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Review

Temporal trends in atrial fibrillation catheter ablation efficacy: A systematic review, meta-analysis and meta-regression from more than 20 years of clinical data

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ABSTRACT

Early rhythm control has been shown to improve cardiovascular outcomes in patients with atrial fibrillation. Atrial fibrillation catheter ablation is a cornerstone of this strategy; however, the evolution of its efficacy over time remains unclear. This study aimed to evaluate temporal trends in atrial fibrillation catheter ablation efficacy over the past two decades. A systematic review was conducted using PubMed and the Cochrane Library, covering studies published between 01 January 2001 and 01 July 2023. Atrial fibrillation catheter ablation efficacy was defined as the absence of atrial arrhythmia recurrence (atrial fibrillation, atrial tachycardia and/or atrial flutter) at 12-month follow-up after a single ablation procedure, without the use of antiarrhythmic drugs. A random-effects meta-analysis of proportions was performed using a generalized linear mixed model. Meta-regression was employed to assess the impact of treatment year on ablation success. The study was registered in the PROSPERO registry: CRD42021258100. The analysis included 477 cohorts comprising 70,703 patients. The pooled estimate of atrial fibrillation catheter ablation efficacy was 66% (95% confidence interval 64% to 67%). A significant improvement in efficacy was observed over time (+1.09% per year; 95% confidence interval: 0.71% to 1.56%; $P < 0.0001$; $R^2 = 7\%$). However, this improvement was primarily driven by early gains (before 2010) in patients with persistent atrial fibrillation. No evidence of publication bias was detected. This is the largest meta-analysis to date assessing temporal trends in atrial fibrillation catheter ablation efficacy. Although a modest, but statistically significant, improvement has occurred over the past two decades, progress has plateaued since 2010. These findings highlight the need for a paradigm shift in atrial fibrillation catheter ablation strategies, with a focus on improving lesion durability and integrating ablation within a comprehensive atrial fibrillation management approach aimed at sustained sinus rhythm maintenance.

1. Abbreviations

AAD	antiarrhythmic drug
AF	atrial fibrillation
AFCA	atrial fibrillation catheter ablation
BMI	body mass index
CI	confidence interval
LVEF	left ventricular ejection fraction
PVI	pulmonary vein isolation

2. Background

Atrial fibrillation (AF) is the most frequent cardiac arrhythmia worldwide, with an increased risk of hospitalizations, stroke, systemic emboli, heart failure and death [1]. Early rhythm control by antiarrhythmic drugs (AADs), risk factor correction and/or

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catheter ablation improve cardiovascular outcomes [2]. Since the first reports of pulmonary vein isolation (PVI) at the end of the 1990s, AF catheter ablation (AFCA) has become the most effective strategy to maintain sinus rhythm [3]. Consequently, over the past decades, AFCA has been performed more frequently in an increasing number of ablation centres worldwide, and with declining rates of complications [4–6]. However, atrial arrhythmia recurrence remains a frequent concern, which drives the continuous development of new ablation strategies and energies to increase AFCA efficacy [3]. Although registry-based studies have suggested a significant improvement in AFCA efficacy over time, the temporal trend in AFCA efficacy remains unknown [7,8].

The aim of the present study was to evaluate the temporal trends in AFCA efficacy at the 12-month postoperative timepoint, after a single procedure and without AADs, with an emphasis on AF subtypes.

3. Methods

3.1. Data sources and searches

PubMed and the Cochrane Library were interrogated from 01 January 2001 to 01 July 2023 using the following search terms for human research, English language, original articles: "atrial fibrillation [Title, MeSH + free text]" AND "catheter ablation [MeSH + free text]" AND "clinical study [MeSH]" OR "clinical trial [MeSH]" OR "multicentre trial [MeSH]" OR "randomized controlled trial [MeSH]" OR "observational study [MeSH]". We found 4094 original articles. Corresponding titles and abstracts were analysed independently by two authors (P. O. and J. F.). The full texts of potentially eligible studies were evaluated independently for eligibility by the two authors, and any disagreement was resolved through evaluation by a third author (C. D.).

