensing: Toccata study. Heart Rhythm 2012;9(1):18-23. doi:10.1016/j.hrthm.2011.08.021.

174. Nies M, Koruth JS, Mlček M, et al. Hemolysis After Pulsed Field Ablation: Impact of Lesion Number and Catheter-Tissue Contact. doi:10.1161/CIRCEP.124.012765

175. Mattison L, Verma A, Tarakji KG, Sigg DC. Hemolysis After Pulsed Field Ablation: The Role of Dose and Contact in an Acute Porcine Model. Circ Arrhythm Electrophysiol 2024;17(12):e013317. doi:10.1161/CIRCEP.124.013317.

176. Turagam MK, Neuzil P, Petru J, et al. PV Isolation Using a Spherical Array PFA Catheter: Application Repetition and Lesion Durability (PULSE-EU Study). JACC Clin Electrophysiol 2023;9(5):638-648. doi:10.1016/j.jacep.2023.01.009.

177. Kottkamp H, Moser F, Rieger A, Schreiber D, Pönisch C, Trofin M. Global multielectrode contact mapping plus ablation with a single catheter: Preclinical and preliminary

experience in humans with atrial fibrillation. J Cardiovasc Electrophysiol 2017;28(11):1247-1256. doi:10.1111/jce.13310.

178. Tohoku S, Bordignon S, Bologna F, et al. Laser balloon in pulmonary vein isolation for atrial fibrillation: current status and future prospects. Expert Rev Med Devices 2021;18(11):1083-1091. doi:10.1080/17434440.2021.1990754.

179. Dello Russo A, Tondo C, Schillaci V, et al. Intracardiac echocardiography-guided pulsed-field ablation for successful ablation of atrial fibrillation: a propensity-matched analysis from a large nationwide multicenter experience. J Interv Card Electrophysiol 2023;67:1257-1266. doi:10.1007/s10840-023-01699-2.

180. Jackson LR, 2nd, Holmqvist F, Parish A, Green CL, Piccini JP, Bahnson TD. Safety of continuous left atrial phased-array intracardiac echocardiography during left atrial ablation for atrial fibrillation. Heart rhythm O2 2022;3(6Part A):673-680. doi:10.1016/j.hroo.2022.08.001.

181. Mohanty S, Casella M, Doty B, et al. Ensuring catheter-tissue contact with intra-cardiac echocardiography during pulsed-field ablation improves procedure outcome in patients with atrial fibrillation. Heart rhythm 2025;22:e875-e881. doi:10.1016/j.hrthm.2025.05.045.

182. Hirata S, Nagashima K, Watanabe R, et al. Workflow of the zero-fluoro pulsed field ablation. J Arrhythm 2024;40(6):1529-1532. doi:10.1002/joa3.13174.

183. Jiang R, Chen M, Yang B, et al. Intraprocedural endpoints to predict durable pulmonary vein isolation: a randomized trial of four post-ablation techniques. Europace 2020;22(4):567-575. doi:10.1093/europace/euz301.

184. McLellan AJA, Kumar S, Smith C, Morton JB, Kalman JM, Kistler PM. The Role of Adenosine Following Pulmonary Vein Isolation in Patients Undergoing Catheter Ablation for Atrial Fibrillation : A Systematic Review. J Cardiovasc Electrophysiol 2013;24(February):742-751. doi:10.1111/jce.12121.

185. Elayi CS, Di Biase L, Bai R, et al. Administration of isoproterenol and adenosine to guide supplemental ablation after pulmonary vein antrum isolation. J Cardiovasc Electrophysiol 2013;24(11):1199-1206. doi:10.1111/jce.12252.

186. Sakamoto Y, Osanai H, Hiramatsu S, et al. Efficacy of isoproterenol in the evaluation of dormant conduction and arrhythmogenic foci identification in atrial fibrillation ablation. BMC Cardiovascular Disorders 2020;20(1):397-397. doi:10.1186/s12872-020-01685-w.

187. Datino T, Macle L, Qi XY, et al. Mechanisms by which adenosine restores conduction in dormant canine pulmonary veins. Circulation 2010;121(8):963-972. doi:10.1161/CIRCULATIONAHA.109.893107.

188. Fiserova I, Fiser O, Novak M, et al. Significant hemolysis is present during irreversible electroporation of cardiomyocytes in vitro. Heart Rhythm 2025;22(2):466-474. doi:https://doi.org/10.1016/j.hrthm.2024.08.019.

189. Rother RP, Bell L, Hillmen P, Gladwin MT. The clinical sequelae of intravascular hemolysis and extracellular plasma hemoglobin: a novel mechanism of human disease. Jama 2005;293(13):1653-1662. doi:10.1001/jama.293.13.1653.

190. Lakkireddy D, Katapadi A, Garg J, et al. NEMESIS-PFA: Investigating Collateral Tissue Injury Associated With Pulsed Field Ablation. JACC Clin Electrophysiol 2025;11:1747-1756. doi:10.1016/j.jacep.2025.04.017.

191. Venier S, Vaxelaire N, Jacon P, et al. Severe acute kidney injury related to haemolysis after pulsed field ablation for atrial fibrillation. Europace 2023;26(1). doi:10.1093/europace/euad371.

192. Mohanty S, Casella M, Compagnucci P, et al. Acute Kidney Injury Resulting From Hemoglobinuria After Pulsed-Field Ablation in Atrial Fibrillation: Is it Preventable? JACC Clin Electrophysiol 2024;10(4):709-715. doi:10.1016/j.jacep.2023.12.008.

193. Dimitrov JD, Roumenina LT, Perrella G, Rayes J. Basic Mechanisms of Hemolysis-Associated Thrombo-Inflammation and Immune Dysregulation. Arterioscler Thromb Vasc Biol 2023;43(8):1349-1361. doi:10.1161/ATVBAHA.123.318780.

194. Dvanajscak Z, Walker PD, Cossey LN, et al. Hemolysis-associated hemoglobin cast nephropathy results from a range of clinicopathologic disorders. Kidney Int 2019;96(6):1400-1407. doi:https://doi.org/10.1016/j.kint.2019.08.026.

195. Osmancik P, Bacova B, Herman D, et al. Periprocedural Intravascular Hemolysis During Atrial Fibrillation Ablation: A Comparison of Pulsed Field With Radiofrequency Ablation. JACC Clin Electrophysiol 2024;10(7):1660-1671.

196. Venier S, Vaxelaire N, Desbiolles A, et al. Severe acute kidney injury related to haemolysis after pulsed field ablation for atrial fibrillation. Europace 2024;26(1):1-9. doi:10.1093/europace/euad371.

197. Nies M, Koruth JS, Mlcek M, et al. Hemolysis After Pulsed Field Ablation: Impact of Lesion Number and Catheter-Tissue Contact. Circ Arrhythm Electrophysiol 2024;17(6):e012765. doi:10.1161/CIRCEP.124.012765.

198. Shapira Y, Vaturi M, Sagie A. Hemolysis associated with prosthetic heart valves: a review. Cardiol Rev 2009;17(3):121-124. doi:10.1097/CRD.0b013e31819f1a83.

199. Maor E, Ivorra A, Rubinsky B. The effect of irreversible electroporation on blood vessels. Technol Cancer Res Treat 2007;6(4):307-312.

200. Vazquez-Calvo S, Ranganathan D, Verma A. Pulsed field ablation: The basics relating to effectiveness, durability, and safety. Prog Cardiovasc Dis 2025;91:38-48. doi:10.1016/j.pcad.2025.05.007.

201. Ladejobi A, Christopoulos G, Tan N, et al. Effects of Pulsed Electric Fields on the Coronary Arteries in Swine. Circ Arrhythm Electrophysiol 2022;15(10):e010668. doi:10.1161/CIRCEP.121.010668.

202. Higuchi S, Im SI, Stillson C, et al. Effect of Epicardial Pulsed Field Ablation Directly on Coronary Arteries. JACC Clin Electrophysiol 2022;8(12):1486-1496. doi:10.1016/j.jacep.2022.09.003.

203. Sassone B, Leone O, Martinelli GN, Pasquale G. Acute myocardial infarction after radiofrequency catheter ablation of typical atrial flutter: histopathological findings and etiopathogenetic hypothesis. Ital Heart J 2004;5:403-407.

204. Viles-Gonzalez JF, de Castro Miranda R, Scanavacca M, Sosa E, d'Avila A. Acute and chronic effects of epicardial radiofrequency applications delivered on epicardial coronary arteries. Circ Arrhythm Electrophysiol 2011;4(4):526-531. doi:10.1161/CIRCEP.110.961508.

205. Aoyama H, Nakagawa H, Pitha JV, et al. Comparison of cryothermia and radiofrequency current in safety and efficacy of catheter ablation within the canine coronary sinus close

to the left circumflex coronary artery. J Cardiovasc Electrophysiol 2005;16(11):1218-1226. doi:10.1111/j.1540-8167.2005.50126.x.

206. Higuchi S, Buck ED, Schneider CW, Gerstenfeld EP. What is a safe distance for delivering pulsed field ablation near coronary arteries? Heart Rhythm 2023;20(7):1066-1067.

207. Koyanagi Y, Nakamura Y, Ishikawa T, Arai S, Asano T, Shinke T. Sudden death from long-standing benign ventricular parasystole after atrial fibrillation ablation. HeartRhythm Case Rep 2025;11(8):824-828. doi:10.1016/j.hrcr.2025.06.004.

208. Luther V, Chiong J, James C, Modi S, Gupta D, Hung J. Diffuse right coronary artery spasm occurring 45 minutes after pulsed field ablation for atrial fibrillation. Heart Rhythm 2025;22(7):1864-1867. doi:10.1016/j.hrthm.2025.03.1978.

209. Gunawardene M, Schmidt B, Peichl P, et al. Life-threatening delayed myocardial ischemia and malignant arrhythmias occurring after pulsed field ablation of atrial fibrillation. Circulation 2025.

210. Guo F, Wang J, Deng Q. Effects of pulsed field ablation on autonomic nervous system in paroxysmal atrial fibrillation: A pilot study. Heart Rhythm 2023;20(3):329-338.

211. Gerstenfeld EP, Mansour M, Whang W. Autonomic effects of pulsed field vs thermal ablation for treating atrial fibrillation: Subanalysis of ADVENT. JACC Clin Electrophysiol 2024;10(7):1634-1644.

212. Tohoku S, Schmidt B, Schaak D. Impact of pulsed field ablation on intrinsic cardiac autonomic nervous system after pulmonary vein isolation. JACC Clin Electrophysiol 2023;9(9):1864-1875.

213. Audiat C, Della Rocca DG, Asmundis C, Chierchia GB. Interference from lobe-and-disk left atrial appendage occluder affecting left superior pulmonary vein pulsed field ablation. Heart Rhythm 2024;21(8):1240-1241.

214. Garza I, Al Taii H, Narayanan A, Jneid H, Sabayon D. Safety and feasibility of pulmonary vein isolation utilizing pulsed field ablation in patients with symptomatic atrial fibrillation and implanted Watchman devices. J Interv Card Electrophysiol 2024;67(8):1727-1734.

215. Lennerz C, O'Connor M, Schaarschmidt C, et al. Pulsed field ablation in patients with cardiac implantable electronic devices: an ex vivo assessment of safety. J Interv Card Electrophysiol 2024. doi:10.1007/s10840-024-01758-2.

216. Chen S, Chun JKR, Bordignon S, et al. Pulsed field ablation-based pulmonary vein isolation in atrial fibrillation patients with cardiac implantable electronic devices: practical approach and device interrogation (PFA in CIEDs). J Interv Card Electrophysiol 2023;66(8):1929-1938.

