ESC European Society of Cardiology
European Heart Journal Open (2025) **5**, oeaf088
https://doi.org/10.1093/ehjopen/oeaf088

ORIGINAL ARTICLE
Arrhythmia and electrophysiology

High-frequency low-tidal volume ventilation improves long-term success in radiofrequency catheter ablation of atrial fibrillation: a meta-analysis

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Received 6 March 2025; revised 12 June 2025; accepted 24 June 2025; online publish-ahead-of-print 2 July 2025

Handling Editor: Emmanouil Charitakis

Aims High-frequency low-tidal volume (HFLTV) ventilation may improve catheter stability and enhance procedural success in radiofrequency (RF) catheter ablation of atrial fibrillation (AF). Long-term findings remained unclear.

Methods and results We conducted a meta-analysis that included all studies that directly compared AF patients who underwent RF ablation under HFLTV compared with standard ventilation. Primary outcomes included acute first-pass pulmonary vein isolation (PVI) and long-term recurrence of AF/atrial arrhythmias after 12 months. Secondary outcomes included total procedure duration, ablation time, and RF time, with pooled standardized mean difference derived using the inverse variance method. Five cohort studies (publication period: 2019–2024) were identified and included in the meta-analysis (final sample: HFLTV $n = 460$ vs. standard ventilation $n = 705$). High-frequency low-tidal volume ventilation was significantly associated with lower risk of AF recurrence after 12 months {pooled odds ratio (OR) = 0.62 [95% confidence interval (CI): 0.42–0.92]}, as well as total atrial arrhythmia [OR = 0.59 (95% CI: 0.42–0.81)], with no between-study heterogeneity ($I^2 = 0\%$). Acutely, HFLTV was associated with higher probability of first-pass PVI with borderline statistical significance [OR = 1.24 (95% CI: 0.94–1.63)]. Furthermore, HFLTV was associated with significant reductions in total procedure time [−0.71 (95% CI: −1.00 to −0.42), unit in standard deviation], ablation time [−0.83 (95% CI: −1.07 to −0.59)], and total RF time [−0.72 (95% CI: −0.85 to −0.59)] (heterogeneity $I^2 = 76\%$). Notably, there was no effect modification by paroxysmal or persistent AF ($P > 0.05$). All studies reported no major complications in either group.

Conclusion High-frequency low-tidal volume ventilation is associated with improved long-term success of arrhythmia control in AF patients who undergo RF catheter ablation, regardless of paroxysmal or persistent status.

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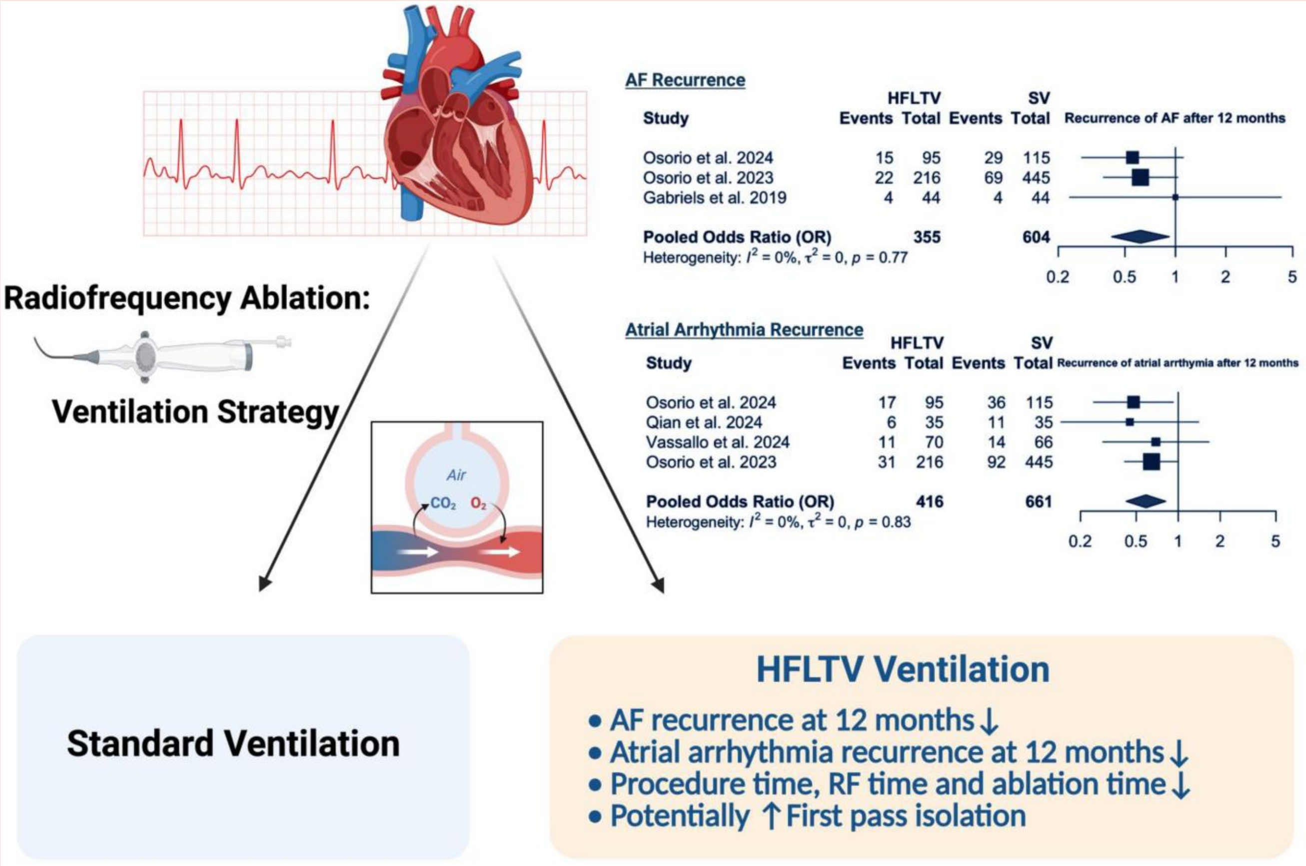
Graphical Abstract



Keywords Atrial fibrillation • Catheter ablation • High-frequency low-tidal volume ventilation

What's new?

