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Comparative analysis of pulmonary vein isolation strategies using pulsed field, cryoballoon, and robotic magnetic navigation ablation

Xiao-Yu Liu#, Ying Liu#, Ling-Ling Qian, Jie Zheng, Ku-Lin Li, Hua-Yan You, Shi-Peng Dang, Xiao-Xi Zhao, Ru-Xing Wang

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Pulsed field ablation, robotic magnetic navigation, cryoballoon, atrial fibrillation

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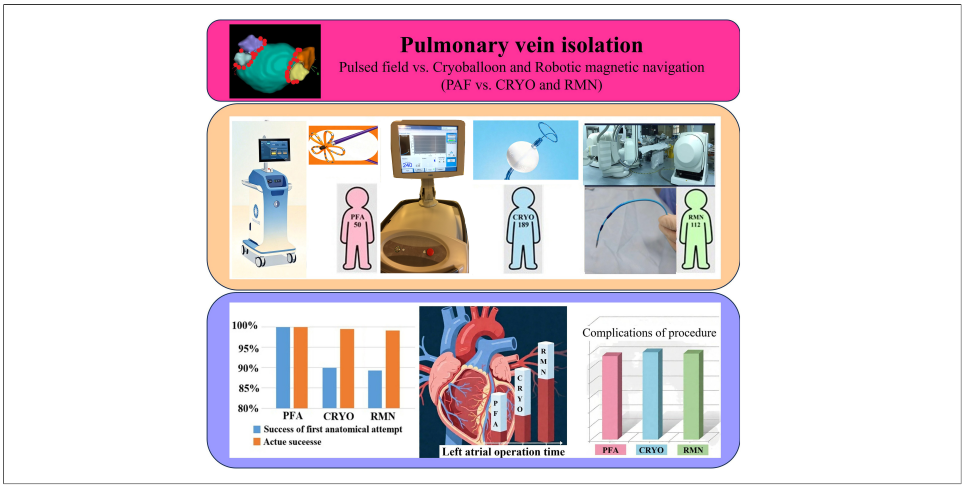

Abstract

Aim: Pulsed field ablation (PFA) has emerged as a promising strategy for catheter ablation of atrial fibrillation (AF). This study compared perioperative outcomes of pulmonary vein isolation (PVI) performed using robotic magnetic navigation (RMN), cryoballoon (CRYO) ablation, and PFA.

Methods: This retrospective study included patients with AF who underwent PVI using RMN ablation (RMN group, n = 112), CRYO ablation (CRYO group, n = 189), or PFA (PFA group, n = 50). Procedural characteristics, perioperative complications, and postoperative recovery were analyzed.

Results: Total procedure time was longer in the PFA group than in the CRYO group but shorter than in the RMN group (123.9 ± 14.0 *vs.* 98.3 ± 14.3 *vs.* 147.9 ± 19.3 min, $P < 0.001$). However, left atrial procedure time was shortest in the PFA group (26.6 ± 6.4 *vs.* 44.7 ± 12.1 *vs.* 95.1 ± 20.5 min, $P < 0.001$). Fluoroscopy time was comparable between the PFA and CRYO groups, and significantly shorter in the RMN group (15.2 ± 3.0 *vs.* 15.0 ± 3.1 *vs.*

Department of Cardiology, Wuxi People's Hospital Affiliated to Nanjing Medical University, Wuxi 214023, Jiangsu, China.
#The first two authors contributed equally to this work.

Correspondence to: Dr. Ru-Xing Wang, Department of Cardiology, Wuxi People's Hospital Affiliated to Nanjing Medical University, Wuxi 214023, Jiangsu, China. E-mail: ruxingw@aliyun.com

7.4 ± 2.5 min, $P < 0.001$). Although acute procedural success was comparable across groups, first-pass PVI was achieved more frequently with PFA than with CRYO or RMN {50/50 [100%] *vs.* 170/189 [89.9%] *vs.* 100/112 [89.3%], $P = 0.030$}. The overall incidence of perioperative complications did not differ significantly among the three groups.

Conclusion: PFA demonstrated acute safety and efficacy comparable to those of RMN and CRYO ablation for AF, while offering shorter left atrial procedure time and a higher rate of first-pass isolation.