217. Elgaard AF, Dinesen PT, Riahi S, et al. Long-term risk of cardiovascular implantable electronic device reinterventions following external cardioversion of atrial fibrillation and flutter: A nationwide cohort study. Heart Rhythm 2023;20(9):1227-1235.

218. Abbas M, Emami M, Kamsani SH, et al. Pulsed-field ablation for atrial fibrillation in patients with cardiac implantable electronic devices. Heart Rhythm 2025. doi:10.1016/j.hrthm.2025.04.045.

219. Koruth J, Kuroki K, Iwasawa J, et al. Preclinical Evaluation of Pulsed Field Ablation: Electrophysiological and Histological Assessment of Thoracic Vein Isolation. Circ Arrhythm Electrophysiol 2019;12(12):e007781.

220. Koruth JS, Kuroki K, Kawamura I, et al. Focal Pulsed Field Ablation for Pulmonary Vein Isolation and Linear Atrial Lesions: A Preclinical Assessment of Safety and Durability. Circ Arrhythm Electrophysiol 2020;13(6):e008716.

221. Franceschi F, Koutbi L, Maille B. Phrenic nerve palsy and pulsed field ablation procedures for atrial fibrillation. EP Europace 2024;26(9). doi:10.1093/europace/euae202.

222. Vogel JA, van Veldhuisen E, Agnass P, et al. Time-Dependent Impact of Irreversible Electroporation on Pancreas, Liver, Blood Vessels and Nerves: A Systematic Review of Experimental Studies. PLoS One 2016;11(11):e0166987. doi:10.1371/journal.pone.0166987.

223. van Zyl M, Khabsa M, Tri JA, et al. Open-chest Pulsed Electric Field Ablation of Cardiac Ganglionated Plexi in Acute Canine Models. J Innov Card Rhythm Manag 2022;13(7):5061-5069. doi:10.19102/icrm.2022.130704.

224. Kwon JH, Kim MD, Kim SH, Lee EW, Kahlid SA. Effects of irreversible electroporation on femoral nerves in a rabbit model. Minim Invasive Ther Allied Technol 2022;31(2):306-312. doi:10.1080/13645706.2020.1799820.

225. Padmanabhan D, Naksuk N, Killu AK. Electroporation of epicardial autonomic ganglia: Safety and efficacy in medium term canine models. J Cardiovasc Electrophysiol 2019;30(4):607-615.

226. Koruth JS, Kuroki K, Kawamura I, et al. Pulsed Field Ablation Versus Radiofrequency Ablation: Esophageal Injury in a Novel Porcine Model. Circ Arrhythm Electrophysiol 2020;13(3):e008303.

227. Cochet H, Nakatani Y, Sridi-Cheniti S, et al. Pulsed field ablation selectively spares the oesophagus during pulmonary vein isolation for atrial fibrillation. Europace 2021;23(9):1391-1399. doi:10.1093/europace/euab090.

228. Kirstein B, Heeger CH, Vogler J, et al. Impact of pulsed field ablation on intraluminal esophageal temperature. J Cardiovasc Electrophysiol 2024;35(1):78-85.

229. Nies M, Watanabe K, Kawamura I, et al. Ablating Myocardium Using Nanosecond Pulsed Electric Fields: Preclinical Assessment of Feasibility, Safety, and Durability. Circ Arrhythm Electrophysiol 2024;17(7):e012854. doi:10.1161/CIRCEP.124.012854.

230. Song Y, Zheng J, Fan L. Nonthermal Irreversible Electroporation to the Esophagus: Evaluation of Acute and Long-Term Pathological Effects in a Rabbit Model. J Am Heart Assoc 2021;10(22):e020731.

231. Triantafyllou K, Karkos CD, Fragakis N, Antoniadis AP, Meletidou M, Vassilikos V. Ultrasound-guided versus anatomic landmark-guided vascular access in cardiac electrophysiology procedures: A systematic review and meta-analysis. Indian Pacing Electrophysiol J 2022;22(3):145-153.

232. Hinkle DA, Raizen DM, McGarvey ML, Liu GT. Cerebral air embolism complicating cardiac ablation procedures. Neurology 2001;56(6):792-794. doi:10.1212/wnl.56.6.792.

233. Lee AC, Voskoboinik A, Cheung CC, et al. A Randomized Trial of High vs Standard Power Radiofrequency Ablation for Pulmonary Vein Isolation: SHORT-AF. JACC Clin Electrophysiol 2023;9(7):1038-1047.

234. Benali K, Khairy P, Hammache N, Petzl A, Costa A, Verma A. Procedure-Related Complications of Catheter Ablation for Atrial Fibrillation. J Am Coll Cardiol 2023;81(21):2089-2099.

235. Wu L, Narasimhan B, Ho KS, Zheng Y, Shah AN, Kantharia BK. Safety and complications of catheter ablation for atrial fibrillation: Predictors of complications from an updated analysis the National Inpatient Database. J Cardiovasc Electrophysiol 2021;32(4):1024-1034.

236. Hsu JC, Darden D, Du C, Marine JE, Nichols S, Marcus GM. Initial Findings From the National Cardiovascular Data Registry of Atrial Fibrillation Ablation Procedures. J Am Coll Cardiol 2023;81(9):867-878.

237. Beitel-White N, Lorenzo MF, Zhao Y, et al. Multi-Tissue Analysis on the Impact of Electroporation on Electrical and Thermal Properties. IEEE Trans Biomed Eng 2021;68(3):771-782. doi:10.1109/TBME.2020.3013572.

238. Zhang J, Blackmore PF, Hargrave BY, Xiao S, Beebe SJ, Schoenbach KH. Nanosecond pulse electric field (nanopulse): A novel non-ligand agonist for platelet activation. Arch Biochem Biophys 2008;471(2):240-248.

239. Cieri IF, Rodriguez AA, Patel S, et al. Comparative thromboelastography with platelet mapping assessment of coagulation profiles in postablation vs nonablated patients with paroxysmal atrial fibrillation and peripheral artery disease: Implications for thrombotic risk. Heart Rhythm O2 2025;6. doi:https://doi.org/10.1016/j.hroo.2025.06.014.

240. Casella M, Valeri Y, Compagnucci P, et al. Cardiac biomarker temporal dynamics after radiofrequency and pulsed field catheter ablation of atrial fibrillation. Heart Rhythm O2 2025;6:1688-1695. doi:10.1016/j.hroo.2025.07.022.

241. Feickert S, D'Ancona G, Biernath K, Pieske-Kraigher E, Ortak J, Ewertsen NC. A comparative analysis of postprocedural troponin levels and the impact of renal impairment in patients undergoing pulmonary vein isolation: pulsed field ablation vs. radiofrequency ablation. Eur J Med Res 2025;30(1):700. doi:10.1186/s40001-025-02964-y.

242. Shen C, Bai R, Jia Z, et al. Unexpected transient atrioventricular block and slow junctional rhythm using pulsed field ablation for slow pathway modification: Excited or cautious for ablators. Heart Rhythm 2025;22(7):1682-1692. doi:10.1016/j.hrthm.2024.09.023.

243. Mahrous N, Blaschke F, Schöppenthau D, Hindricks G, Boldt L-H, Parwani AS. LA PULSE: Evaluating Left Atrial Function Pre- and Post-Atrial Fibrillation Ablation Using PULSEd Field Ablation. Clin Med 2024;14(1):68. doi:10.3390/jcm14010068.

244. Nakatani Y, Sridi-Cheniti S, Cheniti G, et al. Pulsed field ablation prevents chronic atrial fibrotic changes and restrictive mechanics after catheter ablation for atrial fibrillation. Europace 2021;23(11):1767-1776. doi:10.1093/europace/euab155.

245. Marrouche NF, Wazni O, McGann C, et al. Effect of MRI-Guided Fibrosis Ablation vs Conventional Catheter Ablation on Atrial Arrhythmia Recurrence in Patients With Persistent Atrial Fibrillation: The DECAAF II Randomized Clinical Trial. JAMA 2022;327(23):2296-2305. doi:10.1001/jama.2022.8831.

246. Zaher W, Marcon L, Della Rocca DG, et al. Pulsed-field ablation beyond pulmonary vein for persistent atrial fibrillation: efficacy and impact on left atrial function. J Interv Card Electrophysiol 2025;68:1823-1833. doi:10.1007/s10840-025-02080-1.

247. Nies M, Watanabe K, Kawamura I, Santos-Gallego CG, Reddy VY, Koruth JS. Preclinical Study of Pulsed Field Ablation of Difficult Ventricular Targets: Intracavitary Mobile

Structures, Interventricular Septum, and Left Ventricular Free Wall. Circ Arrhythm Electrophysiol 2024;17(6):e012734. doi:10.1161/CIRCEP.124.012734.

248. Blumenthal C, Salas JA, Wright LE, et al. Assessment of scar modulation with cardiac MRI after pulsed field ablation in a porcine infarct model. Heart Rhythm 2025;22(4):S628.

249. Reddy VY, Koruth J, Petru J, et al. Feasibility of creating transmural lesions with endocardial ventricular ablation using a novel high voltage pulsed field catheter: preliminary findings from a first-in-human trial. Heart Rhythm 2025;22(4):S455.

250. Tschabrunn CM, Gurin M, Zado ES, et al. Treatment of refractory ventricular tachycardia with an investigational pulse field ablation system. Heart Rhythm 2025;22(4):S202.

251. Verma A, Moon LB, Fish J, et al. AB-499634-002 PFA PVI ACUTE ASSESSMENT WITH A HIGH-DENSITY MAPPING CATHETER IN THE SWINE MODEL. Heart Rhythm 2025;22(4):S4-S5. doi:10.1016/j.hrthm.2025.03.010.

252. Kawamura I, Reddy VY, Santos-Gallego CG, et al. Electrophysiology, Pathology, and Imaging of Pulsed Field Ablation of Scarred and Healthy Ventricles in Swine. Circ Arrhythm Electrophysiol 2023;16(1):e011369. doi:10.1161/CIRCEP.122.011369.

253. Perez JJ, Gonzalez-Suarez A. How intramyocardial fat can alter the electric field distribution during Pulsed Field Ablation (PFA): Qualitative findings from computer modeling. PLoS One 2023;18(11):e0287614. doi:10.1371/journal.pone.0287614.

254. Younis A, Zilberman I, Krywanczyk A, et al. Effect of Pulsed-Field and Radiofrequency Ablation on Heterogeneous Ventricular Scar in a Swine Model of Healed Myocardial Infarction. Circ Arrhythm Electrophysiol 2022;15(10):e011209. doi:10.1161/CIRCEP.122.011209.

255. Livia C, Sugrue A, Witt T, et al. Elimination of Purkinje Fibers by Electroporation Reduces Ventricular Fibrillation Vulnerability. J Am Heart Assoc 2018;7(15):e009070. doi:10.1161/JAHA.118.009070.

256. Sacher F, Sarkozy A, Pürerfellner H, et al. Safety and efficacy of a lattice-tip catheter for ventricular arrhythmia ablation: the AFFERA Ventricular Arrhythmia Ablation Registry (AVAAR). EP Europace 2025;27(9):euaf139. doi:10.1093/europace/euaf139.

257. Deodhar A, Dickfeld T, Single GW, et al. Irreversible electroporation near the heart: ventricular arrhythmias can be prevented with ECG synchronization. AJR Am J Roentgenol 2011;196(3):W330-335. doi:10.2214/AJR.10.4490.