- High-frequency low-tidal volume ventilation is associated with improved long-term success of arrhythmia control in atrial fibrillation (AF) patients who undergo radiofrequency (RF) catheter ablation.
- Such effects are similar for paroxysmal or persistent AF.
- High-frequency low-tidal volume ventilation is also associated with improved procedural efficiency, without any significant impact on complication rates.

Introduction

Catheter ablation is an established and effective treatment for patients with atrial fibrillation (AF).[1] Despite emerging strategies and interests in the ablation of various novel substrates, pulmonary vein isolation (PVI) has remained the overarching therapeutic backbone that underpins the clinical effectiveness of AF ablation. Nevertheless, improved success rates of AF ablation have generally plateaued in recent years, averaging in the range of 64–66% by a single procedure for paroxysmal AF using various technologies.[2,3] Corresponding estimates for persistent AF are lower.[3,4]

Despite newer forms of ablation technologies beyond conventional thermal ablation, such as pulsed field ablation,[5] any tangible improvement in the clinical effectiveness of AF ablation remains unclear. On the other hand, effective and cost-saving strategies that enhance the impact of existing ablation energy forms to achieve durable PVI are gaining attention. One example is the use of general anaesthesia, which has been shown to reduce pulmonary vein reconnections after PVI[6] and improve both clinical and economical effectiveness in AF ablation.[7]

Various ventilation strategies have been studied in recent years to enhance success rates of AF ablation. These include jet ventilation[8,9] and prolonged apnoeic ventilation.[10] However, each of these ventilatory approaches has its own drawback. The high-frequency low-tidal volume (HFLTV) ventilation strategy was designed to reduce thoracic excursions during AF ablation, using standard equipment at no extra costs or manpower implications. Furthermore, it does not cause any significant interruption to procedural flow. It was shown in several studies that HFLTV ventilation enhanced catheter contact force[11] and stability[12] and resulted in favourable ablation lesional characteristics.[13] These may in turn promote greater durability of PVI. It may also shorten ablation and procedural time whilst not affecting risk of complications.[14,15] Nevertheless, previous studies typically comprised small study samples. Importantly, the overall longer-term clinical efficacy in terms of AF recurrence at 12 months was uncertain.

Here, we hypothesize that HFLTV, compared with standard ventilation, may enhance overall clinical success rates of AF ablation both acutely and at 12 months and improve procedural efficiency. The present manuscript provides a meta-analysis of all currently available literature to date.

Methods

Search strategy and study selection

A systematic review and meta-analysis was performed according to the PRISMA guidelines to compare the outcomes of AF ablation procedures performed under HFLTV compared with standard ventilation (SV). 'HFLTV', 'low-tidal volume ventilation', 'high respiratory rate', 'atrial fibrillation ablation', and 'AF ablation' were used as the keywords in the search process. There were no restrictions on publication year due to the limited number of studies. The inclusion criteria of the studies included any randomized controlled trials, cohort studies, and case–control studies that compared outcomes of AF ablation under HFLTV with SV and reported at least one relevant outcome. Exclusion criteria included duplication of patient samples, non-AF patients, and performing AF ablation under other ventilation strategies. The literature search was performed on PubMed, Scopus, Web of Science, and Embase, with the last search conducted on 2 January 2025.

One investigator collected procedural and long-term outcomes data, including first-pass PVI, procedure time, ablation time, total radiofrequency (RF) time, and recurrence of atrial arrhythmias and AF after 12 months (H.-Y.L.). These were independently verified by a senior investigator (Y.-H.W.C.). Procedure time was defined as the duration from the initial femoral puncture to the removal of the catheter; ablation time was measured from the first to the last PVI lesion that achieved bidirectional block; RF time refers to the time that RF energy was applied.[11] Baseline characteristics in both treatment and control groups were also collected and compared.

The primary outcomes were defined as long-term and acute success of AF ablation, namely, recurrence of AF/all atrial arrhythmias at 12 months and acute first-pass PVI. Secondary outcomes were procedural efficiency indicated by procedure time, total ablation time, and RF time.

As this is a meta-analysis on prior published literature, no direct patient clinical contact was needed or possible. Therefore, there was no requirement for ethics committee approval.

Definition of ventilation methods

High-frequency low-tidal volume ventilation from the reported studies had adopted either a weight-adjusted setting (3–4 mL/kg) at 25–30 ventilations/min or a standardized rate of 200–250 mL at 40–50 ventilations/min. In comparison, the standard ventilation was in the range of 6–10 mL/kg at 10–15 ventilations/min.

Statistical analysis

All analyses used the 'meta' and 'metafor' packages in RStudio version 2024.04.2+764. Baseline characteristics between the HFLTV and SV groups were compared, including age, gender, body mass index (BMI), CHA_2DS_2-VASc score, left ventricle ejection fraction, sleep apnoea, hypertension, and diabetes. Between-group standardized mean difference (SMD) and odds ratio (OR) were used to evaluate the baseline difference of continuous variables and categorical variables among the treatment and control groups, respectively.