INTRODUCTION

Pulmonary vein isolation (PVI) is the cornerstone of catheter ablation for atrial fibrillation (AF)[1]. PVI has been shown to be superior to antiarrhythmic drug therapy in preventing the recurrence of atrial arrhythmias, while also improving symptoms, exercise capacity, and quality of life[2]. The conventional approach involves manual manipulation of an ablation catheter to deliver point-by-point thermal energy at the pulmonary vein (PV) antrum, thereby achieving electrical isolation. Over time, alternative techniques, including robotic magnetic navigation (RMN) and cryoballoon (CRYO) ablation, have been introduced. However, challenges such as AF recurrence, non-selective injury to adjacent structures (e.g., the esophagus and phrenic nerve), and procedure-related complications remain unavoidable in clinical practice[3]. Consequently, the pursuit of more efficient and safer ablation technologies remains an active area of research.

In this context, Pulsed field ablation (PFA) continues to evolve. Beyond conventional continuous energy delivery, emerging evidence suggests that pulsed delivery of radiofrequency energy may offer distinct advantages. The application of pulsed energy modulation has been proposed as a strategy to achieve more controlled and predictable lesion formation, potentially reducing the risk of collateral thermal injury while maintaining ablation efficacy[4]. Collectively, these findings suggest that pulsed radiofrequency energy delivery may represent a promising avenue for improving the safety and precision of thermal ablation.

In recent years, pulsed field ablation (PFA) has emerged as a promising alternative to conventional ablation modalities for PVI[5]. PFA delivers ultrashort, high-amplitude electrical pulses to achieve non-thermal tissue ablation. Its mechanism of action, termed irreversible electroporation, induces cardiomyocyte death through the formation of permanent nanopores in the cell membrane, resulting in irreversible cellular injury independent of thermal effects (heating or freezing). The safety and efficacy of PFA have been demonstrated in several clinical trials[6-11]. Notably, the ADVANCE trial recently showed that PFA was non-inferior to RFA and CRYO ablation with respect to serious adverse events, while achieving comparable rates of acute procedural success[12]. Despite these encouraging results, the comparative performance of PFA versus established ablation strategies remains incompletely defined. In this study, we compare PFA with RMN and CRYO ablation with respect to procedural parameters and perioperative complications.

MATERIALS AND METHODS

Study population

This retrospective study included patients with AF who underwent catheter ablation at the Department of Cardiology, Wuxi People's Hospital, Affiliated to Nanjing Medical University, between January 2020 and October 2025. A total of 567 procedures were initially identified, including 176 in the RMN group, 332 in the CRYO group, and 59 in the PFA group. To ensure a more homogeneous comparison of PVI strategies, patients with persistent AF in the RMN and CRYO groups were excluded, as nearly all underwent additional left atrial (LA) roof ablation. In contrast, in the PFA group, only patients treated using the Farapulse system were included, and PVI was performed as the sole ablation strategy in both paroxysmal and persistent AF cases. Additional exclusion criteria included age < 18 or > 75 years, as well as a history of myocardial

infarction, hypertrophic cardiomyopathy, obstructive or diffuse pulmonary disease, or congenital heart disease. After applying these criteria, the final study cohort comprised 112 patients in the RMN group, 189 in the CRYO group, and 50 in the PFA group. This retrospective study was conducted in accordance with the principles of the Declaration of Helsinki. The study protocol was approved by the Research Ethics Committee of Wuxi People's Hospital (Approval No. KY25204; Approval date: November 10, 2025), and the requirement for written informed consent was waived due to the retrospective nature of the analysis. All patients underwent transesophageal echocardiography prior to the procedure to exclude the presence of LA thrombus.

Procedural preparation time

Procedural preparation time was defined as the interval from patient entry into the catheterization laboratory to the establishment of vascular access. The three ablation strategies differed primarily with respect to the type of anesthesia used, with PFA requiring general anesthesia, whereas RMN and CRYO ablation were performed under conscious sedation or general anesthesia according to operator preference and patient condition. Common procedural steps across all groups included electrocardiographic monitoring, connection to the electroanatomical mapping system, sterile skin preparation, and ultrasound-guided puncture of the femoral vein.

Pre-ablation procedural time and LA access

Pre-ablation procedural time was defined as the interval from vascular puncture to the entry of the ablation catheter into the LA. This phase was comparable across all ablation modalities and included placement of diagnostic catheters in the coronary sinus and right ventricular apex, transseptal puncture using a long sheath, and subsequent LA access with pulmonary venography. Key procedural differences were modality-specific. In RMN ablation, the ablation catheter was advanced into the LA through the long sheath and subsequently integrated with the RMN. In CRYO ablation, the long sheath was exchanged for a steerable FlexCath sheath to facilitate advancement of the balloon catheter into the LA. In PFA, the long sheath was replaced with a steerable Farapulse sheath, through which a multi-electrode, five-pole PFA catheter was introduced into the LA.