258. Weyand S, Lobig S, Seizer P. First in human focal pulsed field ablation to treat an epicardial VT focus with an endocardial approach in non-ischemic cardiomyopathy. J Interv Card Electrophysiol 2023;66(5):1057-1058. doi:10.1007/s10840-023-01534-8.

259. Askarinejad A, Kohansal E, Sabahizadeh A, Hesami H, Adimi S, Haghjoo M. Pulsed-Field Ablation in Management of Ventricular Tachycardia: A Systematic Review of Case Reports and Clinical Outcomes. Clin Cardiol 2024;47(10):e70018. doi:10.1002/clc.70018.

260. Hanley A, Das S, Nguyen T, et al. Pulsed-field ablation in a patient with ventricular arrhythmia storm receiving mechanical circulatory support. HeartRhythm Case Rep 2025;11(5):425-428. doi:10.1016/j.hrcr.2025.02.006.

261. Saleem M, Jin C, Malyshev Y, Maan A, Musikantow DR, Reddy VY. Use of a Focal Pulsed Field Ablation Catheter to Target Premature Ventricular Contractions From the Papillary Muscle. JACC Case Rep 2025;30(18):104031. doi:10.1016/j.jaccas.2025.104031.

262. Peichl P, Bulava A, Wichterle D, et al. Efficacy and safety of focal pulsed-field ablation for ventricular arrhythmias: two-centre experience. Europace 2024;26(7). doi:10.1093/europace/euae192.

263. Reddy VY, Koruth JS, Peichl P, et al. High-Voltage Focal Pulsed Field Ablation to Treat Scar-Related Ventricular Tachycardia: The First-in-Human VCAS Trial. Circulation 2025;152:1691-1704. doi:10.1161/CIRCULATIONAHA.125.077025.

264. Li F, Gong A, Hu H, et al. Pulsed Field Ablation of Paroxysmal Supraventricular Tachycardia: A Prospective Multicenter Single-Arm Study in China. Circ Arrhythm Electrophysiol 2024;17(12):e013206. doi:10.1161/CIRCEP.124.013206.

265. Stewart MT, Haines DE, Verma A, et al. Intracardiac pulsed field ablation: Proof of feasibility in a chronic porcine model. Heart Rhythm 2019;16(5):754-764. doi:10.1016/j.hrthm.2018.10.030.

266. Amorós-Figueras G, Casabella-Ramon S, Moreno-Weidmann Z, Ivorra A, Guerra JM, García-Sánchez T. Dynamics of High-Density Unipolar Epicardial Electrograms During PFA. Circ Arrhythm Electrophysiol 2023;16(9):e011914-e011914. doi:10.1161/CIRCEP.123.011914.

267. Stublar J, Jarm T, Mattison L, et al. Intracardiac electrogram analysis may allow for prediction of lesion transmurality after pulsed field ablation of atria in a porcine model. Heart Rhythm O2 2025;6(3):350-361. doi:10.1016/j.hroo.2024.11.025.

268. Terricabras M, Martins RP, Peinado R, et al. Cardiac Pulsed Field Ablation Lesion Durability Assessed by Polarization-Sensitive Optical Coherence Reflectometry. Circ Arrhythm Electrophysiol 2024;17(3):e012255. doi:10.1161/CIRCEP.123.012255.

269. Martins RP, Papiashvili G, Sabirov A, et al. First-in-human trial of atrial fibrillation ablation using real-time tissue optical assessment to predict pulsed field lesion durability. Europace 2025;27(2):euaf009. doi:10.1093/europace/euaf009.

270. Parag K, Assis FR, Tripathi H, Gasperetti A, Suzuki M, Tandri H. Intraoperative assessment of lesion formation during PFA. Heart Rhythm 2022;19(5):S362-S363.

271. Reddy VY, Kottkamp H, Calkins H, et al. Pulsed-Field Ablation to Enhance the Durability of Pulmonary Vein Isolation and Treat Paroxysmal Atrial Fibrillation. J Am Coll Cardiol 2026. doi:10.1016/j.jacc.2025.10.084.

272. Jais P. PFA versus RFA for the treatment of paroxysmal AF: the BEAT PAROX-AF randomized trial. Presented at ESC Congress 2025; August 31, 2025; Madrid, Spain.

273. Kuck KH, Brugada J, Fürnkranz A, et al. Cryoballoon or Radiofrequency Ablation for Paroxysmal Atrial Fibrillation. N Engl J Med 2016;374(23):2235-2245. doi:10.1056/NEJMoa1602014.

274. Andrade JG, Wells GA, Deyell MW, et al. Cryoablation or Drug Therapy for Initial Treatment of Atrial Fibrillation. N Engl J Med 2021;384(4):305-315. doi:10.1056/NEJMoa2029980.

275. Andrade JG, Champagne J, Dubuc M, et al. Cryoballoon or Radiofrequency Ablation for Atrial Fibrillation Assessed by Continuous Monitoring: A Randomized Clinical Trial. Circulation 2019;140(22):1779-1788. doi:10.1161/circulationaha.119.042622.

276. Wazni OM, Dandamudi G, Sood N, et al. Cryoballoon Ablation as Initial Therapy for Atrial Fibrillation. N Engl J Med 2021;384(4):316-324. doi:10.1056/NEJMoa2029554.

277. Packer DL, Mark DB, Robb RA, et al. Effect of Catheter Ablation vs Antiarrhythmic Drug Therapy on Mortality, Stroke, Bleeding, and Cardiac Arrest Among Patients With Atrial Fibrillation: The CABANA Randomized Clinical Trial. Jama 2019;321(13):1261-1274. doi:10.1001/jama.2019.0693.

278. Sacher F, Monahan KH, Thomas SP, et al. Phrenic nerve injury after atrial fibrillation catheter ablation: characterization and outcome in a multicenter study. J Am Coll Cardiol 2006;47(12):2498-2503. doi:10.1016/j.jacc.2006.02.050.

279. Tilz RR, Schmidt V, Pürerfellner H, et al. A worldwide survey on incidence, management, and prognosis of oesophageal fistula formation following atrial fibrillation catheter ablation: the POTTER-AF study. Eur Heart J 2023;44(27):2458-2469. doi:10.1093/eurheartj/ehad250.

280. Auf Der Heiden C, Bejinariu A, Spieker M, Kelm M, Rana O. Hemolysis after pulsed field ablation in pulmonary vein isolation: a prospective controlled trial. Europace 2025;27(Suppl 1).

Appendix 1 Writing committee member disclosure of relationships with industry and other entities

Writing committee member	Employment	Honoraria/speaking/ consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ partnership/ principal/majority stockholder	Stock or stock options	Intellectual property/ royalties	Other
Atul Verma, MD, FHRS (Chair)	None	Abbott; Biosense Webster; Kardium; Medtronic	None	Adagio Medical; Medlumics	None	None	None	None	None
Mélèze Hocini, MD, PhD (Vice Chair)	None	None	None	None	None	None	None	None	None
Jason G. Andrade, MD, FHRS	None	None	None	None	None	None	None	None	None
Edward P. Gerstenfeld, MD, MS, FHRS	None	Abbott; Biosense Webster, Inc.; Biotronik; Boston Scientific; Medtronic; Varian Medical Systems;	None	Abbott Medical	None	None	None	None	American College of Cardiology Foundation; Abbott; Adiago Medical; Boston Scientific; Farapulse
Melanie Gunawardene, MD	None	Abbott Medical; Biotronik; Boston Scientific; Bristol Myers Squibb; Farapulse; Luma Vision; Medtronic; Zoll, Inc.	None	Medtronic, Inc.	Boston Scientific	None	None	None	Biosense Webster, Inc.; CardioNXT; Field Medical
Suraj Kapa, MD, FHRS	None	Abbott	None	None	None	None	Nanowear , Inc.		Biosense Webster, Inc.; Boston Scientific

Writing committee member	Employment	Honoraria/speaking/ consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ partnership/ principal/majority stockholder	Stock or stock options	Intellectual property/ royalties	Other
Dhanunjaya R. Lakkireddy, MBA, MD, FHRS	None	Abbott; AtriCure; Medtronic; Biosense Webster;	Biosense Webster, Inc.	None	None	None	None	None	None
Damijan Miklavcic, PhD	None	Boston Scientific; Medtronic; Inomagen Therapeutics;	Field Medical	Medtronic	None	None	None	None	None
Andrea Natale, MD, FHRS	None	Abbott; Biosense Webster; Biotronik; Boston Scientific; Field Medical; iRhythm Technologies; Pulse Biosciences	None	None	None	None	None	None	None
Jonathan P. Piccini, MD, MHS	None	Abott; Biotronik; ElectroPhysiology Frontiers; Kardium; Medtronic; Milestone Pharmaceuticals; Philips; Physcade; Sanofi; UpToDate, Inc.;	None	Abbott; American Heart Association; Bayer Healthcare Pharmaceuticals; Boston Scientific; iRhythm Technologies; NIH; Philips	None	None	Physcade	None	Kardium
Boris Schmidt, MD, FHRS	None	Abbott; Biosense Webster; Boston Scientific; Medtronic; Abbott;	None	None	None	None	None	None	None

This table is a comprehensive list of the relationships with industry and other entities (RWI) disclosed by each writing committee member for the 12 months prior to the initial meeting of the writing committee and up through the completion of the document. The table does not necessarily reflect the RWI of the writing committee members at the time of publication. Please refer to the HRS Code of Ethics and Professionalism for definitions of disclosure categories or additional information about the HRS policy on the disclosure of relationships with industry and other entities.

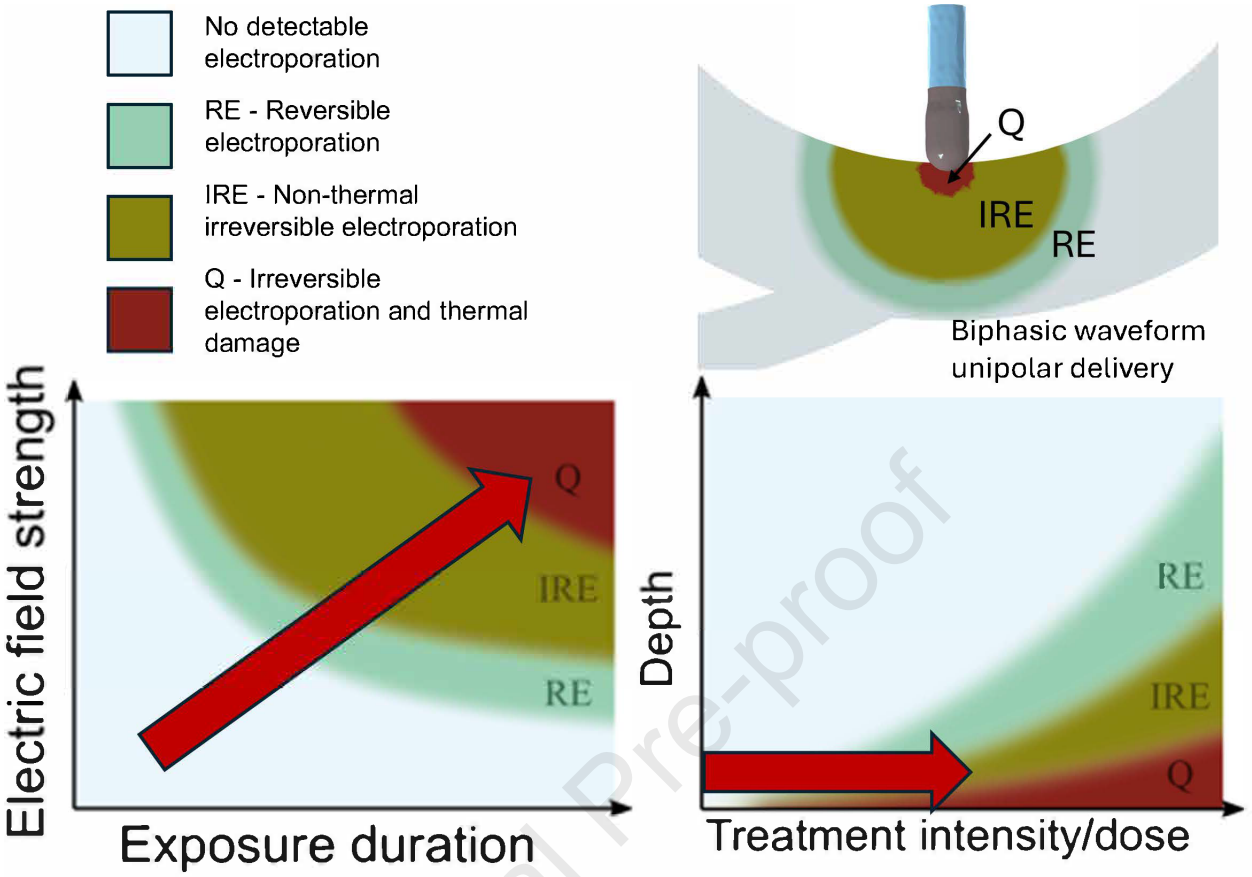
*Research and fellowship support are classed as programmatic support. Sources of programmatic support are disclosed but are not regarded as a relevant relationship with industry for writing group members or reviewers.

