Future Development Directions of Atrial Fibrillation Treatment: Post-Print of Hybrid Ablation

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Date: 2022-10-28T00:00:00+00:00

Abstract

As a common arrhythmia in clinical practice, atrial fibrillation has been demonstrated to be associated with major adverse cardiovascular events (heart failure, severe stroke, and myocardial infarction). The global patient population currently exceeds 33 million, with prevalence projected to more than double over the next 40 years. For many years, substantial efforts have been dedicated to elucidating the pathophysiological mechanisms of atrial fibrillation and developing improved therapeutic approaches. The management of atrial fibrillation remains a clinical challenge, with no universal consensus on the optimal treatment modality or ablation energy selection. Recently, close collaboration between cardiac surgeons and electrophysiologists has led to the emergence of a novel therapeutic strategy for atrial fibrillation—the hybrid ablation model—integrating catheter and minimally invasive surgical ablation. This hybrid approach overcomes the limitations and adverse outcomes associated with catheter ablation and minimally invasive surgery alone, achieving considerable success in treating persistent atrial fibrillation, particularly long-standing persistent atrial fibrillation. This article reviews the pathogenesis, classification, and evolutionary history of ablation therapy for atrial fibrillation, summarizes and analyzes current research findings on the hybrid ablation model, and provides a concise overview of this innovative treatment strategy.

Full Text

Hybrid Ablation: Future Directions in the Management of Atrial Fibrillation

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Abstract: Atrial fibrillation, as a common clinical arrhythmia, has been proven to be associated with serious adverse cardiovascular events (heart failure, severe stroke, and myocardial infarction). Currently, the number of patients worldwide exceeds 33 million, and the prevalence is expected to more than double within the next 40 years. Over the years, substantial efforts have been devoted to exploring the pathophysiological mechanisms of atrial fibrillation and developing improved treatment methods. However, the management of atrial fibrillation remains a challenging problem in clinical medicine, with no consensus on the optimal treatment modality or choice of ablation energy. In recent years, close collaboration between cardiac surgeons and electrophysiologists has given rise to a novel treatment strategy for atrial fibrillation—the hybrid ablation mode—combining catheter and minimally invasive surgical ablation. This hybrid approach overcomes the disadvantages and adverse outcomes associated with catheter ablation and minimally invasive surgery alone, achieving considerable success in treating persistent atrial fibrillation, particularly long-standing persistent atrial fibrillation. This article reviews the pathogenesis, classification, and historical development of ablation therapy for atrial fibrillation, summarizes and analyzes current research findings on hybrid ablation, and provides a brief overview of this emerging treatment strategy.

Key words: Atrial fibrillation; Endocardial catheter ablation; Surgical ablation; Hybrid ablation; Research progress

1. Pathogenesis of Atrial Fibrillation

Atrial fibrillation (AF) results from discordant electrical activity in the atria, leading to ineffective myocardial contraction and eventual structural changes (remodeling). The electrocardiographic characteristics include irregular R-R intervals and the absence of distinct P waves. The mechanisms of AF initiation and maintenance remain incompletely understood, with multiple hypotheses proposed. The most widely accepted theories are the "focal activation theory" and the "multiple wavelet reentry hypothesis." It is now widely recognized that AF is not determined by a single pathophysiological mechanism but rather results from the interplay of multiple mechanisms. The multiple wavelet reentry hypothesis posits that atrial tissue remodeling creates multiple distinct excitable zones that generate independent wavefronts propagating along random pathways, forming reentrant circuits that collide and produce irregular atrial fibrillation. This theory has become the basis for the design of the Maze procedure. In contrast, the focal activation theory, which underlies pulmonary vein isolation, proposes that automatic depolarization of atrial cells generates

ectopic tachycardia that disrupts atrial electrical activity. The most common anatomic sources of ectopic beats triggering AF are abnormal automaticity cells within the muscular sleeves of pulmonary veins, vena cavae, and cardiac veins, with pulmonary vein sources accounting for 90% of cases. Additional mechanisms include the "leading circle with fibrillatory conduction theory," which describes disorganized macro-reentrant activity in the form of small spiral reentrant drivers (rotors). Some researchers have likened these rotors to the "vortex" of a tornado, with superimposed reentry triggering "storms" of atrial fibrillation.