3.2. Study selection and quality assessment

Approval for this study was obtained from the local ethics committee. The systematic review was performed according to PRISMA 2020 standards (Table A.1), and registered in the international prospective register of systematic reviews (PROSPERO: CRD42021258100) before data extraction and analysis. Original articles including patients with symptomatic atrial fibrillation (either paroxysmal, persistent or long-standing persistent), who were undergoing a first AFCA procedure, and with an available 12-month outcome analysis, were included in the present meta-analysis.

3.3. Outcome measures and objectives

The outcome of interest was 12-month AFCA efficacy, defined as the absence of recurrence of atrial arrhythmia after a single procedure, without AADs, at 12-month follow-up. Atrial arrhythmia was defined as AF or atrial tachycardia or atrial flutter on a single 12-lead electrocardiogram or lasting more than 30 seconds on Holter monitoring. The primary objective of the study was to assess the temporal trends in AFCA efficacy, from the first published study to the last published study. Secondary objectives of the study were to: (1) describe the aggregated characteristics of the included cohorts; (2) assess temporal trends in 12-month AFCA efficacy in paroxysmal and persistent AF cohorts; (3) explore a ceiling effect of the treatment year on 12-month AFCA efficacy; (4) identify patient characteristics and study characteristics associated with improvement in 12-month AFCA efficacy; and (5) determine the effect of the treatment year on 12-month AFCA efficacy in a multivariable analysis.

3.4. Exclusion criteria

Studies were excluded in cases of highly selected patients (hypertrophic cardiomyopathy, elderly [aged > 75 years], Brugada syndrome, type 2 diabetes mellitus, obesity), cohorts of < 10 patients, previous catheter ablation procedure, rheumatic heart disease, postoperative AF, surgical and/or hybrid ablation, inappropriate 12-month outcome (i.e. uninterrupted AAD or unknown AAD status, outcome for multiple AFCA procedures, atrial arrhythmia recurrence not accounting for atrial tachycardia or atrial flutter recurrence, duration cut-off > 30 seconds for atrial arrhythmia recurrence) and missing 12-month follow-up for more than 10% of the study population. Duplicated cohorts (i.e. more than one original article from a single cohort) were excluded by analysis of the redundancy in country, inclusion dates and publication teams. The flow diagram of the meta-analysis is illustrated in Fig. 1.

3.5. Statistical analysis

We conducted a random effects meta-analysis of proportions using a generalized linear mixed model for the estimation of the 12-month AFCA efficacy. Studies were sorted into subgroups based on AF type, as follows: studies accruing 95% or more of patients with paroxysmal AF were attributed to the paroxysmal AF group; studies accruing 100% of patients with persistent AF were attributed to the persistent AF group; mixed studies did not contribute to these subgroups. Meta-regression was used to assess the contribution of each variable to this success rate (univariate analysis), which was the primary analysis when focused on the effect of the mean year of treatment, and then altogether in a multivariate meta-regression model. Meta-regression was conducted using a generalized linear mixed model for study estimates. Variables were added to the multivariate model if significantly associated with success rate in the univariate analysis. When several variables were related to a similar variable (e.g. left atrial dimensions), the most available variable (before missing data imputation) was selected. The year ceiling effect was determined by consecutive subgroup analyses, including only studies published before 2004 then before 2005 until before 2016, and then studies published after 2015 then after 2016 until after 2003. Confidence interval (CI) bounds for the ratio were computed, based on the standard error of the variable estimate. As missing data affected more than 5% of the variables used for adjustment, we conducted a missing data imputation procedure before conducting the meta-regression. The missing data reporting complied with the guidelines for reporting analyses potentially affected by missing data [9]. Additional details of the missing data imputation procedures are available in Table A.2. Estimates were combined according to Rubin's rule [10,11]. A P-value < 0.05 was deemed significant. Publication bias was visually assessed with a funnel plot and tested with an Egger test, for the primary outcome. Statistical analyses were performed with R, version 4.3.3 for Windows (R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria), and the packages mice and metafor.