Appendix 2 Peer Reviewer disclosure of relationships with industry and other entities

Peer Reviewer	Employment	Honoraria/ speaking/ consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ partnership/ principal/majority stockholder	Stock or stock options	Intellectual property/ royalties	Other
Amin Al-Ahmad, MD, FHRS, CCDS	None	Biosense Webster, Inc.; Boston Scientific; Abbott; Haemonetics; Mediasphere Medical; Medtronic	None	None	None	None	DRS Vascular; Adona Medical, Inc.; S4 Medical	None	None
Bradley P. Knight, MD, FHRS	None	Boston Scientific; Medtronic; Abbott; Philips; Sanofi; CVRx Inc.; Biotronik; Atraverse Medical, Inc.; AtriCure, Inc.; AltaThera Pharmaceuticals	None	None	None	None	None	None	None
Arian Sultan, MD	None	None	None	None	None	None	None	None	None

This table is a comprehensive list of the relationships with industry and other entities (RWI) disclosed by the reviewers at the time the document was under review. The table does not necessarily reflect the RWI of the reviewers at the time of publication. Please refer to the HRS Code of Ethics and Professionalism for definitions of disclosure categories or additional information about the HRS policy on the disclosure of relationships with industry and other entities.

*Research and fellowship support are classed as programmatic support. Sources of programmatic support are disclosed but are not regarded as a relevant relationship with industry for writing group members or reviewers.

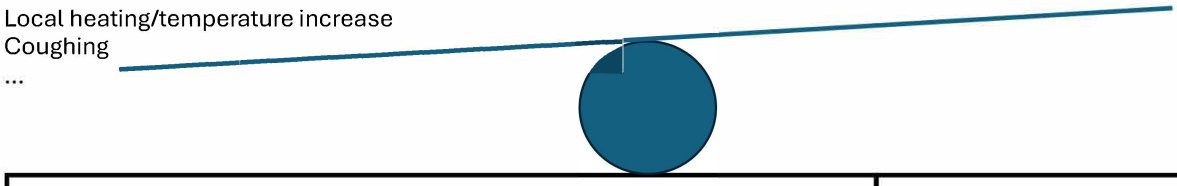


Unwanted effects/side effects

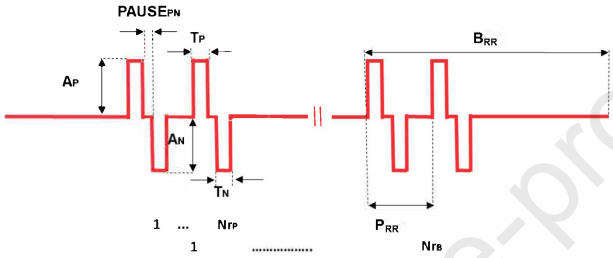
Cardiovascular spasm
Hemolysis
Stroke, TIA, silent cerebral lesions
Bubble formation
Muscle contraction
Nerve damage
Pain
Local heating/temperature increase
Coughing
...

Intended outcome

Cell death
Lesion depth
Transmurality
Size
Predictability
Reproducibility
...

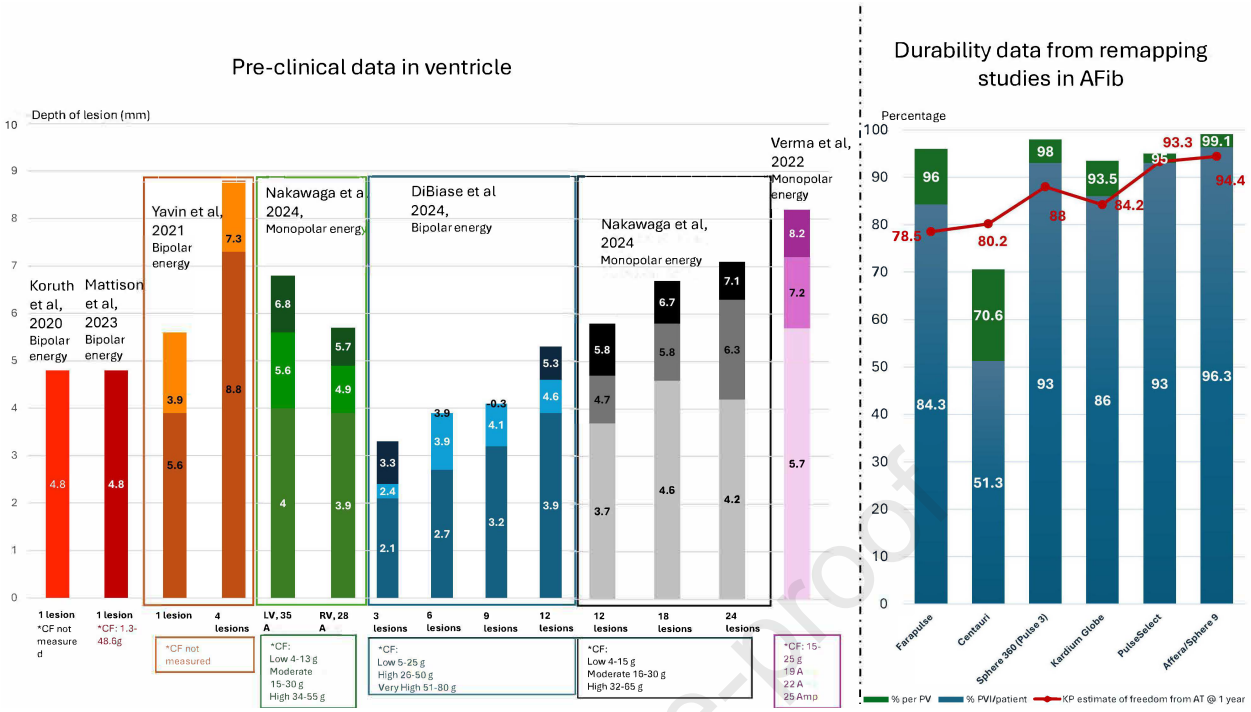


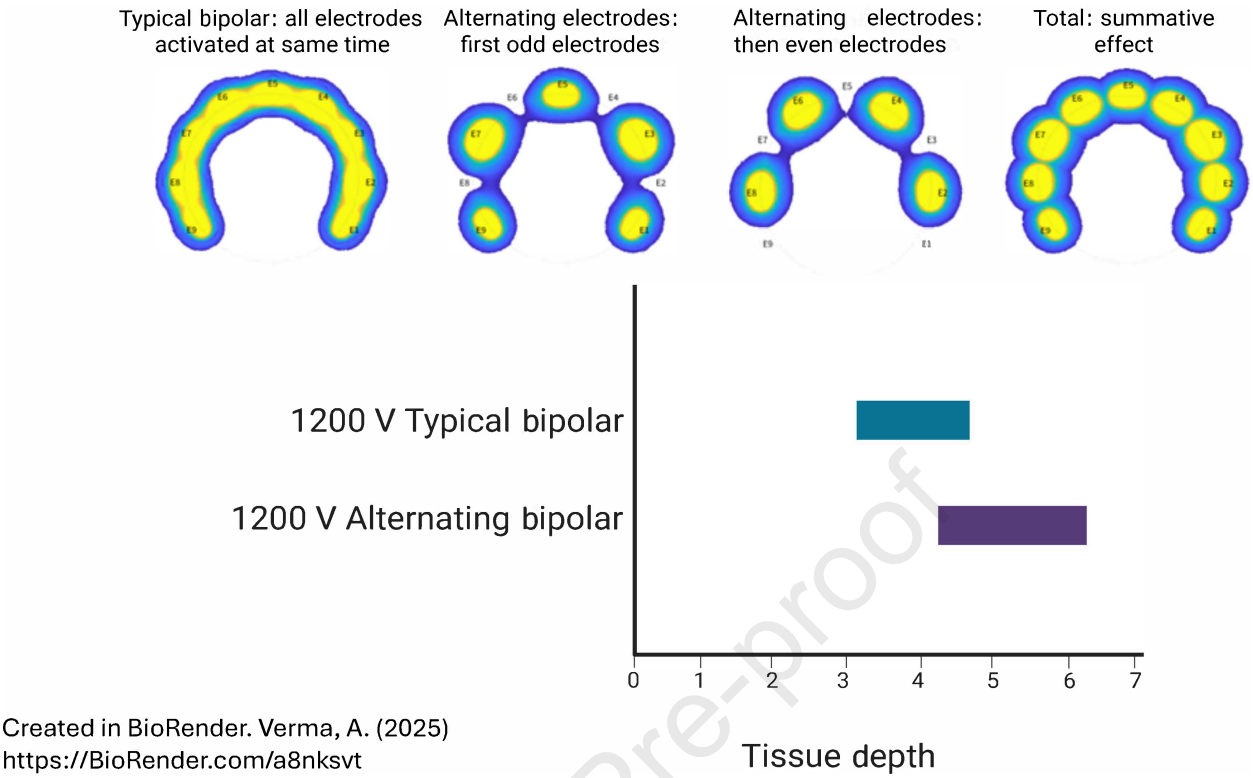
Pulse parameters



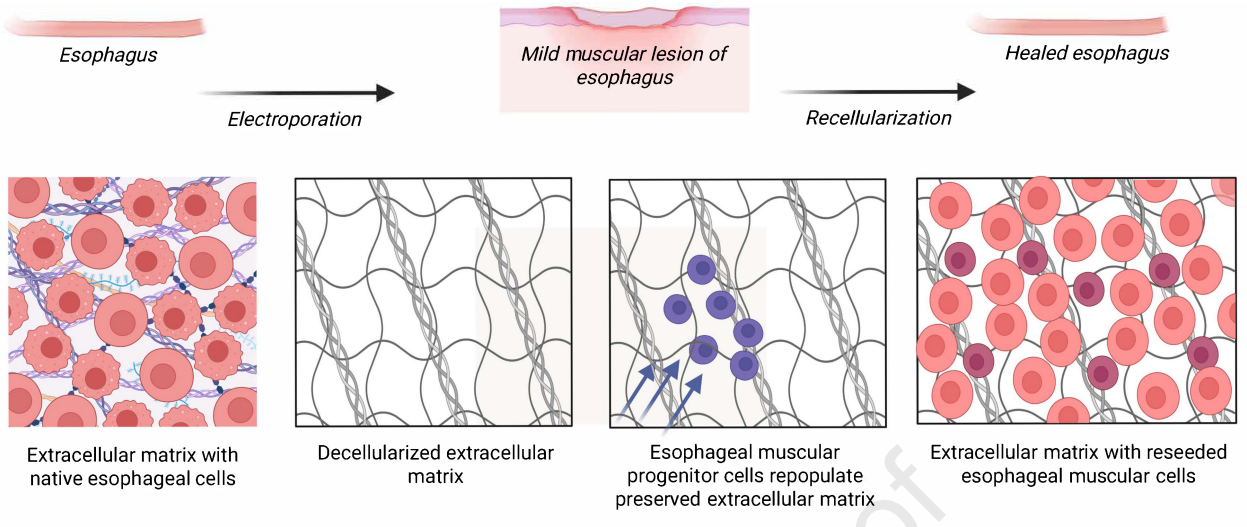
PFA waveform
Catheter design
Vectoring
Contact
Number of applications
Workflow/protocol
Repositioning
Irrigation
...