2. Classification of Atrial Fibrillation

The 2014 AHA/ACC/HRS guidelines for AF management explicitly defined "valvular AF" as AF associated with moderate-to-severe mitral stenosis (amenable to surgical intervention) or mechanical heart valve replacement. AF with mild mitral stenosis, mitral valve repair, or bioprosthetic valve replacement was classified as "non-valvular AF." However, current guidelines no longer recommend terms such as "lone AF," "valvular/non-valvular AF," and "chronic AF." According to the latest ESC/CCS guidelines, AF is classified as a supraventricular tachyarrhythmia into paroxysmal, persistent, long-standing persistent, and permanent categories (Table 1). The guidelines also distinguish between clinical AF, subclinical AF, and atrial high-rate episodes (AHRE). Clinical AF refers to electrical events detected by 12-lead ECG for $ $30 seconds (characterized by irregular R-R intervals and absent P waves). AHRE denotes atrial tachycardia recorded by cardiac implantable electronic devices for $ $5 minutes at $ $175 beats/min. Subclinical AF includes atrial tachycardia, AF, and atrial flutter detected by implanted or wearable electronic devices (confirmed after physician review).

3. Indications for AF Ablation

The 2012 HRS/EHRA/ECAS expert consensus statement addressed indications for AF ablation (both surgical and catheter-based): (1) For all symptomatic AF patients undergoing cardiac surgery, concomitant surgical AF ablation should be considered; (2) Catheter ablation may be considered for paroxysmal or persistent AF patients who have failed antiarrhythmic drug therapy (Class IIa recommendation); (3) Surgical ablation is preferred for long-standing persistent AF patients who have failed antiarrhythmic therapy (Class IIb recommendation); (4) Surgical ablation as a standalone procedure may be considered for AF patients who have failed both antiarrhythmic drugs and catheter ablation (Class IIb recommendation); (5) Standalone surgical ablation is not recommended for AF patients who have not attempted antiarrhythmic drug therapy (Class III recommendation).

The 2016 ESC/EACTS guidelines for AF management further elaborated on ablation indications: (1) Catheter or surgical ablation should be considered for symptomatic control in permanent or long-standing persistent AF patients who have failed antiarrhythmic therapy (Class IIa recommendation); (2) Minimally

invasive pulmonary vein isolation should be considered after failed catheter ablation for symptomatic AF; Maze procedure should be considered for refractory symptomatic AF or recurrent AF post-ablation to alleviate symptoms (Class IIa recommendation); (3) In patients undergoing cardiac surgery, concomitant Maze procedure should be considered for symptomatic AF patients and may be considered for asymptomatic AF patients to improve long-term outcomes (Class IIb recommendation). The guidelines also recommend that AF surgical and catheter ablation be performed by an "AF Heart Team" comprising interventional electrophysiologists, cardiologists with expertise in antiarrhythmic therapy, and cardiac surgeons with expertise in surgical AF treatment.

4. Historical Development of Ablation Therapy

4.1 History of Surgical Ablation In 1987, Cox and colleagues reported the first surgical strategy for AF treatment. After performing computerized mapping of AF in animals and humans, Cox' s team developed the "Maze procedure" (also known as "Cox-Maze procedure") for "drug-refractory AF." The fundamental principle originated from experimental studies by Allessie and Schuessler. Through open-heart surgery, the "cut-and-sew" technique created "maze" pathways from the sinoatrial node to the atrioventricular node in both atria, forming linear lesions that create electrical conduction block between atrial regions to eliminate reentrant wavelets and restore sinus rhythm. This approach validated Moe' s multiple wavelet reentry hypothesis. Further evolution produced the Cox-Maze III procedure, which included left and right atrial appendage excision, sutures between the superior and inferior vena cava and between the inferior vena cava-tricuspid valve isthmus, isolation of pulmonary veins and posterior left atrium, and sutures from the mitral valve to the pulmonary veins. The Cox-Maze III became the gold standard for surgical AF treatment, achieving excellent results in refractory AF. However, its complexity prolonged cardiopulmonary bypass time and increased complication rates, leading to gradual replacement by the Cox-Maze IV procedure, which utilizes multiple energy sources for ablation lesions [Figure 1: see original paper]A and B.