LA procedural time

PFA

Under fluoroscopic guidance, ablation was performed at the ostium and antrum of each PV using a biphasic waveform with a peak voltage of 2,000 V. A guidewire was first advanced into the target PV, followed by a two-stage catheter-based ablation protocol.

Basket-Phase Ablation: The catheter was deployed in a basket configuration within the LA and positioned at the PV ostium. Two pulse trains were delivered at each site, after which the catheter was rotated by approximately 36°, followed by an additional two applications.

Flower-Phase Ablation: The catheter was then reconfigured into a flower-shaped configuration and positioned at the PV antrum. The same application protocol as in the basket phase was repeated. Sequential isolation was performed for the left superior, left inferior, right superior, and right inferior PVs. In cases of a common PV trunk, ablation was performed either at the branch points or within the common trunk, with up to four additional applications delivered per site based on real-time electrophysiological feedback. The electrophysiological endpoint was defined as complete elimination or dissociation of all PV potentials, with additional applications performed if necessary to achieve durable isolation.

CRYO ablation

CRYO ablation was performed using a single-freeze strategy[13]. Following venographic confirmation of complete PV occlusion, a proximal seal technique was applied to position the balloon at the PV antrum. If the balloon temperature reached -40 °C within 60 s, a single 180 s freeze was delivered. If -40 °C was achieved between 60 s and 120 s, the freeze duration was extended to 240 s. If the target temperature was not reached within 120 s, the balloon was repositioned to optimize PV occlusion before reapplication of freezing. The electrophysiological endpoint was defined as complete elimination or dissociation of PV potentials, consistent with that used in the PFA group.

RMN ablation

RMN ablation was performed according to the standard protocol established at our center[14]. Briefly, a bipolar voltage map of the LA was created using a three-dimensional electroanatomical mapping system. Circumferential PV isolation was then performed under robotic magnetic guidance. Radiofrequency energy was delivered at 35 W on the anterior wall and 30 W on the posterior wall. Each lesion was applied for 30-60 s or until the local electrogram amplitude decreased by ≥ 80%. The electrophysiological endpoint was defined as complete elimination or dissociation of PV potentials, consistent with that used in the PFA group.

Procedural clear-up time

Procedural clear-up time was defined as the interval from removal of the sheath from the LA to the patient's departure from the operating room. In the RMN group, the smaller sheath size (3.67 mm) allowed hemostasis to be achieved with manual compression alone. In contrast, patients in the CRYO and PFA groups, in whom larger sheaths were used (5.0 mm and 5.6 mm, respectively), underwent figure-of-eight suture closure to achieve hemostasis. Following completion of the procedure, patients in the RMN and CRYO groups were transferred directly from the operating room. In the PFA group, patients were first transferred to the post-anesthesia care unit for extubation and recovery from general anesthesia before leaving the operating room.

Procedural recovery and follow-up

Following the procedure, sandbags were applied to both femoral venous puncture sites for 6 h to maintain compression and were removed in the absence of bleeding. During this period, patients were instructed to avoid flexion of the lower limbs. On the morning after the procedure (12-24 h postoperatively), wound dressings were changed and sutures were removed, with additional local compression applied when necessary. Patients were subsequently encouraged to ambulate and were assessed for discharge readiness. Postoperative pain intensity was evaluated using the Visual Analog Scale (VAS), a widely used 10-point scale ranging from 0 ("no pain") to 10 ("the worst pain imaginable"). Patients were asked to indicate their pain level on the scale, and the corresponding score was recorded. All patients were followed for 1 month after the procedure, with scheduled outpatient visits at 1 week and 1 month after discharge. Procedure-related complications were systematically assessed and documented during follow-up visits.

Statistical analysis

All statistical analyses were performed using IBM SPSS (Statistical Package for the Social Sciences, version 26.0; IBM Corp., Armonk, NY, USA). Continuous variables are presented as mean ± standard deviation (SD). For normally distributed variables, comparisons among groups were performed using one-way analysis of variance (ANOVA). When the assumption of homogeneity of variance was not met, Welch's ANOVA was applied. Post hoc pairwise comparisons were conducted using the Bonferroni method under equal variance assumptions and the Games-Howell method when variances were unequal. Non-normally distributed continuous variables were compared using the Kruskal-Wallis test, followed by Bonferroni-corrected pairwise comparisons where appropriate. Categorical variables were analyzed using the chi-square test, and