	Lesion depth	Stunning	Heating	Electro-chemistry	Pain	Neuromuscular stimulation	Arrhythmogenic
Pulse amplitude	↑↑	↑	↑↑	↑	↑	↑	↑
Pulse width	↑	↑	↑	↑↑	↑↑	↑↑	↑↑
Number of pulses	↑	↑	↑	↑↑	↑	↑	↑
Monophasic pulse	↑	↑	—	↑↑	↑	↑	↑
Biphasic pulse	↓	↓	—	↓↓	↓	↓	↓
Interphase delay	?	↑	↓	—	↑	↑	↑
Interpulse delay	↑	?	↓	—	↑↑	↑↑	↑↑
Intertrain delay	—	—	↓↓	—	—	—	—

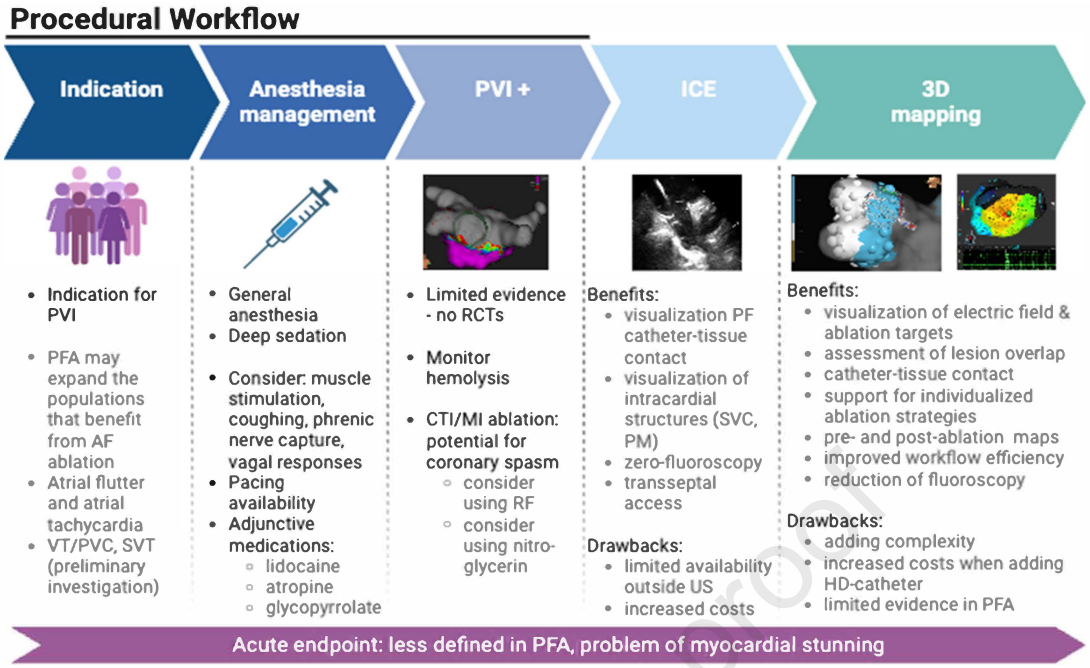




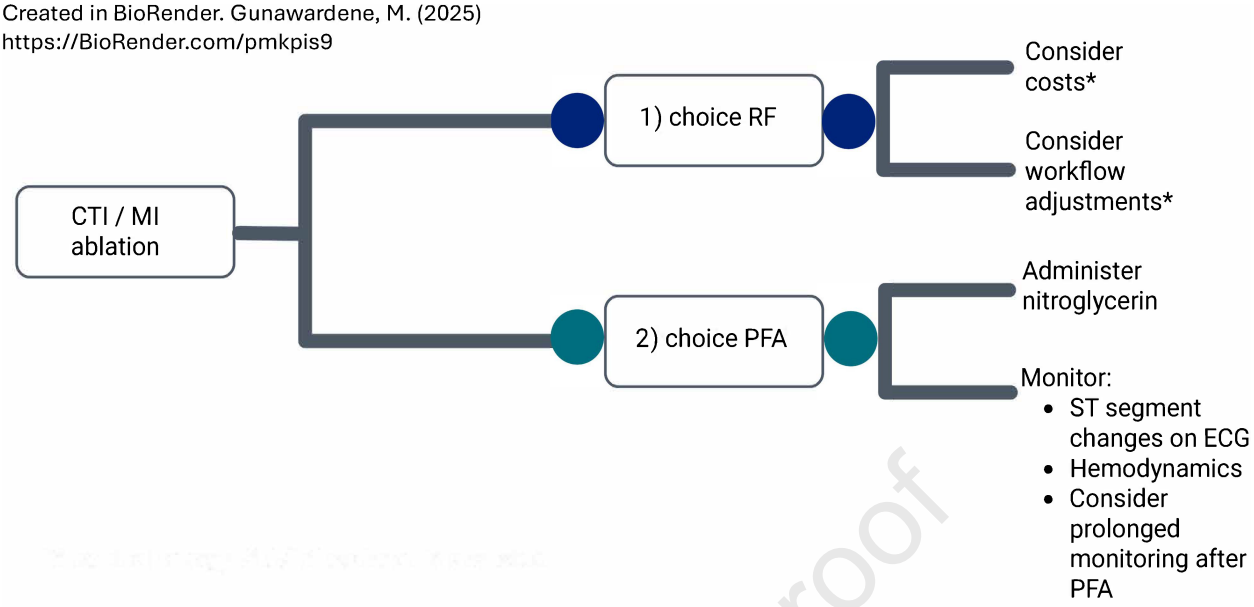
Created in BioRender. Verma, A. (2025)
https://BioRender.com/a8nksvt

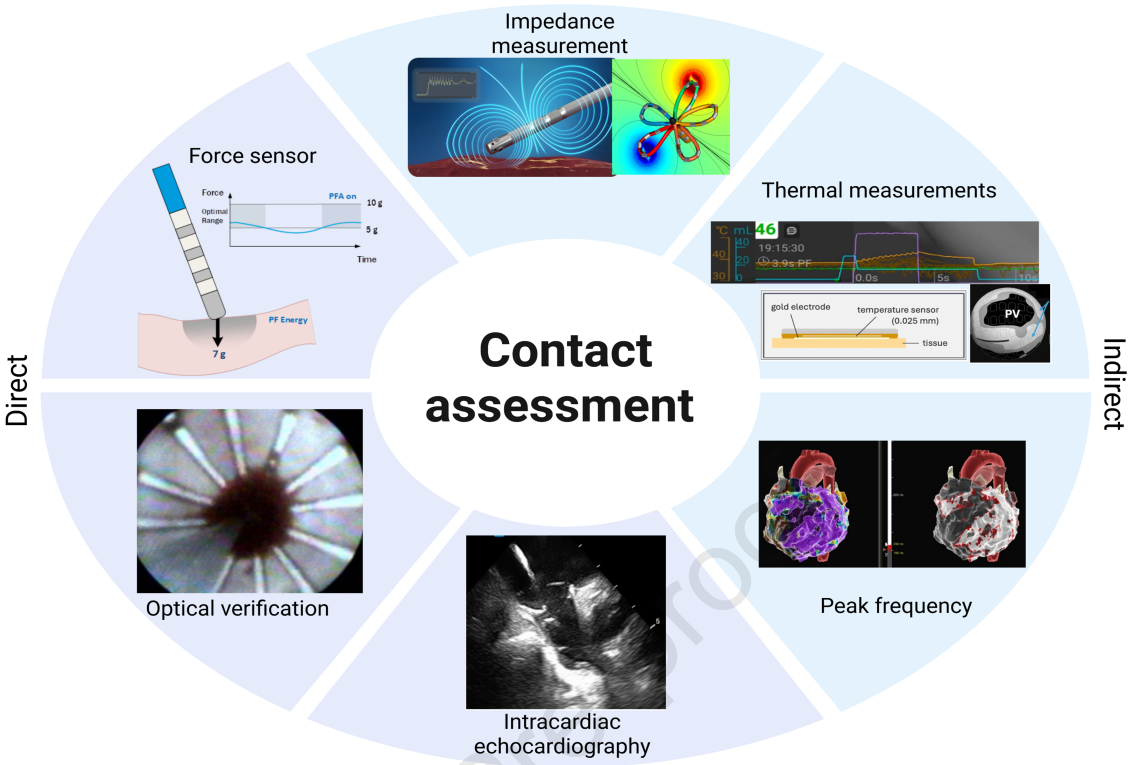


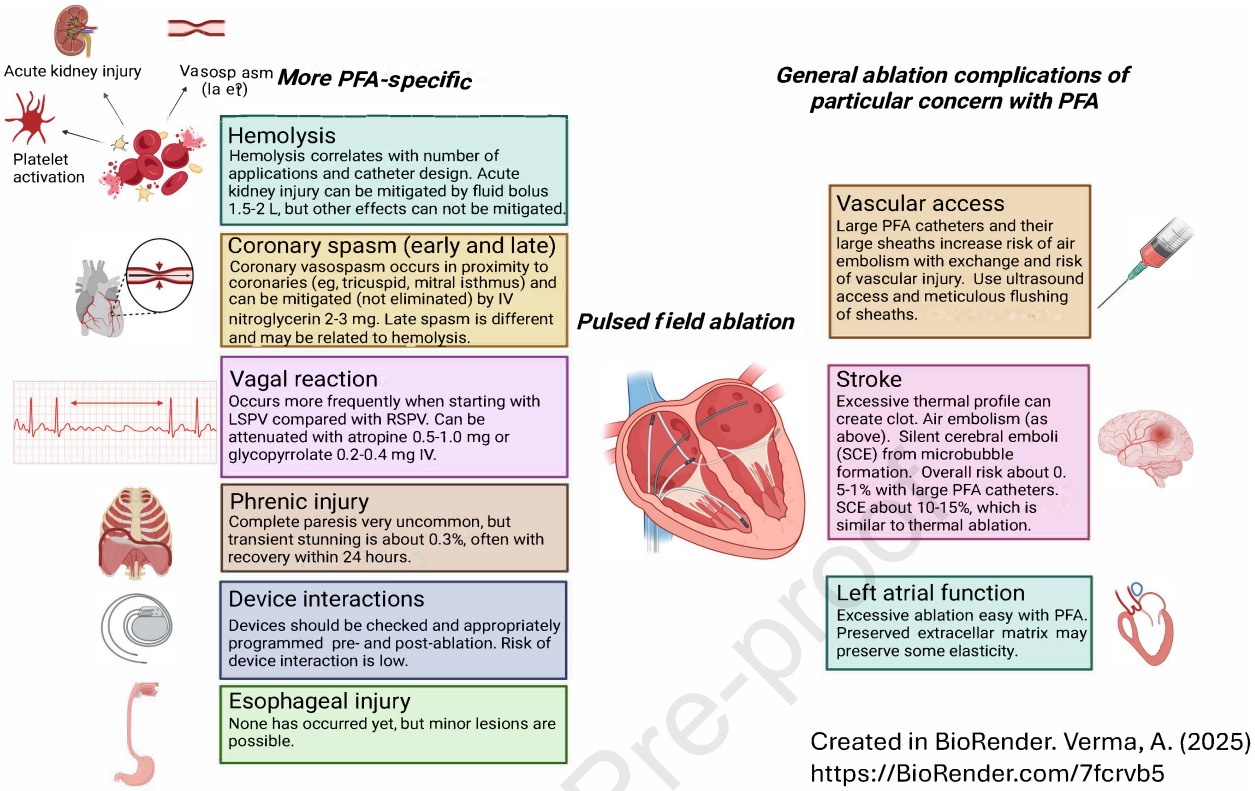
Created in BioRender. Verma, A. (2025) https://BioRender.com/xbc451s