Primary and secondary outcomes in the HFLTV vs. control groups were compared. The Mantel–Haenszel method was used to calculate the pooled OR for the primary outcomes (recurrence of AF and all atrial arrhythmias after 12 months and first-pass PVI). Pooled SMDs were derived using the inverse variance method for continuous outcomes (procedure time, ablation time, and RF time). The median and interquartile ranges (IQRs) were transformed into mean and standard deviation (SD) according to Wan *et al.*[16] for comparison. Heterogeneity between studies was evaluated using the I^2 statistic and Cochran's Q test, with $I^2 > 50\%$ suggesting a significant heterogeneity and $I^2 < 50\%$ indicating a low heterogeneity. Random-effects models were used when the outcomes showed significant heterogeneity, and the DerSimonian–Laird method was used to calculate the between-study variance (τ^2). Fixed-effect models were used when heterogeneity was low.

Forest plots were drawn to visualize the effects of each outcome. Publication bias evaluation and meta-regressions have not been done as the number of studies included was <10. Sensitivity analysis was conducted using the leave-one-out method when the outcome's heterogeneity was high. A priori defined subgroup analyses were performed for differences in treatment effects between paroxysmal AF (PAF) and persistent AF (PeAF) patients. A χ^2 test was used to study any differences between two groups.

Results

A total of 92 records resulted after medical database searching. After removing 29 duplicated papers, studies were included in the title and abstract screening. Full-text screening was later conducted on seven studies, and two studies were excluded due to overlapping cohorts; five cohort studies published between 2019 and 2024 were included in the final meta-analysis (*Figure 1*).[11–15,17] A summary of the included studies is presented in *Table 1*. The ablation procedure and ventilation method of each study are presented in *Table 2*.

A total of 460 patients in the treatment group and 705 patients in the control group were included in the analysis. Most of the studies were from the USA, and one was from Brazil. Two studies were from the same author group; one included exclusively patients with PAF,[15] whilst the other included patients with PeAF.[14] All the included studies are cohort studies, as no randomized controlled trials were undertaken on the topic.

Baseline characteristics of the final sample

Most of the studies presented the baseline characteristics of the patients, except for Gabriels *et al.*[12] where there was limited information. However, it was stated that there were no differences in the demographics of treatment and control groups. The other four studies were included in the baseline characteristics analysis (*Table 3*). The BMI of the HFLTV group was slightly lower with SMD −0.14 [95% confidence interval (CI): −0.26 to −0.02]. The CHA_2DS_2-VASc score and hypertension comorbidity were slightly higher in the HFLTV group with SMD 0.17 (95% CI: 0.05–0.29) and OR 1.43 (95% CI: 1.09–1.86), respectively. Other baseline data had no significant differences.

High-frequency low-tidal volume ventilation improves long-term rhythm control in atrial fibrillation ablation at 12 months

Four and three studies had reported the recurrence of all atrial arrhythmias and AF, respectively, after 12 months. The recurrence rates for AF were 12% (41/355) for HFLTV vs. 17% (102/604) for SV. Recurrence rates for atrial arrhythmias were 16% (65/416) for HFLTV vs. 23% (153/661) for SV.

High-frequency low-tidal volume ventilation was associated with a statistically significantly lower risk of all atrial arrhythmia recurrence at 12 months (pooled OR = 0.59, 95% CI: 0.42–0.81). No heterogeneity was noted among studies ($I^2 = 0\%$). Similarly, there was a statistically significantly lower risk of AF recurrence (pooled OR = 0.62, 95% CI: 0.42–0.92), suggesting 38% reduced odds of AF at 12 months with HFLTV compared with SV. There was no heterogeneity among studies ($I^2 = 0\%$) (*Figure 2*). The results indicated that using HFLTV significantly reduced the recurrence of all atrial arrhythmia and AF 12 months post-ablation.

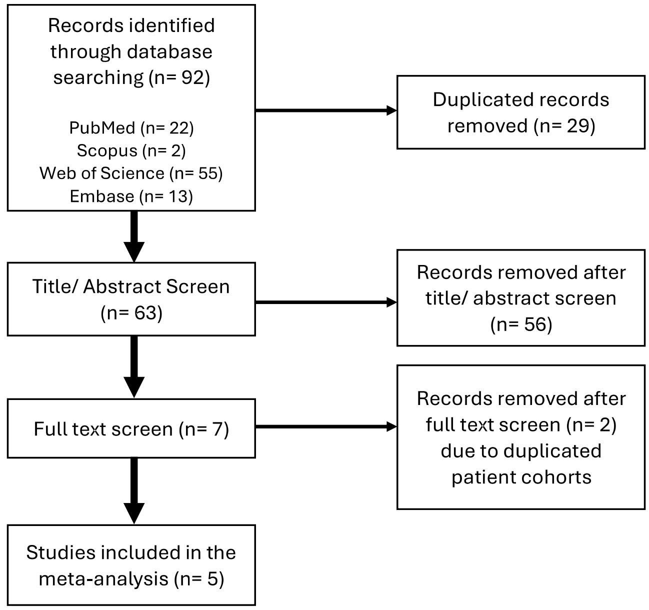


Figure 1 Study flowchart.

High-frequency low-tidal volume ventilation and first-pass pulmonary vein isolation

The proportion of first-pass PVI was reported by four studies (*Figure 2*), with a pooled OR of 1.24 (95% CI: 0.94–1.63) and no heterogeneity among studies ($I^2 = 0\%$). Although the risk estimate was not statistically significant at 95% CI, there was a trend towards higher success rate of first-pass PVI. Of note, Osorio *et al.*[15] had reported a higher proportion of first-pass PVI with HFLTV in their study, when differences were analysed differently using the χ^2 test.