Table 1. Comparison of the overall procedural parameters of three groups

	RMN (n = 112)	CRYO (n = 189)	PFA (n = 50)	*P* value
Gender (male/female)	66/46	107/82	29/21	0.924
Height (cm)	166.1 ± 8.1	167.0 ± 8.6	167.8 ± 8.1	0.418
Weight (kg)	68.1 ± 10.3	69.3 ± 10.8	68.5 ± 11.0	0.602
BMI (kg/m^2)	24.6 ± 2.8	24.8 ± 3.0	24.2 ± 2.9	0.447
Age (years)	60.6 ± 9.5	61.5 ± 11.6	58.2 ± 10.6	0.201
Non-paroxysmal AF	0	0	18	< 0.001
Course of AF (month)	42.7 ± 55.6	47.4 ± 47.8	31.4 ± 43.2	0.130
Basic diseases				
Hypertension	63	116	31	0.643
CHD	16	22	5	0.693
Diabetes	12	30	4	0.226
Stroke/TIA	7	13	2	0.757
Heart failure	3	4	0	0.522
LA diameter (mm)	38.9 ± 4.8	38.1 ± 4.8	38.0 ± 6.7	0.098
LVEF (%)	63.0 ± 3.8	63.9 ± 3.3	64.0 ± 3.2	0.051
CHA_2DS_2-VASc				
0	20	27	6	0.566
1	25	49	16	0.424
2	39	74	20	0.715
3	18	25	6	0.719
4	8	10	1	0.407
≥ 5	2	4	1	0.981
Antiarrhythmic drugs				
β-block	94	176	47	0.197
Amiodarone	92	137	35	0.113
Propafenone	16	32	11	0.478

BMI: Body mass index; AF: atrial fibrillation; CHD: coronary atherosclerotic heart disease; TIA: transient ischemic attack; LA: left atrial; LVEF: left ventricular ejection fraction; RMN: robotic magnetic navigation ablation; CRYO: cryoballoon ablation; PFA: pulsed field ablation.

pairwise comparisons were adjusted using the Holm-Bonferroni method to account for multiple testing. All statistical tests were two-sided, and a P value < 0.05 was considered statistically significant.

RESULTS

Baseline characteristics of the study population

Baseline characteristics of the three groups are summarized in Table 1. Overall, the groups were well balanced, with no significant differences in sex distribution, age, height, body mass index (BMI), duration of AF, left ventricular ejection fraction, prevalence of comorbidities, or medication use. However, the distribution of AF subtype differed significantly among the three groups.

Comparison of intraoperative outcomes

Intraoperative outcomes for the three groups are summarized in Table 2 and Figure 1. Total procedure time differed significantly among groups, being longest in the RMN group, shortest in the CRYO group, and intermediate in the PFA group (147.9 ± 19.3 *vs.* 98.3 ± 14.3 *vs.* 123.9 ± 14.0 min, P < 0.001). In contrast, LA procedural time was significantly shorter in the PFA group than in both the CRYO and RMN groups (26.6 ± 6.4 *vs.* 44.7 ± 12.1 *vs.* 95.1 ± 20.5 min, P < 0.001). Fluoroscopy time was comparable between the PFA and CRYO groups, and both were significantly longer than that in the RMN group (15.2 ± 3.0 *vs.* 15.0 ± 3.1 *vs.* 7.4

± 2.5 min, $P < 0.001$). However, radiation exposure in the PFA group was lower than in the CRYO group but higher than in the RMN group (372.8 ± 90.2 *vs.* 488.4 ± 278.8 *vs.* 202.8 ± 66.7 mGy, $P < 0.001$). Acute procedural success was achieved at a similarly high rate across all groups. However, the rate of successful first-pass PVI was significantly higher in the PFA group than in the CRYO and RMN groups {100% [50/50] *vs.* 89.9% [170/189] *vs.* 89.3% [100/112], $P = 0.030$}.