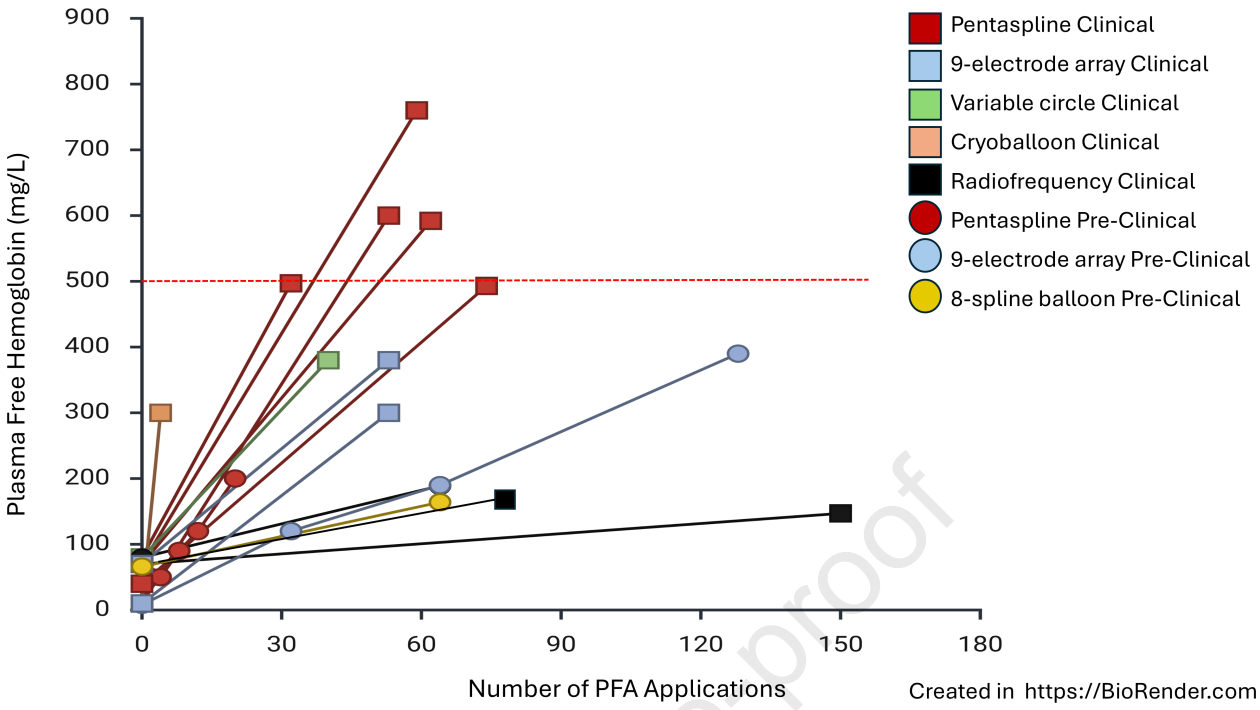
Created in BioRender. Gunawardene, M. (2025)
https://BioRender.com/pmkpis9

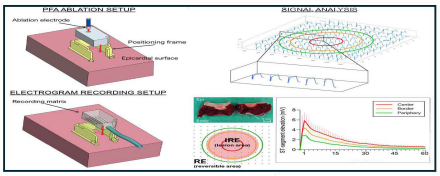
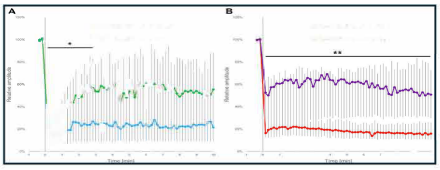
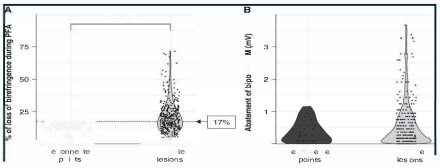
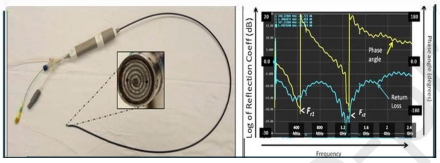






Created in BioRender. Verma, A. (2025) https://BioRender.com/7fcrvb5



Changes in unipolar electrogram morphology		Changes in ST elevation and R/S ratio differentiate irreversible vs reversible electroporation but discriminatory power may disappear after 30 min
Changes in unipolar electrograms by frequency analysis		Changes in ST elevation measured as low frequency components of the signal may differentiate transmural vs non-transmural lesions
Changes in tissue optical birefringence		Pre-clinical and early human analysis show drops in tissue birefringence (an optical property) can differentiate between complete histological lesions and durable PV isolation
Changes in high frequency electrical properties (resonant frequencies)		Changes in resonant frequencies at the tip of an antenna electrode can detect tissue property changes indicative of complete lesions

Brand name	Catheter	Descriptive name	Ablation energy	Approvals	Diameter (mm)/size (F)	Catheter deflection/over the wire	Irrigation/flow (mL/min)	Number of applications recommended	Ablation mode/configuration	Nominal amplitude	Integration in mapping/mapping system	Waveform description	Vectoring/activation pattern	Pulse duration	Number of pulses in train	Number of trains/application	Pause between trains	PFA duration (s)	Syncronized delivery	Duty cycle (%)	Power/energy per train	Contact sensing/type	Clinical experience (0-3)
Farawave Boston Scientific		Pentaspline 20 electrodes (4 electrodes on each of 5	PFA	USA, EU, Japan	31 & 35 mm/12F	Over the wire	Saline drip	8 applications per vein (nominal)	Bipolar	1800-2000 V	Yes	Biphasic	Between spline pairs	Microseconds	Not provided	5	Not provided	2.5 s	No, SYNC Mode available	Not provided	Not provided	Local impedance	3
OptiShot Cardiofocus		Compliant PFA balloon	PFA	Clinical trials ongoing	Up to 40 mm/12F	Unidirectional sheath	No	1 per position/1 per vein	Bipolar	Up to 2 kV	Not required	Biphasic	Simultaneous delivery to non-adjacent splines	Microseconds	Not provided	Not provided	Not provided	27 s	No	Not provided	Not provided	Direct visual confirmation	0
Farapoint Boston Scientific		Focal	PFA	Premarket	8F	Bidirectional	No	3-5 mm between lesions	Bipolar	1400-2000 V	Yes	Biphasic	Between electrode pairs	Microseconds	Not provided	5	Not provided	2.5 s	No, SYNC Mode available	Not provided	Not provided	Local impedance (future)	2
PulseSelect Medtronic		Circular: 9 electrodes	PFA	USA, EU, Japan, Canada, ANZ, China, and more	25 mm/9F	Bidirectional and over the wire	Not irrigated	Minimum of 8 per vein	Bipolar	1500 V	Yes (compatible with all mapping systems)	Biphasic	Dual field: odd and even electrodes activated separately during pulse train	Microseconds	Not provided	4	Dependent on R-wave gating	Dependent on R-wave gating, typically 6-8 s	Yes/R-wave	<1%	Dependent on patient impedance	In development/impedance based	3
Varipulse Biosense Webster		Variable loop: 10 electrodes	PFA	USA, EU, Japan	25-35 variable/8.5F	N/A	Yes	>=12 per vein	Bipolar	1800 V	Yes	Biphasic	Between adjacent electrodes	Microseconds	Not provided	Not provided	Not provided	Not provided	Not provided	Not provided	Not provided	Impedance	3
Sphere-9 Medtronic		Large-tip focal	PFA & RFA	USA, EU	9 mm/8F	Bidirectional	Yes/15 mL/min (PF); 30 mL/min (RF)	5-6 mm between lesions, user configurable	Monopolar	Up to 2000 V	Yes/Affera Prism	Biphasic	Lattice to return patches	Microseconds	125	12	210 ms	4 s	No	<1%	Not provided	Impedance and temperature change after starting ablation	3
Centauri Cardiofocus (Galaxy)		Focal	PFA	CE	3.5-4 mm/8F	Unidirectional/bidirectional	4 mL/min	4-5 mm between lesions	Monopolar	19 A, 22 A, 25 A, up to 3.5 kV	Yes	Biphasic	Unipolar to patch	Microseconds	Not provided	Not provided	Not provided	3, 5, 7 s	Yes/R-wave	Not provided	Not provided	Contact force	2
Globe System Kardium		122 electrode spherical array	PFA RFA (investigational)	USA	30 mm/16F	Offset sphere, bidirectional sheath deflection	Yes/100 mL/h (yes/1.67 mL/min) Heparin coated	1 application per vein /target area	Bipolar	1700 V	Yes/Globe System	Biphasic	2 to 64 electrodes simultaneously	Microseconds	Not provided	2 to 6	5 s	2 s per train	no	Not provided	Not provided	Thermal contact mapping	3
STSF dual energy Biosense Webster		Focal	PFA & RFA	EU	3.5 mm/8F	Unidirectional/bidirectional	Saline drip	Up to 24 applications, 28 s max, duration varies according to PF	Bipolar	1.0-1.5 kV	Yes	Biphasic	Unipolar to patch	Microseconds	Not provided	Not provided	1 s	Up to 24 applications, 28 s max, duration varies according to PF	No	Not provided	Not provided	Contact force with direction vector	2
OMNY pulse Biosense Webster		Large-tip focal	PFA	Pending EU	12 mm/7.5F	Unidirectional/bidirectional	Saline drip	Up to 12 applications, 14.5 s max, duration varies according to PF index target value	Bipolar	1.0-1.5 kV	Yes	Biphasic	Bipolar 3 splines vs 3 splines	Microseconds	Not provided	Not provided	1 s	Up to 12 applications, 14.5 s max, duration varies according to PF index target value	No	Not provided	Not provided	Contact force with direction vector	2
Abbott Volt		Balloon in splined basket	PFA	EU, pending US	28 mm/12.5F	Over the wire, bidirectionally deflectable	None	Nominal waveform: minimum 2, average of 4 Low waveform: minimum of 3	Bipolar	Nominal: 1700 V Low: 1345 V	Yes	Biphasic	Spline to neighboring ppline in sequence around the 8 splines	Microseconds	Not provided	10	Not provided	Nominal: ~20s (10 bursts/trains R-wave gated) Low: ~20-30s (10 bursts/trains R-wave gated)	Yes	Not provided	Not provided	Yes- Complex Impedance (LivePoint)	2
Abbott Tactiflex Duo		Focal	PFA & RFA	pending EU	4 mm tip/8F	Deflectable, multiple configurations available	2 mL/min baseline 13 mL/min on PF and RF	1 application per location for atrial locations	Monopolar	Nominal: 2232 V Low: 1950 V	Yes	Biphasic	Unipolar to patch	Microseconds	Not provided	Nominal: 5 trains Low: 10 trains	Not provided	Nominal: ~5 s Low: ~10 s (R-wave gated)	Yes	Not provided	Not provided	Yes: Light-interferometry contact force	2
Sphere-360		Very large array	PFA	Not approved yet	34 mm/8F	Over the wire	Not irrigated	3-4 per vein	Monopolar	Not provided	Yes/Affera Prism	Biphasic	6 panels activated individually to return patch	Microseconds	Not provided	Not provided	Not provided	5.9 s	No	Not provided	Not provided	Impedance	2
nsPFA, PusleBiosciences		Very large array	PFA	Not approved yet	30 mm/11F	No	No	1 ostial and 1 antral application per vein	Bipolar	Not provided	Feasibility clinical integration with EnSite and CARTO	Monophasic	Between rings	Nanoseconds	Not provided	Not provided	Not provided	5 s	Unsynchronized	<0.0007%	0.4 J/mm^2	No	1
ElectroPulse, CathRx		Variable loop: 10 electrodes	PFA	Not approved yet	2.33 mm/8F	Unidirectional with variable loop sizing	No	1 per location	Bipolar	2800 V	Yes	Biphasic	Between adjacent electrodes	Microseconds	Not provided	7	Gated to heartbeat	2-3 s	Yes	Not provided	Not provided	Yes	1
LotosPFA Insight Medtech		Interconnected spline in spindle and lotus configurations	PFA	China (expected approval in 2026) EU (expected approval in 2027)	28 or 31 mm/11F	Over the wire	Saline drip	8 applications per vein	Bipolar	2100 V	No	Biphasic	Between adjacent electrodes	Nanoseconds	Not provided	5 trains per site	Not provided	5-11 s	No	Not provided	Not provided	No	2
Adagio		Very large array	PFA	Not approved yet	20-25 mm/8.5F	N/A	Not irrigated	Not provided	Bipolar	1100 V	Feasibility with Ensite	Biphasic	Between adjacent electrodes	Not provided	Not provided	1	Not provided	Not provided	Not provided	Not provided	Not provided	Not provided	0
Faraflex Boston Scientific		Large focal	PFA	Pre-market	10 mm/8F	Bidirectional	2 mL/min	5-6 mm between lesions	Monopolar/bipolar	2000 V	Yes	Biphasic	Monopolar: distal electrode-patch; bipolar: distal - proximal electrode pair	Microseconds	Not provided	5	Not provided	2.5 s	No, SYNC Mode available	Not provided	Not provided	Local impedance	0
QuickShot Cardiofocus		Map & ablate mini basket	PFA	Clinical trials ongoing	10 mm/8.5F	Bidirectional asymmetric	2 mL/min	1 per position	Monopolar	33A, 40 A up to 5 kV	Yes	Biphasic	Unipolar to patch	Microseconds	Not provided	Not provided	Not provided	3, 6.5 s	Optional	Not provided	Not provided	Yes, impedance algorithm	0
Field Medical		Focal	PFA	Not approved yet	8.5F	Bidirectional	Irrigated	Not provided	Monopolar	>10 kV	Feasibility with CARTO	Monophasic	Not provided	Nano/microseconds	Not provided	Not provided	Not provided	<200 ms	Not provided	Not provided	Not provided	Yes	1
Arga Medtech SA		Circular, linear, focal	PFA	Not approved yet	25 mm/7F	Bidirectional	No	5-7 applications per PV	Bipolar, monopolar, and combination	2250-3250 V	No	Biphasic, coherent sine wave	Not provided	Microseconds	Not provided	Not provided	Not provided	Not provided	No	Not provided	Not provided	Yes, impedance	1