4. Results

4.1. Baseline characteristics

A total of 279 studies were included, with publication years ranging from 2001 to 2023. The full list of references is detailed in Table A.3. Two hundred and five (72%) studies had a prospective design, including 129 randomized controlled trials (45%). Studies included in the analysis were segregated in one, two, three, four, five and eight cohorts, respectively, for 130 studies, 124 studies, 19

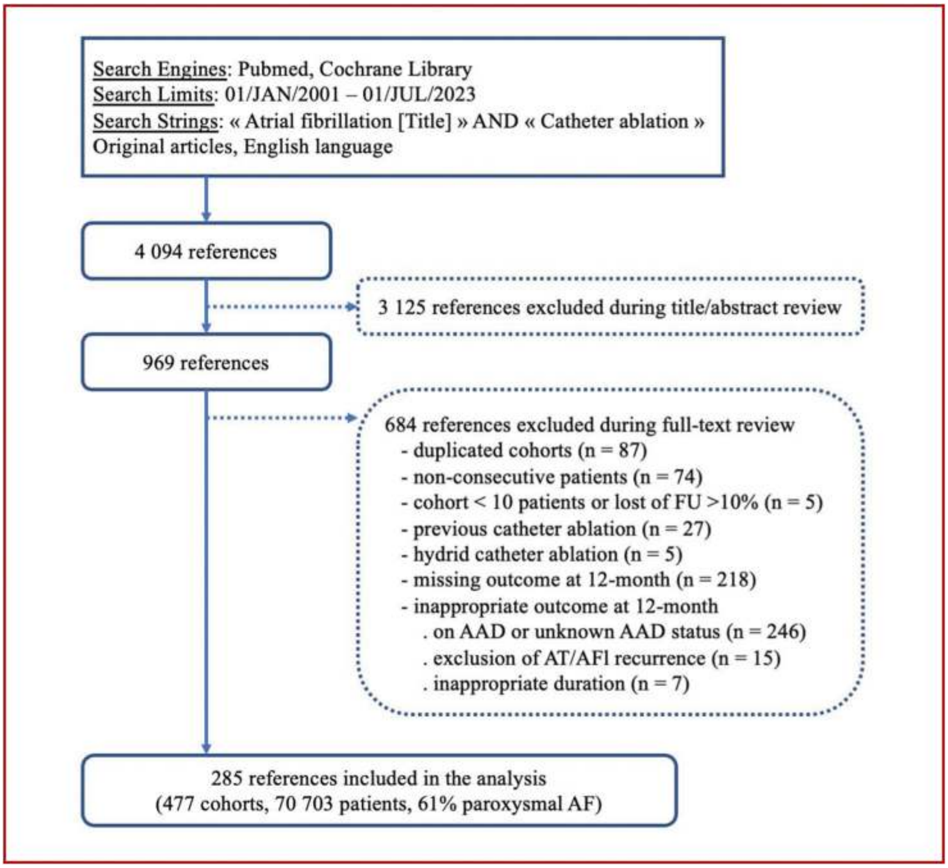


Fig. 1. Search criteria and study flow diagram. AAD: antiarrhythmic drug; AF: atrial fibrillation; AFl: atrial flutter; AT: atrial tachycardia; FU: follow-up.