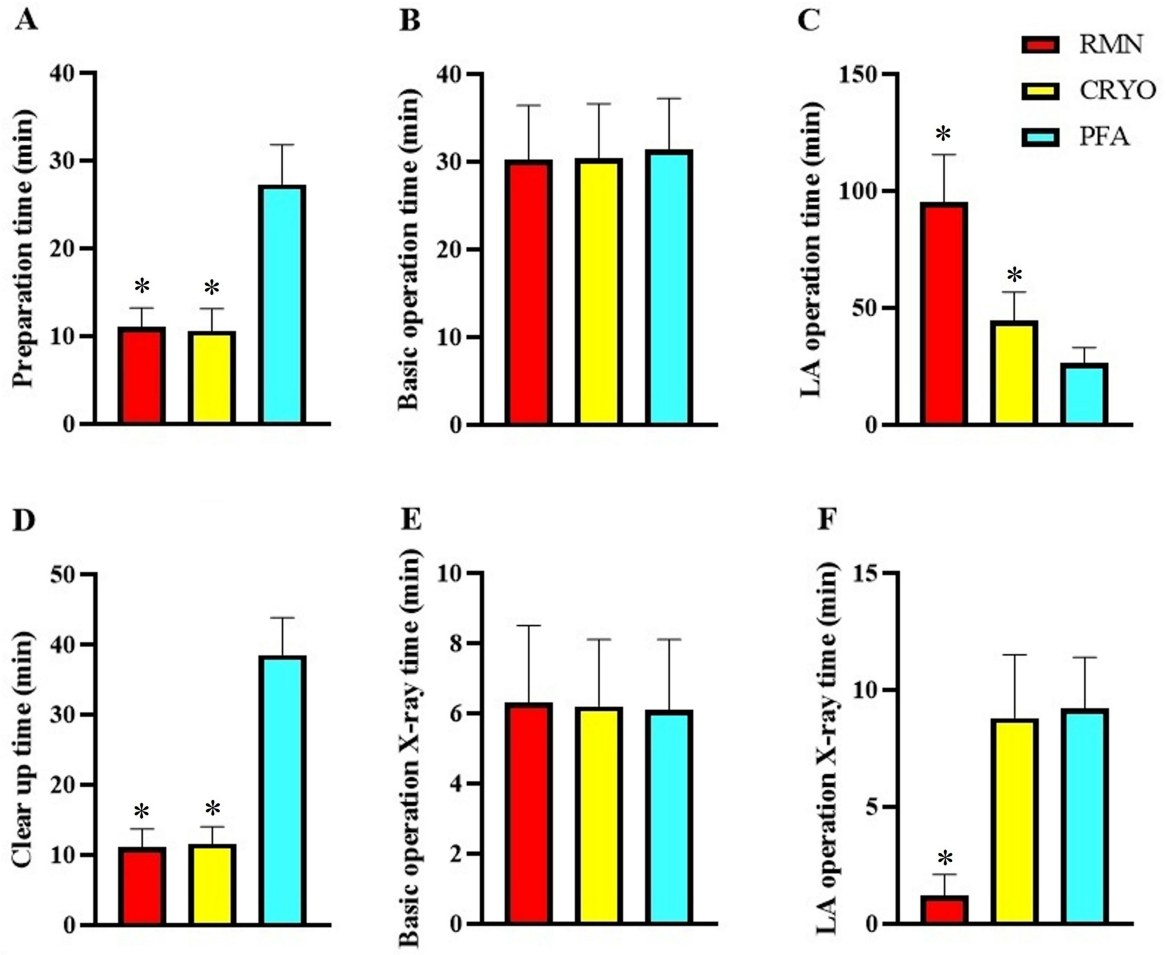

Figure 1. Procedural duration and fluoroscopy time at each procedural stage among the three ablation strategies. (A) Preparation time; (B) Pre-ablation procedural time; (C) LA procedural time; (D) Post-procedural completion time; (E) Fluoroscopy time during the baseline procedural phase; (F) Fluoroscopy time during the LA procedural phase. LA: Left atrial; RMN, robotic magnetic navigation ablation; CRYO, cryoballoon ablation; PFA, pulsed field ablation. *$P < 0.05$ versus the PFA group. Data are presented as mean ± standard deviation (SD). Statistical comparisons were performed using one-way analysis of variance (ANOVA) for normally distributed variables; Welch's ANOVA was applied when homogeneity of variance was not met. Post-hoc pairwise comparisons were performed using the Bonferroni method when variances were equal and the Games-Howell method when variances were unequal.

Comparison of perioperative and follow-up complications

Perioperative and follow-up complications are summarized in Table 3. No significant differences were observed among the three ablation strategies with respect to the incidence of major complications. Pericardial tamponade occurred in both the CRYO and PFA groups. Additionally, one case of persistent phrenic nerve palsy was reported in the CRYO group. Among minor complications, transient phrenic nerve palsy occurred exclusively in the CRYO group, resulting in a statistically significant difference among the three groups.