Data were retrieved from public sources and compiled. The table was sent to companies to confirm, modify, and provide more information. Fields that are not populated indicate data that are either not available or were not disclosed by the companies. PFA = pulsed field ablation; PV = pulmonary vein; RFA = radiofrequency ablation.

*Clinical experience: 3 - FDA approved, RCT, registries; 2 - clinical studies with 12 months follow-up; 1 - FIH study published; 0 - no clinical data published

SUPPLEMENTAL APPENDIX

Supplemental Figure 1 – Anatomy OF right coronary artery and left circumflex artery in relation to cavotricuspid and mitral isthmuses

Supplemental Table 1 – Summary of deep sedation and general anesthesia protocols for pulsed field ablation

SUPPLEMENTAL FIGURE 1 – Anatomy of right coronary artery and left circumflex artery in relation to cavotricuspid and mitral isthmuses. The blue bars represent typical areas of ablation for the cavotricuspid isthmus line or the posterior mitral line.

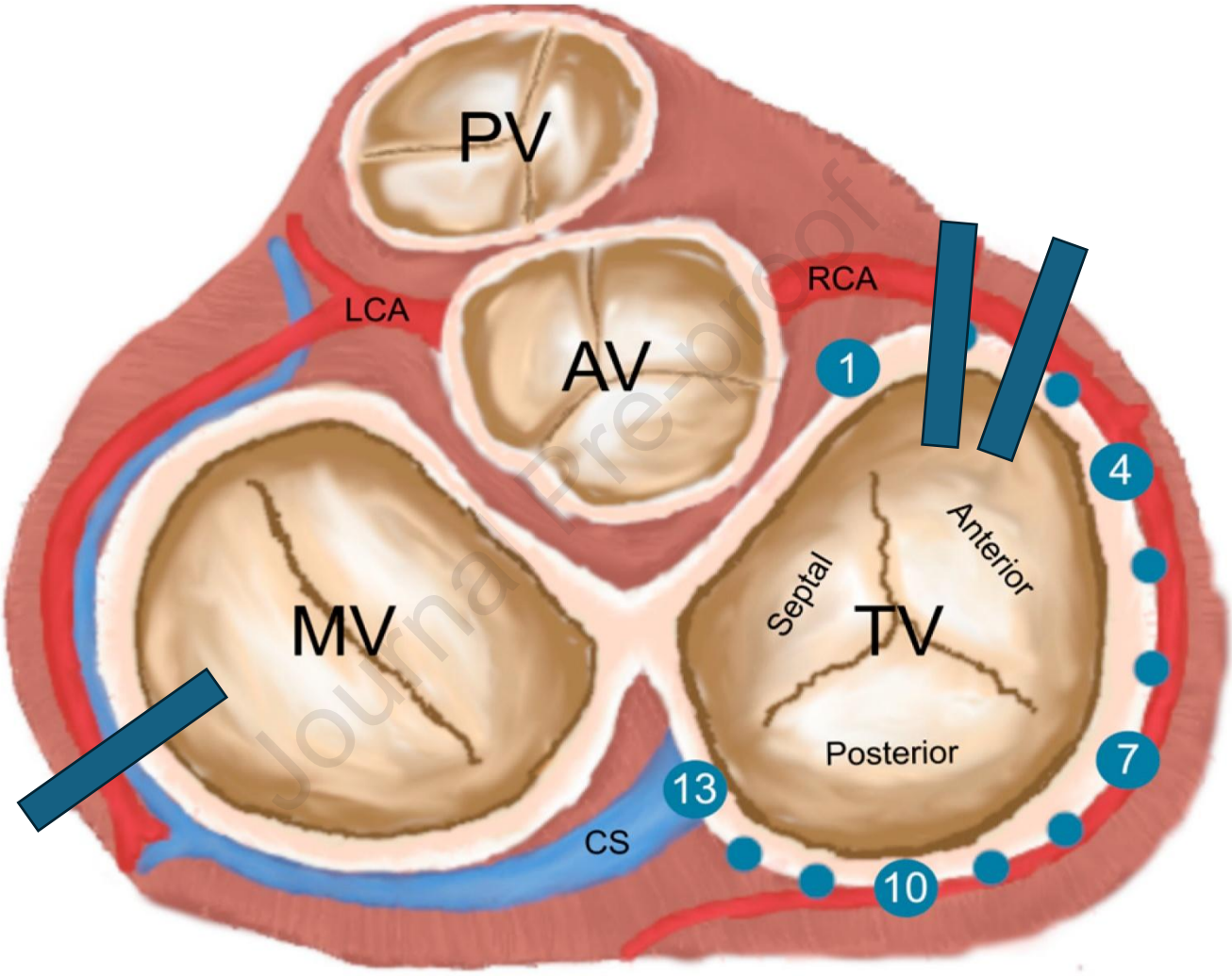


Image is open access from Piotrowski M, Burysz M, Batko J, et al. The right coronary anatomy and operative topography of the tricuspid valve annulus. J Cardiovasc Dev Dis 2024;11:159. https://doi.org/10.3390/jcdd11060159. Blue bars have been added to the original image. AV = aortic valve; CS = coronary sinus; LCA = left coronary artery; MV = mitral valve; PV = pulmonary valve; RCA = right coronary artery; TV = tricuspid valve.

SUPPLEMENTAL TABLE 1 – Summary of deep sedation and general anesthesia protocols for pulsed field ablation

Study	Type	Sedation strategy	Patient population	Ablation strategy	PFA system	Endpoints	Complications regarding sedation	Procedural complications	Arrhythmia outcome
Sochorová et al. (1) *COOPERATIVE-PFA*	RCT	(1) DAS using intermittent propofol-opioid boluses (arm P), (2) continuous remimazolam-ketamine DAS (arm R), or (3) continuous propofol-opioid TIVA with secured airways (arm TIVA)	Paroxysmal and persistent AF, n = 127	PVI for paroxysmal AF, PVI + PWI/MI in non-paroxysmal AF, CTI if necessary	Pentasplin e PFA catheter (FARAPULSE™, Boston Scientific)	Primary endpoint composite of hypoxemia, hypotensive, or hypertensive events	85.7% of P patients., 27.9% of R patients, and 66.7% of TIVA patients ($p < 0.001$), driven by hypoxemia in the P arm (100% of patients with the primary endpoint) and by hypotension in the TIVA arm (100%).	n = 2 in arm P, n = 2 in arm R, n = 1 in arm TIVA): 1 arteriovenous fistula, 1 pseudoaneurysm, 1 pharyngeal hematoma, 1 circumflex artery vasospasm, and 1 case of ketamine-related agitation	Not reported
Schmidt et al. (2) *5S Study*	Single-center experience	Intravenous deep sedation using propofol, midazolam, and fentanyl	Paroxysmal and persistent AF, n = 191	PVI	Pentasplin e PFA catheter (FARAPULSE™, Boston Scientific)	Adoption and streamlining procedures	Neither a switch to GA nor mechanical ventilation was required	N = 1 pericardial effusion,	17/191 patients (9%) with recurrence (3-6 months follow-up)
Grimaldi et al. (3) - from inspIRE study (4)	Prospective	Deep sedation: midazolam, dexmedetomidine, remifentanil, dexamethasone, and ondansetron	Paroxysmal AF, n = 29	PVI	Variable-loop biphasic PFA catheter (VARIPULSE™, Biosense Webster)	Sedation-associated complications and patient satisfaction	No intubation, no relevant sedation-related hypotension. Naloxone was not used. No muscular fasciculations or cough. Positive patient satisfaction in most patients (LSQ)	N = 2 pseudoaneurysm of right femoral artery	Not reported (sub-cohort of published inspIRE study[4])