Prasad et al. conducted a long-term follow-up study of 198 patients with paroxysmal and persistent AF who underwent Cox-Maze III (mean follow-up 5.3 years), reporting freedom from AF in approximately 95% of patients at five years, with a major complication rate of 12%, including two perioperative deaths. The Cox-Maze IV procedure aimed to reduce surgical complexity and operative time by decreasing the time required to construct atrial "maze" circuits. With growing understanding of AF pathophysiology, particularly the sources of abnormal pacemaking (typically located in pulmonary veins), further modifications simplified the Cox-Maze IV: left atrial appendage (LAA) excision and bilateral pulmonary vein isolation (PVI) [Figure 2: see original paper]. Alternative energy sources (radiofrequency, cryoablation, and microwave) emerged during continuous refinement, further simplifying the procedure. Simultaneously, minimally

invasive techniques such as video-assisted thoracoscopic surgery (VATS) were developed for AF ablation and could be performed as standalone cardiac surgical procedures.

4.2 History of Catheter Ablation Catheters were first applied to the heart in the 1960s, initially limited to electrical signal recording and cardiac stimulation. Durrer et al. first reported intracardiac catheter use for recording intracardiac electrical signals in patients with Wolff-Parkinson-White (WPW) syndrome. In 1979, a patient undergoing electrophysiologic study for recurrent syncope accidentally developed complete atrioventricular (AV) block. It was hypothesized that contact between the intracardiac bipolar recording catheter and the bundle of His allowed externally delivered direct current energy to be transmitted through the recording catheter, resulting in complete AV block. This catheter-mediated AV block was subsequently confirmed in later studies. Scheinman et al. then reported a study in which five patients with drug-refractory supraventricular tachycardia underwent AV node ablation using high-energy direct current shocks delivered via intracardiac electrode catheters after pacemaker implantation, achieving satisfactory results.

Although high-energy direct current catheter ablation had value in early arrhythmia treatment, serious adverse events (including cardiac tamponade and sudden death) represented major drawbacks. Continuous high-energy direct current created irregular electrical arcs on the myocardial surface, generating shock waves of varying sizes during rapid transmission through cardiac conduction tissue, ultimately causing barotrauma. In the late 1980s, the introduction of radiofrequency (RF) energy for catheter ablation led to a surge in RF catheter ablation and abandonment of high-energy direct current ablation. In the early 1990s, due to the complexity and invasiveness of the Maze procedure, RF catheter ablation for various arrhythmias gained attention. Numerous studies demonstrated that RF catheter ablation could modify AV nodal conduction structure through accessory pathway ablation, proving effective for treating AV nodal reentrant tachycardia, ventricular tachycardia, and atrial flutter.

5. Hybrid Ablation Mode for Atrial Fibrillation

For many years, interventional rhythm control methods have been widely used to treat symptomatic AF refractory to medical therapy. The Cox-Maze III procedure, as a standalone AF ablation approach, was once considered the gold standard for surgical AF treatment but was complex and required cardiopulmonary bypass. The modified Cox-Maze IV procedure further simplified the technique by using alternative energy sources (RF, cryoablation, microwave) to reduce bypass time. However, current surgical ablation methods cannot fully utilize precise mapping of ablation circuits to target arrhythmic tissue. Since the inception of interventional catheter ablation for AF, the technique has advanced considerably. The most common method is endocardial catheter-based pulmonary vein isolation, which works well for paroxysmal AF but has lower

success rates in persistent and long-standing persistent AF patients. Moreover, while endocardial catheter ablation shows reasonable short-term efficacy, success rates do not remain stable over time, with recurrence rates continuously increasing. A long-term follow-up study (>3 years) found freedom from atrial arrhythmias in 54.1% of paroxysmal AF patients after catheter or standalone surgical ablation, compared to only 41.8% in persistent or long-standing persistent AF patients. Recurrence rates are even higher in patients with significant cardiac structural abnormalities, such as marked left atrial enlargement or hypertrophic cardiomyopathy. These limitations of surgical and catheter ablation alone have led to the development of the hybrid ablation mode, which combines both methods to provide a new treatment option for AF rhythm control. The 2016 ESC guidelines for AF management defined hybrid therapy as only the combination of antiarrhythmic drugs (AAD) and endocardial catheter ablation —a narrow definition yielding unsatisfactory results without avoiding AAD adverse events. In recent years, expert consensus and research data indicate that appropriate hybrid therapy should involve planned combination of surgical and catheter ablation.