Table 2. Procedural parameters

	RMN (n = 112)	CRYO (n = 189)	PFA (n = 50)	*P* value
Procedure time (min)	147.9 ± 19.3[a]	98.3 ± 14.3[a]	123.9 ± 14.0	< 0.001
Preparation time (min)	11.0 ± 2.2[a]	10.6 ± 2.5[a]	27.3 ± 4.5	< 0.001
Basic operation time (min)	30.2 ± 6.2	30.4 ± 6.2	31.4 ± 5.8	0.473
LA operation time (min)	95.1 ± 20.5[a]	44.7 ± 12.1[a]	26.6 ± 6.4	< 0.001
Clear up time (min)	11.1 ± 2.6[a]	11.6 ± 2.4[a]	38.5 ± 5.3	< 0.001
X-ray time (min)	7.4 ± 2.5[a]	15.0 ± 3.1	15.2 ± 3.0	< 0.001
Basic operation X-ray time (min)	6.3 ± 2.2	6.2 ± 1.9	6.1 ± 2.0	0.856
LA operation X-ray time (min)	1.2 ± 0.9[a]	8.8 ± 2.7	9.2 ± 2.2	< 0.001
X-ray dose (mGy)	202.8 ± 66.7[a]	488.4 ± 278.8[a]	372.8 ± 90.2	< 0.001
Basic operation X-ray dose (mGy)	179.4 ± 51.2	174.6 ± 86.7	170.3 ± 47.9	0.109
LA operation X-ray dose (mGy)	23.4 ± 18.2[a]	313.9 ± 238.8[a]	202.5 ± 82.4	< 0.001
General anesthesia	0 [a]	0 [a]	50	< 0.001
Classical four PV ostia	25	33	9	0.571
Success of first anatomical attempt	100 [a]	170 [a]	50	0.030
Acute success	111	188	50	1.000
Heparin (IU)	8,008.9 ± 2,621.8	7,859.8 ± 1,698.8	7,500.0 ± 1,446.3	0.894

LA: Left atrial; PV: pulmonary vein; RMN: robotic magnetic navigation ablation; CRYO: cryoballoon ablation; PFA: pulsed field ablation. [a]: Compared with the pulse group, $P < 0.05$.

Table 3. Complications of procedure

	RMN (n = 112)	CRYO (n = 189)	PFA (n = 50)	Total (n = 351)	*P* value
Complications (major)	0 (0%)	4 (2.1%)	1 (2%)	5 (1.4%)	0.341
Cardiac tamponade	0 (0%)	2 (1.1%)	1 (2%)	3 (0.9%)	0.254
Symptomatic stroke/TIA	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-
Acute coronary syndrome	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-
Persistent phrenic nerve palsy	0 (0%)	1 (0.5%)	0 (0%)	1 (0.3%)	1.000
Thromboembolism	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-
Atrioesophageal fistula	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-
Pulmonary vein stenosis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-
Acute kidney injury	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-
Symptomatic hemolysis	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-
Major bleeding event	0 (0%)	1 (0.5%)	0 (0%)	1 (0.3%)	1.000
Complications (minor)	10 (8.9%)	19 (10.1%)	1 (2%)	30 (8.5%)	0.191
Hematoma	3 (2.7%)	2 (1.1%)	1 (2%)	7 (2.0%)	0.569
Arteriovenous fistula	0 (0%)	1 (0.5%)	0 (0%)	1 (0.3%)	1.000
Transient phrenic nerve palsy	0 (0%)	8 (4.2%)	0 (0%)	8 (2.3%)	0.041
Vasovagal reaction	7 (6.3%)	8 (4.2%)	0 (0%)	15 (4.3%)	0.182

TIA: Transient ischemic attack; RMN: robotic magnetic navigation ablation; CRYO: cryoballoon ablation; PFA: pulsed field ablation.

Comparison of postoperative recovery

Postoperative recovery outcomes are summarized in Table 4. Resting wound pain, assessed using the VAS, was comparable among the three groups. However, patients in both the CRYO and PFA groups reported higher VAS scores during dressing changes or suture removal than those in the RMN group. A substantial

Table 4. Recovery of procedure

	RMN (n = 112)	CRYO (n = 189)	PFA (n = 50)	*P* value
Postoperative VAS				
0	52	74	22	0.448
1	48	87	17	0.440
2	8	15	8	0.151
3	4	13	3	0.486
≥ 4	0	0	0	-
Dressing change VAS				
0	45[a]	0	0	< 0.001
1	55[a]	19	8	< 0.001
2	8[a]	80	18	< 0.001
3	4[a]	74	22	< 0.001
≥ 4	0	16	2	0.005
Hemostasis during dressing change	3[a]	32	8	0.001
Postoperative hospital stay				
0 day	102	172	45	0.973
1 day	6	10	3	0.980
≥ 2 day	4	7	2	0.991

VAS: Visual analog scale; RMN: robotic magnetic navigation ablation; CRYO: cryoballoon ablation; PFA: pulsed field ablation. [a]: Compared with the pulse group, $P < 0.05$.

proportion of patients in all three groups experienced minor wound bleeding requiring additional compression to achieve hemostasis. Nevertheless, the duration of postoperative hospital stay was comparable across groups.