High-frequency low-tidal volume ventilation improves procedural efficiency in atrial fibrillation ablation

Procedure time and total RF time were reported by four studies, and ablation time was reported by three studies (*Figure 3*). All included studies showed statistically significant reductions in the procedure, ablation, and total RF time by using HFLTV vs. SV. The pooled effects of HFLTV (in SMD) were −0.71 (95% CI: −1.00 to −0.42), −0.83 (95% CI: −1.07 to −0.59), and −0.72 (95% CI: −0.85 to −0.59) for procedure time, ablation time, and total RF time, respectively. The heterogeneity of procedure time difference between studies was large ($I^2 = 76\%$). Translated into quantity time, HFLTV was associated with significant reductions in the mean total procedure time of −23.0 min (95% CI: −31.0 to −15.1 min), ablation time of −13.1 min (95% CI: −23.3 to −2.9), and total RF time of −5.8 min (95% CI: −6.7 to −4.8).

All studies reported that there were no major complications in either group.[1,3,4,5,6,11–15,17] Osorio *et al.* (2023)[5] and Osorio *et al.* (2024)[4] also reported that there was no CO_2 retention observed.

Sensitivity analysis

Leave-one-out analyses were performed to assess the robustness of the findings on procedure time due to the high heterogeneity. After taking out each study at a time, the pooled SMD remained statistically significant, suggesting no dominated influence from any single study. Subgroup analyses were also performed according to the type of AF (PAF vs. PeAF). As shown in *Figure 4*, there were no statistically significant differences between PAF vs. PeAF in terms of the impact of HFLTV on the primary and secondary outcomes (all *P*-values for between-group comparisons > 0.05). Furthermore, follow-up periods also showed variations for each included study: Vassallo *et al.*,[13] mean follow-up of 15.2 ± 4.4 months; Gabriels *et al.*,[12] median follow-up of 10 months (IQR: 8–13 months); Osorio *et al.*,[15] 12 months of follow-up; Osorio *et al.*,[14] at least 12 months of follow-up; and Qian *et al.*,[11] 12 months follow-up. Nevertheless, there was no heterogeneity in terms of clinical endpoints of arrhythmia recurrence at 12 months. Risk of Bias Assessment using the Newcastle–Ottawa Scale showed that the risk of bias for each study was low or moderate (*Figure 5*).

Discussion

To our knowledge, this is the first meta-analysis to date that investigated the role of HFLTV ventilation compared with SV in AF patients who undergo RF catheter ablation. Our results indicated that HFLTV, compared with SV, was associated with significantly better long-term outcomes in AF ablation, indicated by reduced recurrence of AF and all atrial arrhythmias at 12 months post-ablation (*Graphical Abstract*). Furthermore, HFLTV was also associated with improved procedural efficiency, reflected by reductions in total procedural, ablation, and RF time (saving 23, 13, and 5.8 min, respectively, compared with SV). Such magnitudes of reductions in procedural time were tangible and

Table 1 Summary of included studies

Author	Publish year	Country	Study period	HFLTV group (*n*)	SV group (*n*)	Centre (*n*)	Type of AF	Type of ablation	Study type	Exclusion criteria
Osorio *et al.*[14]	2024	USA	February 2021 to April 2023	95	115	16	PeAF	PVI with WACA; left atrial PWI in all patients	Prospective cohort study	• Advanced COPD • Asthma • Pulmonary fibrosis • Long-term PeAF patients underwent complex RFCA
Qian *et al.*[11]	2024	USA	August 2022 to March 2023	35	35	1	PAF	PVI with WACA	Retrospective cohort study	• Abnormal LVEF • BMI > 35 kg/m^2 • LAVI > 34 mL/m^2 • Significant respiratory conditions • Anaesthesia-related complications • Phrenic nerve injury
Vassallo *et al.*[13]	2024	Brazil	August 2020 to January 2023	70	66	2	PAF + PeAF	PVI with WACA	Prospective cohort study	• Developed AF during the procedure • Did not return to SR after synchronized cardioversion
Osorio *et al.*[15]	2023	USA	January 2019 to August 2021	216	445	18	PAF	PVI with WACA; CTI line if CTI-dependent flutter	Prospective cohort study	• Advanced COPD • Asthma • Pulmonary fibrosis • On AADs after the blanking period
Gabriels *et al.*[12]	2019	USA	February 2017 to June 2018	44	44	1	PAF + PeAF	PVI with WACA	Retrospective cohort study	• Advanced COPD • Asthma • Pulmonary fibrosis

AAD, antiarrhythmic drugs; AF, atrial fibrillation; BMI, body mass index; COPD, chronic obstructive pulmonary disease; CTI, cavotricuspid isthmus; HFLTV, high-frequency low-tidal volume ventilation; LAVI, left atrial volume index; LVEF, left ventricular ejection fraction; RFCA, radiofrequency catheter ablation; SR, sinus rhythm; SV, standard ventilation; PAF, paroxysmal atrial fibrillation; PeAF, persistent atrial fibrillation; PVI, pulmonary vein isolation; PWI, pulmonary wall isolation; WACA, wide area circumferential ablation.