Wahedi et al. (5)	Prospective PFA vs. cryoballoon	Deep sedation: propofol, midazolam, and sufentanyl	Paroxysmal and persistent AF, n = 50 PFA and n= 50 cryoballoon	PVI	Pentasplin e PFA catheter (FARAPULSE™, Boston Scientific)	Aspiration pneumonia, bag-mask ventilation, vasopressor support, intubation	N = 1 Aspiration pneumonia in PFA group	N = 1 tamponade (PFA), 1 groin complication (PFA), 1 transient phrenic nerve palsy (cryoballoon)	Not reported
Patel et al. (6)	Retrospective	Deep sedation: propofol, dexmedetomidine, fentanyl, and midazolam	Paroxysmal and persistent AF, n = 100	PVI, additional non-PV ablation in 39%	Pentasplin e PFA catheter (FARAPULSE™, Boston Scientific) and circular array catheter (PulseSelect™, Medtronic)	Primary endpoint: rate of airway complications or requirement for conversion to GA	There were no instances of airway complications or conversion from DAS to GA.	Not reported	Not reported
Rillig et al. (7)	retrospective, multicentre study	GA and deep sedation GA: remifentanil, propofol, succinylcholine or rocuronium. Deep sedation: fentanyl. propofol	Paroxysmal and persistent AF, n = 23 GA and n = 40 deep sedation	PVI, and with extensive LA low voltage areas or with additional atrial tachycardia, linear lesions were applied at operator's discretion	Large-tip catheter (Sphere-9™, Medtronic)		N = 1 conversion from deep sedation to GA in patient (BMI > 40 kg/m^2), and the tongue repeatedly slipped back and blocked the airways	N = 1 Pericardial tamponade in deep sedation group	Not reported

Chen et al. (8) *PF-Beat-AF study*	prospective, multicenter, single-arm study	Conscious sedation was used in 68.6 % of cases	Paroxysmal AF N = 159		Variable-diameter circular catheter (AccuPulse, AccuPulse Medical Technology Co.)	Incidence of primary adverse events occurring within 7 days post-procedure, including device or procedure-related death, atrioesophageal fistula, PV stenosis, myocardial infarction, pericarditis, cardiac perforation/tamponade, phrenic nerve injury, cerebrovascular events/stroke, transient ischemic attack, thromboembolism, hemolysis, major vascular access complication/bleeding	Not reported	N = 1 Pericardial tamponadeg	At 12 months, 87.7 % (95% CI, 82.5-92.9) free from atrial arrhythmia after the blanking period; the primary effectiveness was comparable between conscious sedation and GA/deep sedation (87.2% vs. 88.9%; p = 0.7823), despite longer procedure times under conscious sedation (142.3 ± 36.3 vs 110.4 ± 40.7 min; p < 0.001)
Calvert et al. (9)	single-center, prospect	Mild conscious sedation: intravenous	Paroxysmal and persistent	PVI	Pentasplin e PFA catheter	Primary outcome was the need for	Mild conscious sedation arm: - 1 patient (12.5%)	None	Median 101 days (IQR, 94–123), 1/7

	ive, non-randomized	midazolam and fentanyl Or GA	AF, N = 8 mild conscious sedation and N = 15 GA		(FARAPULSE™, Boston Scientific)	conversion to GA in the mild conscious sedation arm	required conversion to GA due to non-tolerance of the procedure. - median pain score 45/100 (IQR, 22.5–72.5), discomfort 0/100 (IQR, 0–12.5), anxiety was 10/100 (IQR, 0–10) - no respiratory depression, apnea, or hypotension necessitating use of reversal agents, nor was airway support required		(14.3%) mild conscious sedation and 3/9 (33.3%) GA patients had recurrence of AF (p = 0.585).
Weyand et al. (10)	retrospective	Deep sedation: propofol and remifentanil	Paroxysmal and persistent AF, n = 30	PVI, Re-PVI, anterior mitral line or lateral mitral isthmus ablation in isolated PVs	Focal PFA, (CENTAURI, Galaxy Medical),	Primary procedural endpoint: acute success of the procedure (isolation of all PV, bidirectional linear anatomical block of additional ablation), further sedation-related	N = 1 map-shift; no intubation or mask ventilation Primary endpoint achieved in all patients.	N = 1 coronary spasm	Not reported

						endpoints, need for intubation, mapshift requiring remapping, and any oxygen drop requiring mask ventilation			
Iacopino et al. (11)	Single-center, observational, prospective, nonrandomized fashion	Deep sedation: midazolam, fentanyl, ketamine	Paroxysmal and persistent AF, N = 66	PVI	Pentasplin e PFA catheter (FARAPULS E™, Boston Scientific)	To report experience of a protocol for deep sedation with ketamine in spontaneous respiration during the PFA of AF	No anesthesia-related complications were reported	No major procedure related complications were reported	Not reported
Iacopino et al. (12)	Single-center, observational, prospective, nonrandomized fashion	Deep sedation: midazolam, fentanyl, ketamine	Paroxysmal and persistent AF. N = 117	PVI	Pentasplin e PFA catheter (FARAPULS E™, Boston Scientific)	To assess anesthetic strategy and ablation outcomes involving deep sedation, focused on the enhancement and streamlining of mapping and ablation conditions	No significant drop of oxygen saturation or blood pressure	No adverse events	3/53 patients (5.7%) with 6-month follow-up had a recurrence of AF/atrial tachycardia

Jiang et al. (13) *PF-Beat-AF study*	prospective, multi-center, single-arm study; in this sub study: respiratory control group: delivering PFA energy only at the end of expiration vs. conventional group: PFA application during any phase of respiratory cycle	Conscious sedation: midazolam and fentanyl	Paroxysmal AF, N = 28	PVI and vena cava superior isolation	Variable-diameter circular catheter (AccuPulse, AccuPulse Medical Technology Co.)	Assess impact of PFA on stimulated diaphragmatic contraction and dry cough during AF ablation; diaphragmatic contraction and dry cough scores were rated from 0 (no response) to 3 (strong response)	The respiratory control group had significantly lower scores for diaphragmatic contraction ($p < 0.01$) and dry cough ($p < 0.001$) in all PVs compared with the control group. The average relative reductions in scores for all PVs were 33–47% for diaphragmatic contraction and 67–83% for dry cough.	No acute adverse events were reported for any of the 28 patients within 7 days after the procedure	Not reported
Galuszka et al. (14)	Single-center comparison	deep sedation: midazolam, fentanyl, and propofol	Paroxysmal and persistent	PVI	Pentasplin e PFA catheter (FARAPULS	To compare feasibility and safety of a deep sedation	Periprocedural conversion to GA in 1/427 (0.23%) PFA, 2/410	Not reported	Not reported

			AF, N = 1049 patients (PFA in 429 patients [41%], cryoballoon in 412 [39%], and radiofrequency in 208 [20%])		E^{TM}, Boston Scientific)	protocol in PFA, cryoballoon and radiofrequency ablation	(0.49%) cryoballoon, and 0/208 (0%) radiofrequency patients (PFA versus cryoballoon p = 0.485; PFA versus radiofrequency p = 0.672; cryoballoon versus radiofrequency p = 0.440): N = 2 insufficient analgosedation resulting in pain and patient movement in 2 cases N = 1 airflow obstruction in patient with chronic obstructive pulmonary disease requiring intubation and mechanical ventilation		

AF = atrial fibrillation; CTI = cavotricuspid isthmus; DAS = deep analgosedation; GA = general anesthesia; IQR = interquartile range; LSQ = Likert Scale Questionnaire for patient satisfaction; MI = mitral isthmus; PFA = pulsed field ablation; PV = pulmonary vein; PVI = pulmonary vein isolation; PWI = posterior wall isolation; RCT = randomized controlled trial; TIVA = total intravenous anesthesia.

References:

1. Sochorová V, Kunštátová V, OsmanČík P, et al. COnventional vs. Optimized PERiprocedural Analgosedation vs. Total IntraVEnous Anesthesia for Pulsed-Field Ablation: a Three-Arm Randomized Controlled Trial (COOPERATIVE-PFA). Circulation 2025.
2. Schmidt B, Bordignon S, Tohoku S, et al. 5S study: Safe and simple single shot pulmonary vein isolation with pulsed field ablation using sedation. Circ Arrhythm Electrophysiol 2022;15:e010817.
3. Grimaldi M, Quadrini F, Caporusso N, et al. Deep sedation protocol during atrial fibrillation ablation using a novel variable-loop biphasic pulsed field ablation catheter. Europace 2023;25.
4. Duytschaever M, De Potter T, Grimaldi M, et al. Paroxysmal atrial fibrillation ablation using a novel variable-loop biphasic pulsed field ablation catheter integrated with a 3-dimensional mapping system: 1-year outcomes of the multicenter inspIRE study. Circ Arrhythm Electrophysiol 2023;16:e011780.
5. Wahedi R, Willems S, Feldhege J, et al. Pulsed-field versus cryoballoon ablation for atrial fibrillation-Impact of energy source on sedation and analgesia requirement. J Cardiovasc Electrophysiol 2024;35:162–170.
6. Patel R, Sam R, Singh L, et al. Feasibility of deep sedation for catheter ablation of atrial fibrillation using pulsed field ablation. J Interv Card Electrophysiol 2025;68:1283–1286.
7. Rillig A, Hirokami J, Moser F, et al. General anaesthesia and deep sedation for monopolar pulsed field ablation using a lattice-tip catheter combined with a novel three-dimensional mapping system. Europace 2024;26.
8. Chen S, Liu Q, Yin X, et al. 12-month outcomes of pulsed-field ablation with a variable-diameter circular catheter for paroxysmal atrial fibrillation: Insights into conscious sedation and fluoroscopy use. Int J Cardiol 2025;429:133135.
9. Calvert P, Mills MT, Murray B, et al. Feasibility of pulsed field ablation for atrial fibrillation under mild conscious sedation. J Interv Card Electrophysiol 2025;68:1429–1436.
10. Weyand S, Adam V, Biehler P, et al. Focal pulsed field ablation for atrial arrhythmias: Efficacy and safety under deep sedation. J Clin Med 2024;13.
11. Iacopino S, Colella J, Dini D, et al. Sedation strategies for pulsed-field ablation of atrial fibrillation: Focus on deep sedation with intravenous ketamine in spontaneous respiration. Europace 2023;25.
12. Iacopino S, Filannino P, Artale P, et al. investigating deep sedation with intravenous ketamine in spontaneous respiration during pulsed-field ablation. J Cardiothorac Vasc Anesth 2024;38:148–154.
13. Jiang R, Liu Q, Chen L, et al. Respiratory control minimizes diaphragmatic contraction and dry cough during pulsed-field ablation of atrial fibrillation. Europace 2023;26.
14. Galuszka OM, Kueffer T, Madaffari A, et al. Comparison of the feasibility and safety of a deep sedation protocol for pulmonary vein isolation with pulsed field ablation, cryoballoon ablation, and radiofrequency ablation. J Am Heart Assoc 2024;13:e033210.