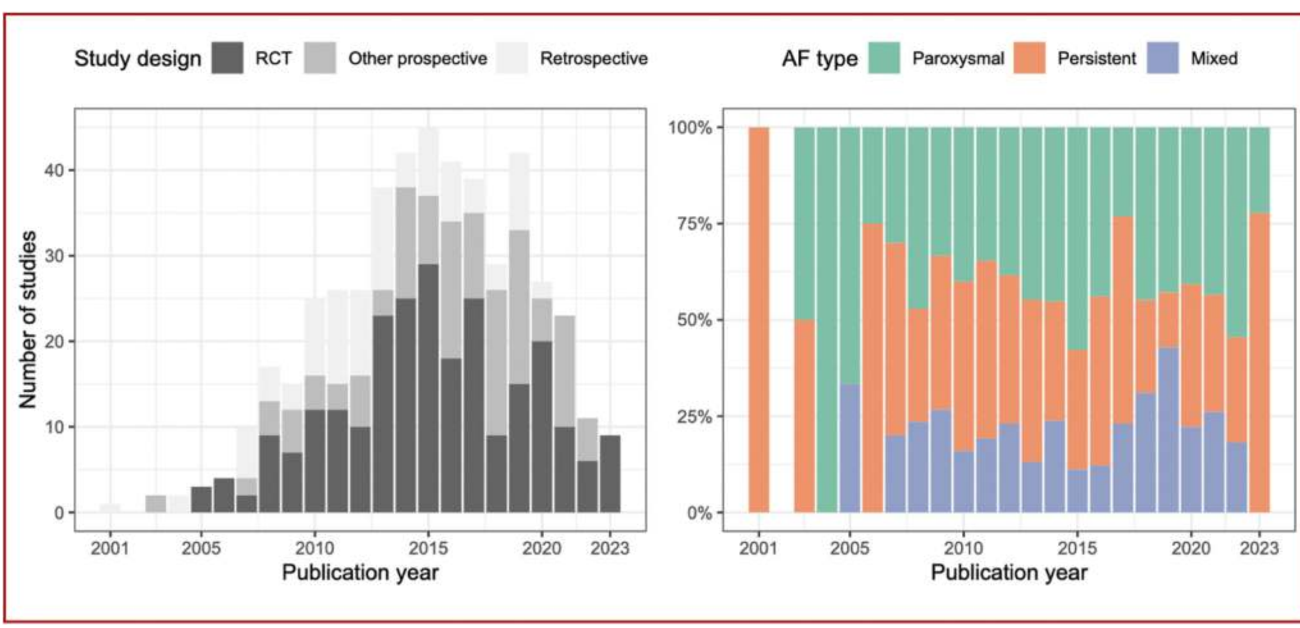


Fig. 2. Distribution of publication year (left panel: by type of study; right panel: by atrial fibrillation [AF] type). RCT: randomized controlled trial.

studies, six studies, two studies and one study, accounting for a total of 477 cohorts. Those cohorts included a total of 70,703 patients (61% with paroxysmal AF) who underwent a first AFCA between 1998 and 2021. Distribution of cohorts according to publication year and AF type is illustrated in Fig. 2. Descriptive characteristics of the 477 cohorts are detailed in Table 1. The study included 202 paroxysmal AF cohorts, 176 persistent AF cohorts and 99 mixed AF cohorts. In the mixed AF cohorts, the mean proportion of patients with paroxysmal AF was 61%. Energy used for AFCA was point-by-point radiofrequency ablation, single-shot cryoablation, mixed between radiofrequency and cryoablation, other (laser, ultrasound) or unknown in 401 (84%), 56 (12%), 9 (2%), six (1%)

Table 1
Descriptive characteristics of the 477 cohorts included in the meta-analysis, after imputation of missing data.

	Median (IQR)	Range
Cohort size (*n*)	80.0 (52.0–147.0)	(11.0–2497.0)
Mean age (years)	59.5 (57.0–62.1)	(47.7–75.3)
Male sex (%)	72.0 (63.7–77.9)	(0.6–95.0)
Mean AF duration (months)	4.0 (2.3–5.0)	(0.3–45.2)
Mean LA diameter (mm)	42.0 (40.0–44.5)	(30.8–56.0)
Mean BMI (kg/m^2)	27.1 (24.9–29.0)	(22.1–35.1)
OSA (%)	10.4 (4.4–18.0)	(0.9–59.0)
Hypertension (%)	49.5 (40.5–58.4)	(5.9–100.0)
Diabetes (%)	9.9 (6.8–13.9)	(0.0–33.0)
Stroke or TIA (%)	6.7 (4.1–10.1)	(0.0–26.7)
Mean LVEF (%)	60.0 (56.5–62.8)	(29.7–69.6)
Mean $CHADS_2$ or CHA_2DS_2-VASc score	1.5 (1.0–1.9)	(0.6–3.6)

Data are expressed as aggregated means of each variable, across the 50 imputed datasets. AF: atrial fibrillation; BMI; body mass index; $CHADS_2$: Congestive heart failure, Hypertension, Age ≥ 75 years, Diabetes, Stroke/TIA/thromboembolism (Doubled); CHA_2DS_2-VASC: Congestive heart failure, Hypertension, Age ≥ 75 years (Doubled), Diabetes, Stroke/TIA/thromboembolism (Doubled) – Vascular disease, Age 65–74 years and Sex category (Female); IQR: interquartile range; LA; left atrial; LVEF; left ventricular ejection fraction; OSA; obstructive sleep apnoea; TIA; transient ischaemic attack.

and five (1%) cohorts, respectively. Atrial lesion set during AFCA was PVI only, PVI and atrial substrate, atrial substrate only, other (mainly ganglionated plexi ablation) or unknown in 258 (54%), 191 (42%), five (1%), seven (1%) and five (1%) cohorts, respectively. During a follow-up duration of 12 months, monitoring of the outcome was performed using a symptom-based electrocardiography (including transtelephonic monitoring), systematic repeated electrocardiography, systematic repeated Holter electrocardiography and implantable loop recorder in 437 (92%), 439 (92%), 429 (90%) and 21 cohorts (4%), respectively.