Table 2 Ablation and ventilation strategies

Study	Ablation catheter	Ablation index	Contact force	Ablation power	Lesion marker/algorithm	HFLTV V_T	HFLTV RR (per min)	SV V_T	SV RR (per min)
Osorio et al.[14]	ThermoCool SmartTouch SurroundFlow®CF-sensing	500–550 (A) 380–420 (P)	10–20 g	HPSD ablation (power 40–50 W; <20 s/lesion)	Point-by-point with VISITAG SURPOINT®	3–3.5 mL/kg	25–30	6–8 mL/kg	10–12
Qian et al.[11]	ThermoCool SmartTouch SurroundFlow®CF-sensing	450–500 (A) 400–450 (P)	10 g	HPSD ablation (power 40–50 W; <20 s/lesion)	Point-by-point with VISITAG SURPOINT®	3–3.5 mL/kg	25–30	6–8 mL/kg	10–12
Vassallo et al.[13]	NS	NS	10–20 g (A) 5–10 g (P)	HPSD ablation (50 W at all sites)	Dragging technique with perpetual radiofrequency delivery	4 mL/kg	25	6–10 mL/kg	12–14
Osorio et al.[15]	ThermoCool SmartTouch SurroundFlow®CF-sensing	500–550 (A) 380–420 (P)	10–20 g	40–50 W	Point-by-point with VISITAG SURPOINT®	3–3.5 mL/kg	25–30	6–8 mL/kg	10–12
Gabriels et al.[12]	(ThermoCool) SmartTouch D/F-curve	NS	10–40 g	NS	NS Impedance drop: 5–10 Ω	200–250 mL	40–50	6–8 mL/kg	14–15

A, anterior; P, posterior; NS, not specified; HFLTV, high-frequency low-tidal volume ventilation; HPSD, high-power, short-duration; RR, respiratory rate; SV, standard ventilation; V_T, tidal volume.

Table 3 Baseline characteristics

	HFLTV ($n = 416$)	SV ($n = 661$)	P-value
Age (year)	65.65 ± 11.08	64.79 ± 11.14	0.2237
Male	56.25%	58.85%	0.1586
BMI	29.52 ± 6.39	30.47 ± 6.89	0.0271*
CHA_2DS_2-VASc score	2.71 ± 1.59	2.43 ± 1.52	0.0075*
LVEF (%)	56.86 ± 8.67	57.57 ± 9.67	0.0688
Sleep apnoea	43.75%	44.63%	0.9577
Hypertension	67.55%	57.94%	0.009*
Diabetes	14.90%	17.55%	0.1970

* Statistically significant at level $P < 0.05$. Values are given as mean ± SD or %.
BMI, body mass index; HFLTV, high-frequency, low-tidal volume ventilation; LVEF, left ventricular ejection fraction; SV, standard ventilation.

clinically meaningful. Importantly, there were no statistically significant differences in complication rates in HFLTV compared with SV. Although there was a trend towards higher rates of acute first-pass PVI in HFLTV, the result was not statistically significant. This could be potentially due to the as-yet insufficient power of the currently pooled sample size. Encouragingly, the beneficial effects of HFLTV on both AF recurrence and procedural time appeared to be consistent across the PAF vs. PeAF patient groups. Slight variations in follow-up duration also had no tangible impact on the findings of reduced arrhythmia recurrence at 12 months.

Ablation power, contact force, and the time of catheter and target lesion in good contact are all important parameters in delivering transmural lesions and to achieve enhanced durability of PVI.[18–20] High-frequency low-tidal volume ventilation reduces diaphragmatic and thoracic excursions, thereby improving catheter stability during ablation and reducing variability of contact force. These changes are reflected by increased impedance drop and improved lesional size index associated with HFLTV. When these are factored into the equation, HFLTV should enhance the ultimate durability of PVI, and this is the likely mechanism through which HFLTV could result in lower recurrence of AF and all atrial arrhythmia observed in the longer term.

To achieve similar aims, previous studies had explored the role of jet ventilation,[8,9] as well as prolonged apnoeic ventilation in AF ablation.[10] Although potentially harbouring similar benefits, these approaches each had their own limitations. For example, jet ventilation requires specific ventilation equipment and a specialized anaesthetic team for support, and frequent arterial blood taking is required. Cost implications are therefore higher. On the other hand, prolonged apnoeic ventilation may cause interruptions to the procedural flow. There is also a limited timeframe for mapping and ablation each time, as each apnoeic episode must be prolonged within a certain limit. Therefore, HFLTV may represent an attractive option combining several benefits of these alternative ventilation approaches, but without a significant requirement for additional manpower or resources. Nevertheless, end-tidal CO_2 retention needs to be routinely monitored, and certain patient groups, especially those with chronic lung diseases such as those with chronic obstructive pulmonary diseases, may not be suitable. How it may compare directly with these alternative ventilation approaches is also unclear and will require further studies.

With the rapidly developing therapeutic landscapes in AF ablation, newer forms of ablation technologies have been developed beyond conventional thermal ablations. These include pulsed field ablation[5] or its combination with RF. Novel mapping and ablation catheters may also assist in enhancing the ultimate success of AF ablation. Nevertheless, how these various kinds of ablation modalities could