DISCUSSION

PFA, CRYO ablation, and RMN ablation are emerging catheter-based strategies developed from conventional RFA for the treatment of AF. To our knowledge, no previous study has directly compared these three modalities within the same analysis. In this comparative study, we found that: (1) PFA was associated with shorter LA procedural time and lower radiation exposure than conventional thermal ablation approaches, suggesting greater procedural efficiency; (2) the acute procedural success of PVI was similarly high across all three groups, supporting the efficacy of PFA; and (3) the overall incidence of complications was comparable among treatment strategies, although PFA was associated with fewer procedure-specific complications, indicating a favorable safety profile.

Regarding procedural efficiency, previous studies have shown that PFA significantly shortens both total procedure time and LA procedural time compared with conventional RFA[9,15,16]. Although RMN ablation has generally been reported to require longer procedure times than manual RFA[17,18], direct comparisons between PFA and RMN have been lacking. Our findings help address this gap, demonstrating that RMN was associated with the longest total procedure time, consistent with procedural expectations. Comparison between PFA and CRYO ablation appears more complex. While some studies have reported shorter procedure times with PFA, others have found no significant difference, which may reflect variations in procedural definitions and the use of three-dimensional electroanatomical mapping[19,20]. To better characterize these differences, we performed a detailed analysis of individual procedural stages. Although PFA required general anesthesia and post-anesthesia recovery, which contributed to a longer total

procedural time, it was associated with the shortest LA procedural time, consistent with previous reports[12]. Analysis of the LA procedural phase further highlighted differences among techniques. RMN required point-by-point lesion delivery and was therefore the most time-consuming. Similarly, CRYO required optimization of PV occlusion before each application, followed by a freezing cycle of 180-240 s and a subsequent thawing period, all of which contributed substantially to procedural duration. In contrast, PFA required less stringent tissue contact and involved ultrashort energy delivery, resulting in the shortest LA operation time and the lowest proportion of overall procedure time dedicated to this phase.

In terms of procedural efficacy, previous studies have demonstrated that PFA is non-inferior to both RFA and CRYO ablation with respect to acute procedural success, freedom from atrial tachyarrhythmia after the 3-month blanking period, and the incidence of serious adverse events within 1 year[5,21]. More notably, the unique properties of pulsed-field energy have been associated with higher rates of first-pass PVI compared with conventional thermal ablation strategies[22,23]. Our findings are consistent with these observations. In the PFA group, all targeted PVs in 50 patients were successfully isolated with the initial application set, without the need for supplemental ablation. In contrast, additional "touch-up" ablation or repeat freezing was more frequently required in the RMN and CRYO groups. This procedural efficiency likely reflects the mechanism of field-based ablation, which is less dependent on precise catheter-tissue contact for effective lesion formation. A limitation of the present study is the absence of long-term follow-up data at our center. Ongoing follow-up will evaluate long-term rhythm outcomes after ablation, and planned subgroup analyses will further explore potential associations between PFA efficacy and baseline patient characteristics.

Regarding radiation exposure, the available literature remains inconsistent. Some studies have reported longer fluoroscopy time and higher radiation exposure with PFA than with RFA[15,24], whereas comparisons between PFA and CRYO ablation have yielded variable results[8,12,25]. The SINGLE SHOT CHAMPION study suggested that PFA may reduce radiation exposure, with further reductions potentially achievable through integration with three-dimensional electroanatomical mapping systems[5]. Our phase-based analysis provides additional insight into these differences. During the preprocedural preparation phase, fluoroscopy time and radiation dose were broadly similar across all three groups. However, marked differences became apparent during LA manipulation. As anticipated, RMN ablation was associated with the lowest fluoroscopy time and radiation dose, reflecting its dependence on three-dimensional mapping and remote robotic catheter navigation[14]. PFA and CRYO demonstrated comparable fluoroscopy times during the LA phase, likely owing to similar requirements for real-time imaging guidance. Repeated adjustment of catheter orientation during PFA is procedurally analogous to repositioning the CRYO to achieve optimal PV occlusion under fluoroscopy. However, radiation dose was significantly lower in the PFA group than in the CRYO group. This difference likely reflects the greater reliance on repeated contrast injections during CRYO ablation for pulmonary venography and confirmation of complete vein occlusion.