4.2. Meta-analysis of the outcome

In the overall studies included (n = 477), unadjusted reported 12-month AFCA efficacy ranged from 9% (95% CI: 1% to 28%) to 94% (95% CI: 87% to 98%) with a significant heterogeneity in outcomes (I^2 = 92%; P < 0.001) and summary random effects estimate of 66% (95% CI: 64% to 67%). The funnel plot and Egger test did not suggest any publication bias (Fig. A.1). Temporal trends in AFCA efficacy are illustrated in Fig. 3. In the univariate analysis, a significant increase in 12-month AFCA efficacy was noted during the study period (regression analysis R^2 = 7%; +1.09% increase per year, 95% CI: 0.71% to 1.56%; P < 0.0001). For paroxysmal AF cohorts (n = 202), there was no significant increase in 12-month AFCA efficacy during the considered time-period (regression analysis R^2 = 3%; +0.47% per year, 95% CI: −0.05 to 0.99; P = 0.08) (Fig. 4). For persistent AF cohorts (n = 176), a significant increase in 12-month AFCA efficacy was noted (regression analysis R^2 = 26%; +1.60% per year, 95% CI: 1.07% to 2.14%; P < 0.0001) (Fig. 4). In the latest cohorts, a year ceiling effect in 12-month AFCA efficacy was found in 2011–2012, after which AFCA efficacy stopped improving (Table A.4).

4.3. Meta-regression of predictors of the outcome

In the overall cohorts included (n = 477), and after imputation of missing data, body mass index (BMI), left ventricular ejection fraction (LVEF), left atrial diameter, sex, AF type, postoperative monitoring duration, energy and ablation set were significantly associated with 12-month AFCA efficacy, as detailed in Table 2 and Fig. A.2. Results of the non-imputed dataset are shown in Table A.5, and were all consistent with the imputed analysis. In a multivariable meta-regression model adjusted on BMI, LVEF, left atrial diameter, sex, AF type, monitoring duration, energy and ablation set, 12-month AFCA efficacy still improved significantly over the study period, with a 0.94% increase per year (95% CI: 0.58% to 1.30%; P < 0.0001).

5. Discussion

The main findings of this study can be summarized as follows: (1) from a meta-analysis of 477 AF cohorts, including more than 70,000 patients over two decades, we found a minor but significant improvement in AFCA efficacy; and (2) this effect is mainly driven by an improvement in the early years (i.e. 2010 and before) in persistent AFCA cohorts. The success rate of AFCA remained unchanged for paroxysmal AF and for late years (i.e. from 2011) in persistent AF cohorts.

The number of catheter ablation centres is growing continuously worldwide, and the annual number of AFCA procedures rose by 339% between 2007 and 2016, to finally represent approximately 40% of all catheter ablation procedures [4]. Despite procedures performed in older patients and/or those with a higher co-morbidity burden, the evolutions in terms of patient selection, operator experience and ablation techniques have allowed shorter procedure durations and lower procedure-related complication rates to be reached [7,12–14]. Recently, a comprehensive meta-analysis by Benali et al. found that procedure-related complications and death rates for AFCA steadily declined between 2013 and 2022, which is in accordance with previous meta-analyses from early years data, and with the findings of the USA National Cardiovascular Data Registry of Atrial Fibrillation Ablation Procedures [6,13,15,16]. This improvement in safety now enables a same-day discharge strategy following AFCA [17]. However, atrial arrhythmia recurrence is still a frequent concern after a first procedure, and the question of the evolution of AFCA efficacy over the past two decades remains unanswered [3].

From studies published between 2001 and 2023, representing cohorts treated between 1998 and 2020, we found an overall AFCA success rate of 66%, which was defined as the absence of recurrence of any atrial arrhythmia at 12 months, after a single procedure and without AADs. Our study confirms factors previously described as improving AFCA efficacy, such as lower BMI, smaller left atrial diameter, higher LVEF, paroxysmal AF type and shorter postoperative monitoring duration [18–21]. Our work also underlines the fact that PVI remains the cornerstone of AFCA, as atrial substrate modification (alone or in combination with PVI) led to a significantly worse outcome. Surprisingly, the energy type (cryoablation) was associated with a slightly better AFCA efficacy, which might reflect the superiority of the PVI-only strategy.