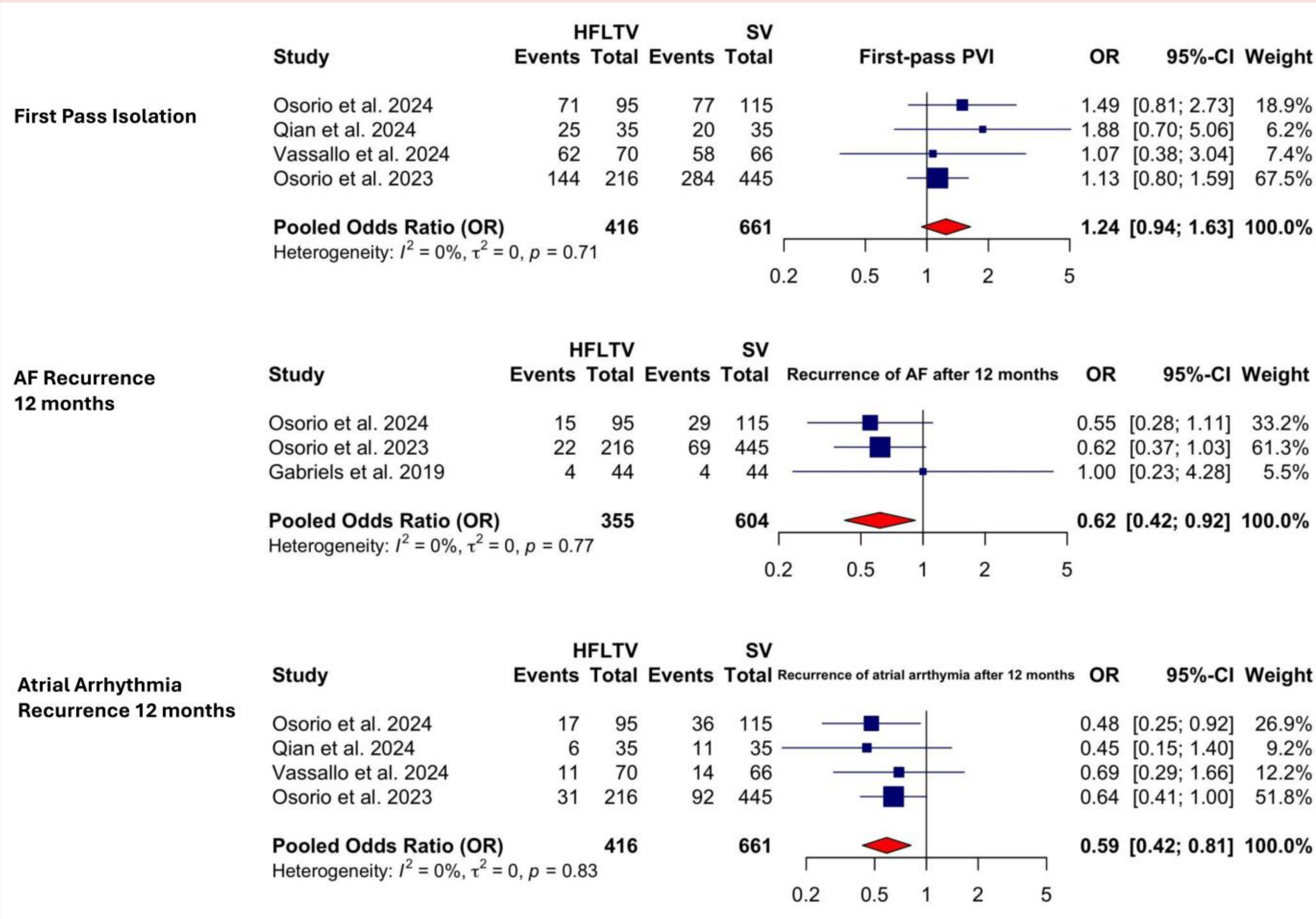


Figure 2 High-frequency low-tidal volume ventilation improves atrial fibrillation ablation success. High-frequency low-tidal volume ventilation was associated with significantly reduced risk of all atrial arrhythmia recurrence (pooled odds ratio = 0.59, 95% confidence interval: 0.42–0.81, $I^2 = 0\%$) and atrial fibrillation recurrence (odds ratio = 0.62, 95% confidence interval: 0.42–0.92, $I^2 = 0\%$) at 12 months after catheter ablation. high-frequency low-tidal volume ventilation appeared to be associated with higher chance of first-pass pulmonary vein isolation but with borderline statistical significance (odds ratio = 1.24, 95% confidence interval: 0.94–1.63, $I^2 = 0\%$). AF, atrial fibrillation; CI, confidence interval; HFLTV, high-frequency low-tidal volume ventilation; OR, odds ratio; PVI, pulmonary vein isolation.

translate into furthering the clinical effectiveness of AF ablation remains an active area of research. In this setting, maximizing capabilities of AF ablation with existing technologies through optimizing the benefits of supportive approaches remains crucial. For example, general anaesthesia significantly reduces pulmonary vein reconnection in PVI.[6] There was also evidence that it improves clinical and economical effectiveness in AF ablation in the UK setting.[7] Here in this meta-analysis, HFLTV presents another dimension in which we could improve the success rate of AF ablation without significant increases in cost, provided that background support of general anaesthesia is available. Nevertheless, it should also be acknowledged that in various electrophysiology centres in Europe and worldwide, AF ablation is often performed under sedation without intubation or an anaesthesiologist on-site. Such variations in health system and clinical resources may ultimately impact on the generalizability of our findings of HFLTV at the implementation and health economical level. Furthermore, the role of general anaesthesia in AF ablation, compared with sedation, is itself a research area in which divergent results have been found. Compared with Martin *et al.*,[7] a retrospective cohort study showed that sedation was non-inferior to general anaesthesia in terms of AF recurrence post-ablation and potentially associated with reduced total procedure time and cost.[21] In addition, a meta-analysis that studied oesophageal complications showed that general anaesthesia was associated with more oesophageal lesions in patients who underwent AF ablation. Therefore, the suitability of anaesthesia and ventilation approach will likely need to be individualized according to the settings of each electrophysiology centre, as well as taking into consideration patient characteristics and operator preferences.