In terms of safety, PFA may offer distinct advantages in reducing certain procedure-specific complications. The tissue selectivity of irreversible electroporation has the potential to limit energy-related injury to adjacent extracardiac structures, particularly atrio-esophageal injury and phrenic nerve palsy[26,27], both of which may result in severe or even life-threatening consequences. Meta-analyses have further supported the potential advantages of PFA with respect to procedural efficiency and lower risks of phrenic nerve and esophageal injury compared with conventional thermal ablation strategies[23-25]. In the present study, the overall incidence of complications was comparable among the PFA, RMN and CRYO groups. The absence of statistically significant differences may reflect the limited sample size and low event rates. Importantly, complications inherent to LA ablation procedures, including pericardial tamponade and stroke, remain relevant with PFA[20]. PFA may also be associated with procedure-specific risks, most notably intravascular hemolysis, which in severe cases can contribute to acute kidney injury[28]. However, previous studies have

suggested that clinically significant anemia or renal impairment is uncommon[29]. Consistent with current evidence, renal function was carefully assessed preoperatively in all patients, and adequate perioperative hydration was routinely provided. None of the 50 patients treated with PFA in this cohort developed symptomatic hemolysis or renal impairment, suggesting that this perioperative management approach was effective in our clinical setting[30].

Regarding perioperative recovery, although PFA requires general anesthesia and larger-diameter sheath, our findings indicate that postoperative recovery was comparable to that observed after RMN and CRYO ablation. General anesthesia has been widely adopted internationally across different catheter ablation strategies[31], and the cumulative experience from high-volume centers provides practical reassurance regarding its perioperative feasibility and safety. The larger sheath used for PFA may theoretically contribute to greater access-site discomfort and increase the need for hemostasis following suture removal. However, in our cohort these factors did not appear to influence postoperative recovery or decisions regarding hospital discharge under routine standardized care. Emerging international evidence further suggests that same-day discharge after PFA may be feasible. The non-thermal mechanism of electroporation reduces collateral tissue injury and may lower the incidence of procedure-related complications, thereby supporting more favorable early recovery and facilitating earlier discharge[32]. Nevertheless, implementation of an accelerated discharge pathway remains challenging in the current Chinese clinical setting. This is likely influenced not only by institutional workflow considerations but also by patient acceptance and expectations regarding postoperative observation.

Limitations

This study has several limitations. First, its retrospective, observational design is inherently subject to potential biases, and the findings therefore require validation in larger, well-controlled studies. Second, the sample size, particularly in the PFA group, was relatively small, largely reflecting the recent introduction of pulsed-field ablation technology. Future studies with expanded cohorts are warranted. Third, the cohort included patients with both paroxysmal and persistent AF, although the ablation strategy was applied consistent for across all patients. Fourth, this study did not examine the influence of varying pulse parameters on PFA efficacy. Systematic investigations to optimize these parameters are needed in future research. Finally, long-term follow-up data on the efficacy of the three ablation techniques are currently lacking. Ongoing follow-up at our center aims to assess medium- to long-term recurrence of AF in this cohort.

Conclusion

In this retrospective comparative study, PFA demonstrated acute safety and procedural efficacy comparable to those of established PVI techniques, including RMN and CRYO ablation. PFA was associated with the shortest LA procedural time, a higher rate of first-pass PVI, and a complication profile similar to that of the other two strategies, highlighting its procedural efficiency and favorable safety profile. These findings support PFA as a promising alternative for PVI in patients with AF, particularly given its rapid lesion delivery and tissue-selective non-thermal mechanism. Further prospective studies with larger sample sizes and long-term follow-up are warranted to confirm the durability of these outcomes and to further define the role of PFA in routine clinical practice.

DECLARATIONS

Authors' contributions

Proposed research ideas, designed research plans, and drafted papers: Liu XY

Participated in the procedure process, data collection, and analysis: Liu Y, Qian LL, Zheng J, Li KL, You HY, Dang SP, Zhao XX

Led the procedure process, guided the topic selection and design of the paper, and revised the paper: Wang RX

All authors commented on previous versions of the manuscript, and all authors read and approved the final manuscript.

Availability of data and materials

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool MedPeer AI (version v3.8.250514, released 2025-05-14) was used solely for generating preliminary graphical elements for the Graphical Abstract, including basic structural layouts, conceptual icon suggestions, and initial composition drafts. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

This retrospective study was conducted in accordance with the principles of the Declaration of Helsinki. This study has been approved by the Research Ethics Committee of Wuxi People's Hospital (Approval No. KY25204; Approval date: November 10, 2025), and the requirement for written informed consent was waived due to the retrospective nature of the analysis.

Consent for publication

Not applicable.

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