5.1 Basic Principles of AF Hybrid Ablation AF hybrid ablation is a closed-chest, minimally invasive procedure performed on the beating heart, combining epicardial RF ablation and endocardial catheter ablation to treat AF while avoiding sternotomy and cardiopulmonary bypass. In persistent AF, hybrid ablation enables extensive isolation of pulmonary veins and the posterior left atrium, not only eliminating ectopic foci within pulmonary veins but also addressing reentrant circuits and abnormal potentials in these regions. Through thoracoscopic access, hybrid ablation can deliver RF energy to the epicardium to create a "box" lesion (isolating all four pulmonary veins and the posterior left atrium) [Figure 3: see original paper], and ablate lesions near ganglionated plexi and the ligament of Marshall under direct visualization, reducing the risk of aortoesophageal fistula after endocardial catheter ablation. The left atrial appendage can also be excised during the epicardial procedure when necessary. Meanwhile, the endocardial catheter ablation component of hybrid ablation allows electrophysiologic mapping to identify and treat residual gaps after surgical ablation (including mitral isthmus near the left circumflex artery, coronary sinus, and cavotricuspid isthmus lesions) and to customize ablation lines according to individual patient needs.

5.2 Indications for AF Hybrid Ablation Current research on hybrid AF ablation remains limited, with scarce available data. A multicenter study reported that freedom from AF or any atrial arrhythmia at one year after hybrid ablation ranged from 66% to 95%, with 52% to 81% of patients free from antiarrhythmic drugs after three months. Additionally, Gersak et al. reported long-term follow-up data showing 81% sinus rhythm (SR) maintenance at four years post-hybrid ablation, though this was a single-center retrospective study with small sample size requiring further long-term data support. These results

are encouraging, particularly since the procedure has been used in refractory AF populations. Some researchers suggest that hybrid epicardial-endocardial AF ablation may be considered for symptomatic persistent or long-standing persistent AF patients refractory to pharmacologic or conventional endocardial catheter ablation. While numerous studies have confirmed the effectiveness of hybrid AF ablation for refractory AF, no unified consensus exists regarding indications. Initially, collaborative teams of cardiac surgeons and electrophysiologists applied strict inclusion criteria . With advancing medical technology and ensured patient safety, indications have been broadened to relative contraindications after patient reassessment .

5.3 Energy Sources for AF Hybrid Ablation Early efforts to improve ablation efficiency, promote recovery, and reduce complications led to the exploration of various alternative energy sources for surgical and catheter ablation, including radiofrequency, cryoablation, microwave, and pulsed electric field. RF ablation has become mainstream due to its widespread application and proven efficacy. The technique of creating transmural and continuous scar tissue rings around pulmonary veins using RF point-by-point ablation with 3D mapping has been developed in many centers. In recent years, 3D mapping and catheter ablation systems based on different energy sources have been developed, significantly improving safety, efficiency, and effectiveness. In endocardial catheter ablation, balloon-based technologies using multiple energy sources, circular multielectrode, and contact-tip electrode ablation systems have been developed. For surgical ablation, clamp devices (bipolar RF pulmonary vein clamps and linear ablation pens) have been developed to improve lesion transmurality.

5.3.1 Cryoablation Cryoablation was first applied by Gallagher et al. for WPW syndrome treatment. The principle involves evaporative cooling of liquid refrigerants (nitrous oxide and argon) within a balloon, causing rapid temperature drops that damage or kill myocardial cells with abnormal rhythms. Cox et al. initially applied this energy source in minimally invasive surgery for the Cox-Maze III procedure, performing a 7cm right thoracotomy with cardiopulmonary bypass via aortic, femoral venous, and superior vena caval cannulation, using endocardial cryoablation instead of "cut-and-sew" techniques. In 2012, Johnsson et al. highlighted the role of cryoablation in restoring and maintaining SR in mitral valve disease. In a multicenter prospective study of 69 patients undergoing mitral valve replacement or repair, those receiving concomitant cryoablation showed 73.3% SR restoration at 6 or 12 months, compared to 45.7% and 42.9% in those undergoing mitral surgery alone at 6 and 12 months, respectively. Although cryoablation has proven safe and effective for AF treatment, its implementation can cause blood coagulation from freezing, leading to thromboembolic events.