Despite the encouraging findings, there are several limitations of this study. Although this is a meta-analysis, there are only five studies, and all of them are observational in design. Causal inference cannot be definitely confirmed; biases and confounding remained possible. There were also no mechanistic studies that confirmed enhanced durability of PVI as the mechanism of the observed clinical benefits. Nevertheless, this is the largest study to date to incorporate all clinically available and relevant evidence. Although two out of the five studies were included from the REAL-AF registry,[14,15] we carefully studied the relevant manuscripts of these published studies and found that there is no effective overlap of patient samples. Nevertheless, there still existed a small theoretical possibility that some patients with paroxysmal AF could have

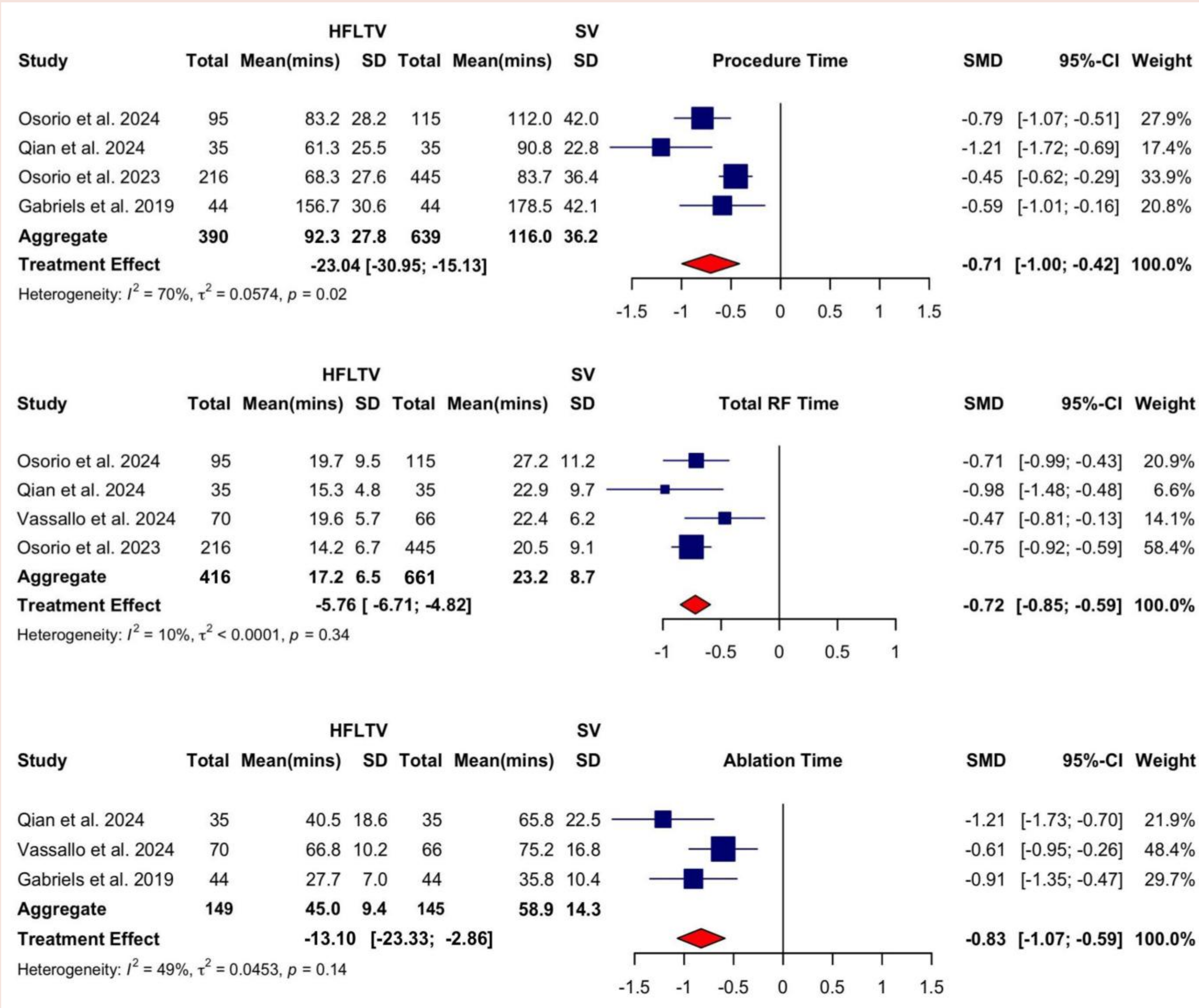


Figure 3 High-frequency low-tidal volume ventilation reduces atrial fibrillation procedure and radiofrequency time. High-frequency low-tidal volume ventilation was associated with significant reductions in the procedure time (pooled standardized mean difference = −0.71, 95% confidence intereval: −1.00 to −0.42), ablation time (pooled standardized mean difference = −0.83, 95% confidence interval: −1.07 to −0.59), and total radiofrequency time (pooled standardized mean difference = −0.72, 95% confidence interval: −0.85 to −0.59). Heterogeneity of procedure time difference between studies was large ($I^2 = 76\%$). AF, atrial fibrillation; CI, confidence interval; HFLTV, high-frequency low-tidal volume ventilation; RF, radiofrequency; SMD, standardized mean difference.

progressed to persistent AF and included again in the latter study. However, even if this happened, the number should be small, and there was no effective overlapping of study period in these studies. This is therefore unlikely to have caused a material impact on the results of our meta-analysis, although a minimal possibility of result inflation cannot be totally excluded. Also, recurrence rates for AF at 12 months in this pooled data appeared to be lower than the generally reported estimates from the literature.[2,3] This could be potentially related to different methodologies, including how recurrence was detected in various studies. A small study bias cannot be excluded. Further randomized controlled, and preferably multi-centre, trials with standardized methods in assessing AF recurrence are needed to confirm the definitive benefits of HFLTV on AF ablation long-term outcomes.