Most importantly, our study demonstrated a significant 1.09% per year improvement in AFCA efficacy (0.94% per year in a multivariable meta-regression model), which can be considered as a relatively disappointing evolution. Our work is tempering the results of previous registry-based studies that suggested a larger improvement in AFCA efficacy over past decades [7,8]. In their Danish nationwide registry-based study, Pallisgaard et al. found that recurrent AF following first-time ablation had almost halved from 2006 to 2014 [8]. These findings are corroborated by data from the nationwide Swedish Catheter Ablation Registry, in which Holmqvist et al. found a notable decrease in the rate of redo AFCA procedures from 2009 to 2016 [7]. However, those data were not included in the present meta-analysis, as registry-based methodology makes outcome definition unclear by definition (e.g. type of recurrence, AAD use, etc.). Moreover, the rate of redo AFCA procedure seems an inappropriate surrogate for first-time ACFA success rate. Finally, uncontrolled confounders (e.g. co-morbidity management, patient selection, operator experience) might have overestimated the evolution of AFCA success rate in the latter

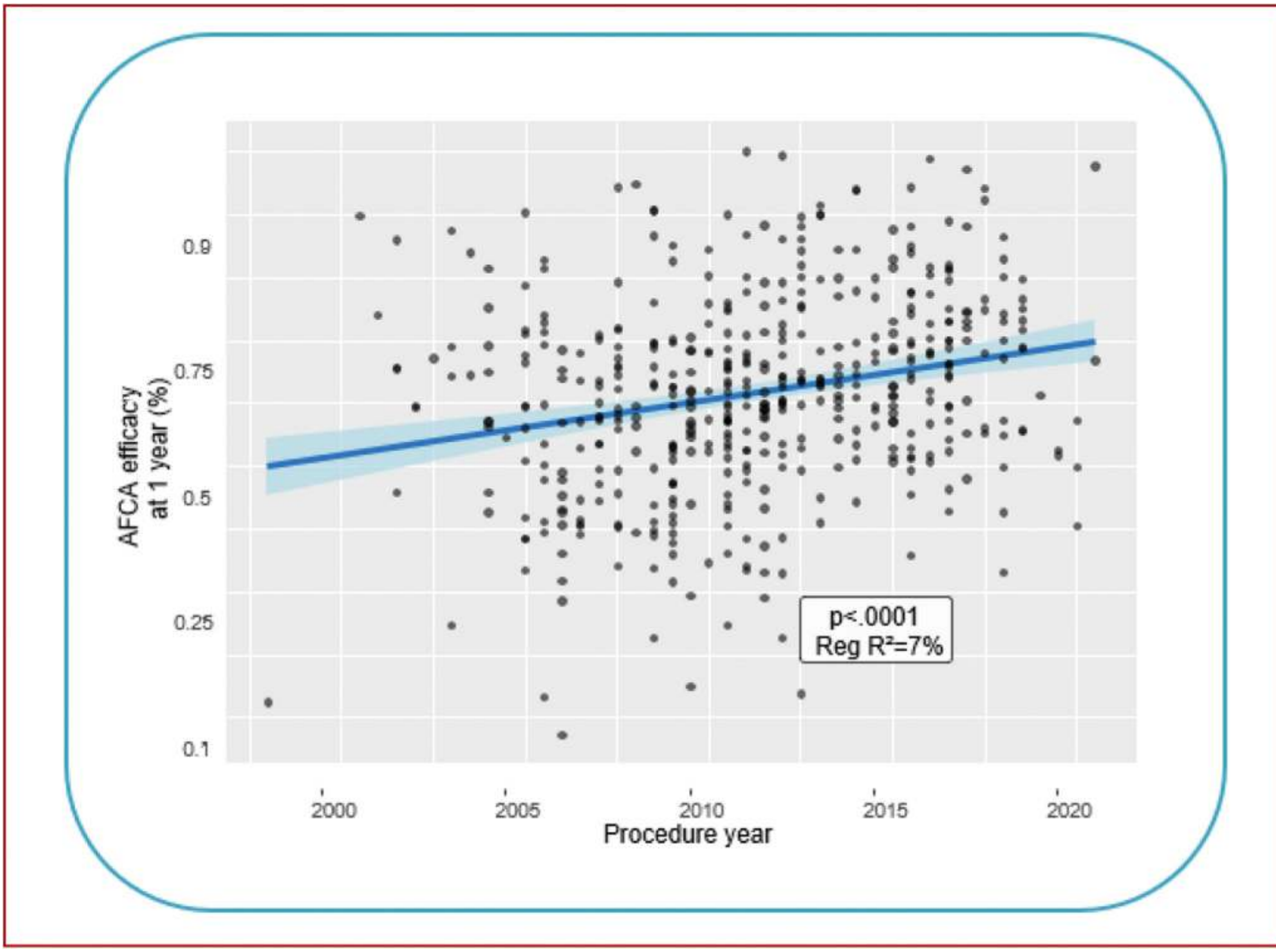


Fig. 3. Temporal trends in atrial fibrillation catheter ablation (AFCA) efficacy across all atrial fibrillation subtypes (main analysis). Reg: regression analysis.

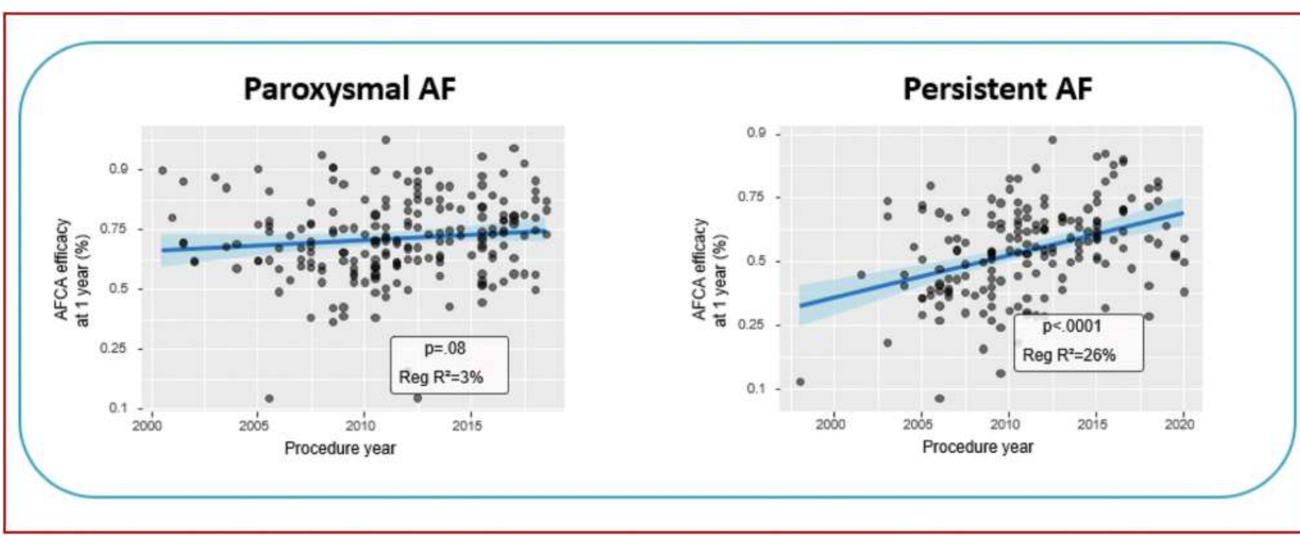


Fig. 4. Temporal trends in atrial fibrillation catheter ablation (AFCA) efficacy by atrial fibrillation (AF) subtype: paroxysmal (left) and persistent (right). Reg: regression analysis.

registries. This minor improvement in AFCA efficacy over the past two decades strongly reinforces the need for an integrated AF management pathway focusing on risk factor modification in order to reduce AF burden and ensure durable sinus rhythm maintenance [22,23].

The absence of improvement in paroxysmal AFCA efficacy is in contradiction with the recent SMASH-AF meta-analysis (155 studies; 24,477 patients), in which the authors found a significant improvement in paroxysmal AFCA efficacy of 1.6% per annum between 2003 and 2016 [24]. However, several limitations

Table 2
Bivariate meta-regression model on imputed datasets; adjusted relative chances of 12-month AFCA efficacy.