5.3.2 Radiofrequency Ablation As the first alternative energy source applied in AF surgery, RF ablation achieves isolation by delivering RF current to

inactivate myocardial cells with abnormal rhythms. It has been widely used in both endocardial and epicardial ablation. In point-by-point RF ablation, Breda et al. reported that RF energy can rapidly achieve complete transmurality at ablation targets, improving surgical efficiency and reducing complications. In 2014, Phan et al. conducted a meta-analysis of 16 randomized controlled trials on AF RF ablation, demonstrating that RF energy is effective and safe for restoring SR during concomitant cardiac surgery. Domestic literature also supports RF efficacy in surgical ablation. Li et al. analyzed 191 rheumatic valve disease patients undergoing valve surgery with concomitant AF RF ablation, finding 79.11% maintained SR at one-year follow-up. With the growing emphasis on minimally invasive concepts, RF application in endocardial catheter ablation has expanded. Early multicenter studies by Williams et al. described effective endocardial RF catheter application for pulmonary vein isolation, with 81% of 48 patients restoring SR during 4-month follow-up and 87.5% survival. With continuous development, multi-electrode RF catheters have been developed for endocardial ablation. Studies reported multi-electrode catheter RF application in epicardial surgical ablation for 40 patients with mitral valve disease, showing 76.9% SR restoration at mean 11.6-month follow-up, with significant left atrial diameter reduction and restored contractility.

5.3.3 Other Energy Sources Beyond conventional RF and cryoablation, several special energy sources exist. In 2002, Gillinov et al. used microwave energy in 10 patients undergoing mitral valve replacement and pulmonary vein isolation, observing complete transmural lesions. However, studies suggest microwave ablation is less effective than RF. Lin et al. compared 93 patients receiving bipolar RF ablation versus 94 receiving microwave ablation during valve surgery, finding significantly higher SR conversion with RF at three-month follow-up. Ultrasound has also been applied due to its minimally invasive characteristics. Ultrasound ablation induces cellular degeneration through thermal effects, achieving transmurality and tissue isolation without damaging adjacent structures. In 2001, Brick et al. began using ultrasound for unipolar endocardial catheter ablation, restoring SR in AF patients. Intraoperative ultrasound ablation reduces operative time while providing better understanding of left atrial and pulmonary vein structural roles in chronic AF. Ninet et al. demonstrated ultrasound advantages in a multicenter prospective study, creating transmural lines around the left atrium without cardiopulmonary bypass. Using high-frequency ultrasound EpiCor (St. Jude Medical Inc.) for epicardial surgical ablation in 103 AF patients, 85% maintained SR at 6-month follow-up.

Pulsed electric field has recently emerged as a future alternative energy source for AF ablation. Pulsed field ablation (PFA), also known as irreversible electroporation, uses multiple short-duration, high-voltage pulses as ablation energy, creating a non-thermal ablation process (without Joule heating) that effectively induces electroporation in target myocardial cells (extracellular cations enter cells, altering osmotic pressure and causing cell fragmentation and death). Experimental data demonstrate that PFA offers higher safety than RF or cryoab-

lation, selectively affecting myocardial cells without damaging blood vessels, nerves, or surrounding cardiac structures (lungs, esophagus, phrenic nerve), thereby avoiding complications from collateral tissue damage. PFA also acts faster, requires less intimate catheter-tissue contact, and produces more continuous and uniform ablation scars. Recent studies have reported PFA for pulmonary vein isolation in AF patients, using different catheter designs to demonstrate acute PVI feasibility, including a 14-electrode circular catheter and a length-adjustable linear catheter containing 20 independent electrodes.

5.4 Ablation Devices and Materials Initially, unipolar RF devices were developed for surgical AF ablation. While effective, they had significant drawbacks. Unipolar RF devices (such as unipolar linear ablation pens) require the ablation electrode and negative electrode pad on the patient' s body to form a circuit, often failing to achieve complete transmurality. Additionally, using the body as an electrical circuit delivers substantial energy, potentially damaging low-impedance tissues like the esophagus and causing complications. Subsequently, AtriCure introduced bipolar RF ablation clamps that achieve complete transmurality in clamped tissue while focusing the RF circuit exclusively on target tissue, perfectly avoiding damage to other body tissues. On December 14, 2011, the FDA approved AtriCure' s Synergy™ RF ablation system PMA for persistent and long-standing persistent AF patients. Canale et al. confirmed in a 2011 retrospective study that 68% of patients maintained SR at 14 months post-bipolar RF ablation, with 73% converting within 7 months. A 2018 study from the Royal Adelaide Hospital Cardiac Center revealed that contact pressure and ablation efficacy are closely related to clamp engineering design. Bipolar RF clamps feature two curved, parallel upper and lower jaws that enable continuous, full electrode-tissue contact when closed, further validating their rationale for AF ablation. Domestic studies comparing unipolar and bipolar RF for AF ablation found both effective for chronic AF, but bipolar RF more convenient and efficient. Since 2005, China' s Med-Zenith Medical Device Company has focused on cardiovascular disease research, developing a disposable sterile bipolar RF clamp (model MZ-RFK) for surgical AF ablation. In 2012, clinical trials were conducted at several centers including Beijing Anzhen Hospital, Zhongshan Hospital of Fudan University, and TEDA International Cardiovascular Hospital, achieving favorable results.