Conclusions

High-frequency low-tidal volume ventilation is associated with improved long-term success of arrhythmia control in AF patients who undergo RF catheter ablation, regardless of paroxysmal or persistent status. It also improves procedural efficiency, without any significant impact on complication rates.

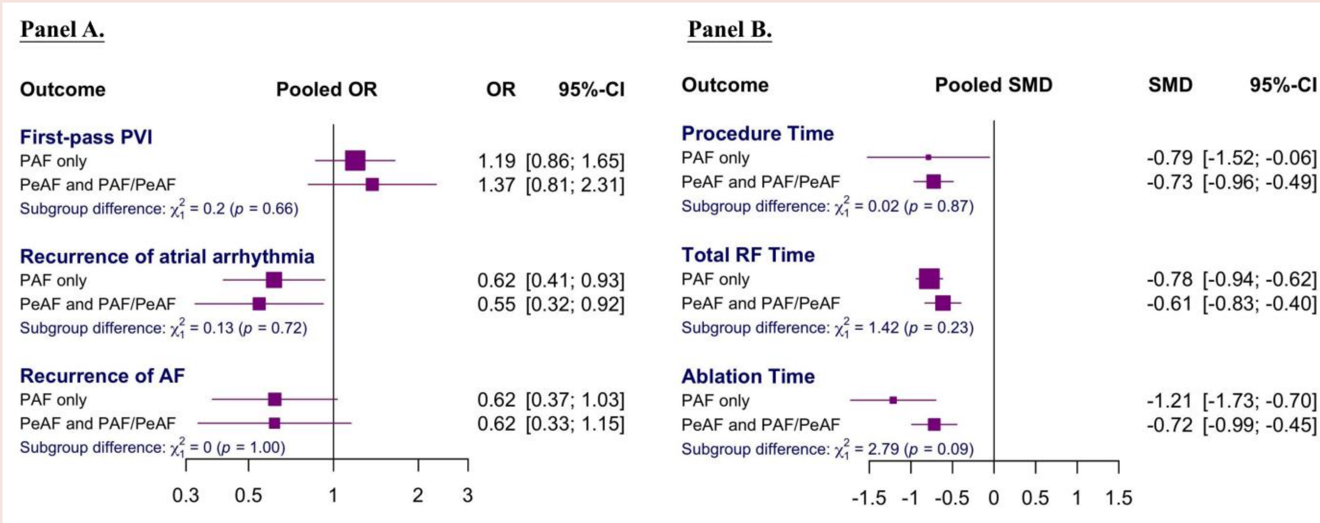


Figure 4 Study outcomes stratified according to paroxysmal versus persistent atrial fibrillation. There were no statistically significant differences between paroxysmal atrial fibrillation vs. persistent atrial fibrillation in terms of the impact of high-frequency low-tidal volume ventilation on the primary and secondary outcomes (all *P*-values for between-group comparisons > 0.05). AF, atrial fibrillation; HFLTV, high-frequency low-tidal volume ventilation; PAF, paroxysmal atrial fibrillation; PeAF, persistent atrial fibrillation.

Study	Selection	Comparability	Outcome	Total Score	Risk of Bias
Gabriels et al., 2019	3	0	3	6	Moderate
Osorio et al., 2023	4	1	3	8	Low
Osorio et al., 2024	4	2	3	9	Low
Qian et al., 2024	3	1	3	7	Low
Vassallo et al., 2024	3	1	2	6	Moderate

Figure 5 Risk of bias assessment using the Newcastle–Ottawa Scale. The risk of bias for each study was low or moderate.

Lead author biography

Dr Yap-Hang Will Chan is a clinical assistant professor and honorary associate consultant cardiologist at Queen Mary Hospital, University of Hong Kong. He received advanced cardiology training in interventional cardiac electrophysiology as senior EP fellow at Royal Papworth Hospital, Cambridge. He completed his overseas clinical training in Cambridge in the capacity of the Sir David Todd Memorial Scholar awarded by the Hong Kong College of Physicians and subsequently returned as a visiting fellow at Hughes Hall, University of Cambridge, in 2025. Dr Chan's interests entail clinical and invasive cardiology, interventional cardiac electrophysiology and catheter ablation of arrhythmias, atrial fibrillation, cardiovascular genetics, and novel cardiovascular pharmacotherapeutics.

Data availability

The data used are from previously published studies. Derived data in this study are not publicly available but are available upon reasonable request made to the corresponding author.

Acknowledgements

We sincerely thank all participants in the original studies that were included in this meta-analysis and the excellent works from previous study groups and authors cited. Without any of their input, this study would not have been at all possible.

Funding

This study was supported by Li Shu Pui Medical Foundation Fellowship 2022; Seed Funding for Basic Research (104006735) and Start-Up Funding, The University of Hong Kong; and Hong Kong Research Grants Council General Research Fund (GRF 17110122 and 17108523). Y.-H.W.C. was supported by the Hong Kong Research Grants Council Clinical Research

Fellowship 2024/25 and Doris Zimmern HKU-Cambridge Hughes Hall Fellowship 2024/25.

Conflict of interest: None declared.

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