With maturing endocardial catheter ablation technology, various novel catheter materials have been developed. Multi-electrode circular RF ablation catheters, for instance, allow creation of circular ablation lines at PV ostia during multiple transmural ablations, simplifying pulmonary vein isolation. First-generation multi-electrode catheters are no longer used because electrode overlap caused tissue and blood overheating, leading to asymptomatic cerebral embolism. Second-generation multi-electrode ablation catheters (PVAC GOLD™, Medtronic) are now clinically applied, reducing transmural time and significantly decreasing procedure duration. However, some studies report that PVAC catheters may affect postoperative survival. Balloon ablation catheters based on multiple energy

sources (laser, cryo) have also been developed. Early cryoballoon catheters (Arctic Front Advance™, Boston) used liquid nitrous oxide injected into balloons to freeze target tissue for PVI, cooling lesions below -40°C to freeze intracellular water and cause irreversible organelle and membrane damage for transmurality. Current second-generation cryoballoon catheters (Arctic Front Advance, Medtronic) feature 8 cryojets for single circumferential ablation, greatly simplifying and shortening PVI procedures, making cryoablation the most common alternative to RF ablation. A multicenter randomized clinical trial proved cryoballoon catheter ablation safe and effective for paroxysmal AF. The most common complication is phrenic nerve injury (2-5% incidence), though studies show most injuries are temporary and resolve with rehabilitation. A recent long-term follow-up study by Chan et al. of 122 AF patients treated with second-generation cryoballoon catheters reported 3.9% phrenic nerve injury, with 57.5% resolving by procedure end and most recovering by one year, leaving only 0.08% with persistent injury.

5.5 Surgical Approaches for AF Hybrid Ablation The hybrid ablation mode combines advantages of surgical and minimally invasive epicardial ablation with endocardial catheter ablation while minimizing drawbacks of single-modality approaches. Hybrid (epicardial and endocardial) ablation can be performed simultaneously or in stages. The simultaneous approach accesses the pericardial space through a transdiaphragmatic window to reach the posterior left atrium, avoiding pneumothorax and surrounding cardiac tissue injury. Many centers prefer the staged approach, typically performing thoracoscopic-assisted epicardial ablation first, followed by endocardial catheter ablation days to weeks later. A common hybrid procedure uses a bipolar RF probe via minimally invasive video-assisted thoracoscopy without cardiopulmonary bypass, creating ablation lines in the posterior left atrium to replicate the modified Maze strategy. Hybrid ablation provides detailed 3D anatomic mapping systems and multipolar catheters to ensure adequate pulmonary vein isolation, translesion block, and targeted ablation of incomplete arrhythmias remaining after epicardial ablation. This approach also enables ablation of difficult-to-reach epicardial regions such as the cavotricuspid isthmus, mitral isthmus, and interatrial septum. Recent literature confirms hybrid ablation as a safe technique with satisfactory outcomes, though it requires multidisciplinary collaboration with close cooperation among surgeons, electrophysiologists, and cardiologists.

5.5.1 Transdiaphragmatic Pericardial Approach This novel device accesses the pericardial space via the diaphragm to reach the posterior left atrium for epicardial ablation, simultaneously performing endocardial catheter ablation of adjacent tissue gaps to reduce hospitalizations. Studies show 12-month success rates of 75%, 67%, and 43% for paroxysmal, persistent, and long-standing persistent AF, respectively. Despite reduced success in non-paroxysmal AF, single-procedure success reached 79% at 12-month follow-up. Gersak et al. reported a multicenter prospective study of 73 non-paroxysmal AF patients under-

going transdiaphragmatic hybrid ablation, with 73% freedom from arrhythmia at 12 months. Safety studies reveal this approach avoids thoracic incisions and single-lung ventilation, reducing complication rates. However, achieving ideal ablation efficacy remains challenging. Schuessler et al. found that this hybrid mode is limited by intraoperative instrumentation, with less transmural lesion efficacy than bilateral thoracoscopic-assisted hybrid ablation.

5.5.2 Bilateral Thoracic Approach Minimally invasive thoracoscopic-assisted hybrid ablation uses endoscopic epicardial surgical ablation followed by catheter ablation, achieving Cox-Maze IV effects while avoiding sternotomy and cardiopulmonary bypass, providing optimal AF management. Under direct thoracoscopic visualization, surgeons can completely encircle the pulmonary vein antrum using bipolar RF clamps for pulmonary vein isolation. Epicardial access avoids structural damage during catheter ablation (including phrenic nerve, pulmonary vein ostia, and esophagus). The left atrial appendage can be excised during epicardial surgery to further reduce stroke risk. After epicardial surgery, electrophysiologists can perform supplementary endocardial ablation to address residual gaps in epicardial "box lines," ensure pulmonary vein isolation, and ablate regions inaccessible via epicardial approach. In patients with increased epicardial fat limiting transmurality, endocardial access can better achieve tissue penetration. In 2014, Kurfirst et al. reported 90% early conversion in 30 valvular AF patients undergoing thoracoscopic epicardial ablation followed by catheter RF ablation at three months, with 24% complication rates (7% wound infection, 7% phrenic nerve palsy, 7% conversion to sternotomy for bleeding, 3% cardiac tamponade), most occurring early post-ablation. Richardson et al. further confirmed hybrid ablation safety, showing similar AF recurrence rates at 12 months with low overall complication and mortality rates. Studies suggest thoracoscopic-assisted hybrid ablation may achieve higher success than transdiaphragmatic approaches. Krul et al. reported 80% of non-paroxysmal AF patients free from atrial arrhythmias at 12 months, while Pison et al. found 89.8% maintained SR at follow-up (>12 months).

5.6 Advantages and Challenges of AF Hybrid Ablation Standalone epicardial surgical ablation has limitations, as epicardial fat affects lesion transmurality and heat dissipation in left atrial circulation, limiting ablation depth. Endocardial catheter ablation alone risks collateral damage to adjacent cardiac structures. The hybrid approach combining both methods improves AF ablation efficacy while reducing complications. Team-based hybrid ablation allows electrophysiologists to address insufficient epicardial lesion transmurality and fill gaps in ablation lines. Timing of epicardial surgical and endocardial catheter ablation components remains controversial. Compared to staged approaches, simultaneous procedures reduce healthcare costs and typically require only one hospitalization. However, epicardial surgical ablation often causes peri-lesion edema; after edema resolution, incomplete conduction may emerge in these

areas. Staged hybrid ablation allows time for fibrotic scar formation around ablation lines, clarifying lesion status before considering endocardial catheter ablation. However, determining optimal timing between procedures remains challenging. Insufficient data exist to prove simultaneous hybrid ablation superior to staged approaches, though studies recommend endocardial catheter ablation 1-3 months after epicardial ablation.

6. Summary and Outlook

AF management continues to face significant challenges, particularly for persistent and long-standing persistent AF patients. Team-based hybrid ablation combining electrophysiology and surgical advantages offers a novel strategic concept for current AF management. Current trial data demonstrate high safety and excellent short-term efficacy of hybrid AF ablation, particularly in non-paroxysmal AF patients. However, significant variations exist among centers in surgical methods, operator expertise, staging timing, energy types, left atrial appendage management, and follow-up rigor/duration. In the future, hybrid AF ablation may become the standard treatment for persistent or long-standing persistent AF, but this requires support from extensive long-term follow-up data and further procedural refinement to improve success rates and reduce adverse events.

Author Contributions: ZHANG Ning proposed the research direction and drafted the manuscript; HOU Ming conceived and designed the article framework; MEI Bo provided funding support; JIN Weitao and TAN Xiong performed literature search and data collection; YANG Mingchuan and WANG Liang revised the initial draft; LIU Yong and LAI Yinglong reviewed the article and provided quality control, taking overall responsibility; all authors approved the final manuscript.

Conflict of Interest: The authors declare no conflict of interest.

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