	Adjusted relative chance of AFCA efficacy, % (95% CI)	*P*
Procedure year (+1 year)	+1.09 (+0.71; +1.46)	< 0.0001
Age (+5 years)	+0.15 (−2.09; +2.33)	0.89
BMI (+5 kg/m^2)	−13.24 (−17.66; −8.86)	< 0.0001
AF duration (+1 year)	−0.30 (−1.03; +0.43)	0.43
LVEF (+10%)	+10.77 (+7.46; +13.80)	< 0.0001
LA diameter (+5 mm)	−11.46 (−14.04; −8.90)	< 0.0001
Male sex (versus female)	−24.42 (−37.01; −10.46)	< 0.001
OSA	−31.92 (−53.95; +1.30)	0.07
Hypertension	−10.24 (−23.46; +2.34)	0.12
Diabetes	+17.59 (−14.79; +30.71)	0.24
Stroke or TIA history	−27.46 (−57.28; +16.20)	0.26
$CHADS_2$ (+1 point)	−1.41 (−9.30; +5.81)	0.72
CHA_2DS_2-VASc (+1 point)	+0.66 (−3.41; +4.51)	0.75
Paroxysmal AF (versus persistent)	+14.74 (+12.23; +17.04)	< 0.0001
Energy		0.03
Radiofrequency (reference)		
Cryoablation	+6.31 (+1.49; +10.68)	0.01
Mixed	+3.50 (−8.80; +13.67)	0.56
Other	+12.02 (−1.88; +21.78)	0.09
Atrial lesion set		< 0.0001
PVI alone (reference)		
PVI and atrial substrate	−4.58 (−8.13; −1.13)	< 0.01
Atrial substrate alone	−43.21 (−53.92; −26.63)	< 0.0001
Other	−9.08 (−24.68; +5.43)	0.24
Monitoring duration (+30 days)	−1.11 (−1.77; −0.45)	< 0.01

Results are expressed as relative increase/decrease based on the mean probability of success estimated from the main analysis (66% success). AF: atrial fibrillation; AFCA: atrial fibrillation catheter ablation; BMI: body mass index; $CHADS_2$: Congestive heart failure, Hypertension, Age ≥ 75 years, Diabetes, Stroke/TIA/thromboembolism (Doubled); CHA_2DS_2-VASC: Congestive heart failure, Hypertension, Age ≥ 75 years (Doubled), Diabetes, Stroke/TIA/thromboembolism (Doubled) – Vascular disease, Age 65–74 years and Sex category (Female); CI: confidence interval; LA: left atrial; LVEF: left ventricular ejection fraction; OSA: obstructive sleep apnoea; PVI: pulmonary vein isolation; TIA: transient ischaemic attack.

regarding the outcome analysis might limit the validity of their findings. Firstly, the timepoint of outcome measurement was not defined. Secondly, the authors included studies not accounting for atrial tachycardia or atrial flutter recurrence as well as studies evaluating AFCA efficacy with uninterrupted AAD, which can both overestimate AFCA success rate. Our methodology is in line with the latest worldwide expert consensus statement on catheter and surgical ablation of AF, which reaffirmed the use of freedom from any atrial arrhythmia (AF, atrial tachycardia or atrial flutter) and without AADs as the gold standard for reporting AFCA efficacy. The lack of improvement in the efficacy of paroxysmal AFCA observed in our study is supported by the fact that, since the original description of PVI by Haissaguerre et al., new energies and ablation strategies have emerged, but without reaching a reproducible superiority compared with the standard of care (including in recent studies focusing on pulsed-field ablation, which were not included in the present meta-analysis because they were published after 2023) [25,26]. Indeed, pulsed-field ablation has emerged as a fast, effective and safe alternative for to AFCA. However, regarding efficacy, no superiority of pulsed-field ablation over thermal ablation has yet been demonstrated [27]. Therefore, it is unlikely that the inclusion of the currently available pulsed-field ablation trials would alter the results of our meta-analysis. Nevertheless, it will be important to perform an updated meta-analysis once the body of evidence is sufficient, particularly as data emerging from the SINGLE SHOT CHAMPION randomized controlled trial begin to suggest potential superiority of pulsed-field ablation in terms of efficacy [28].

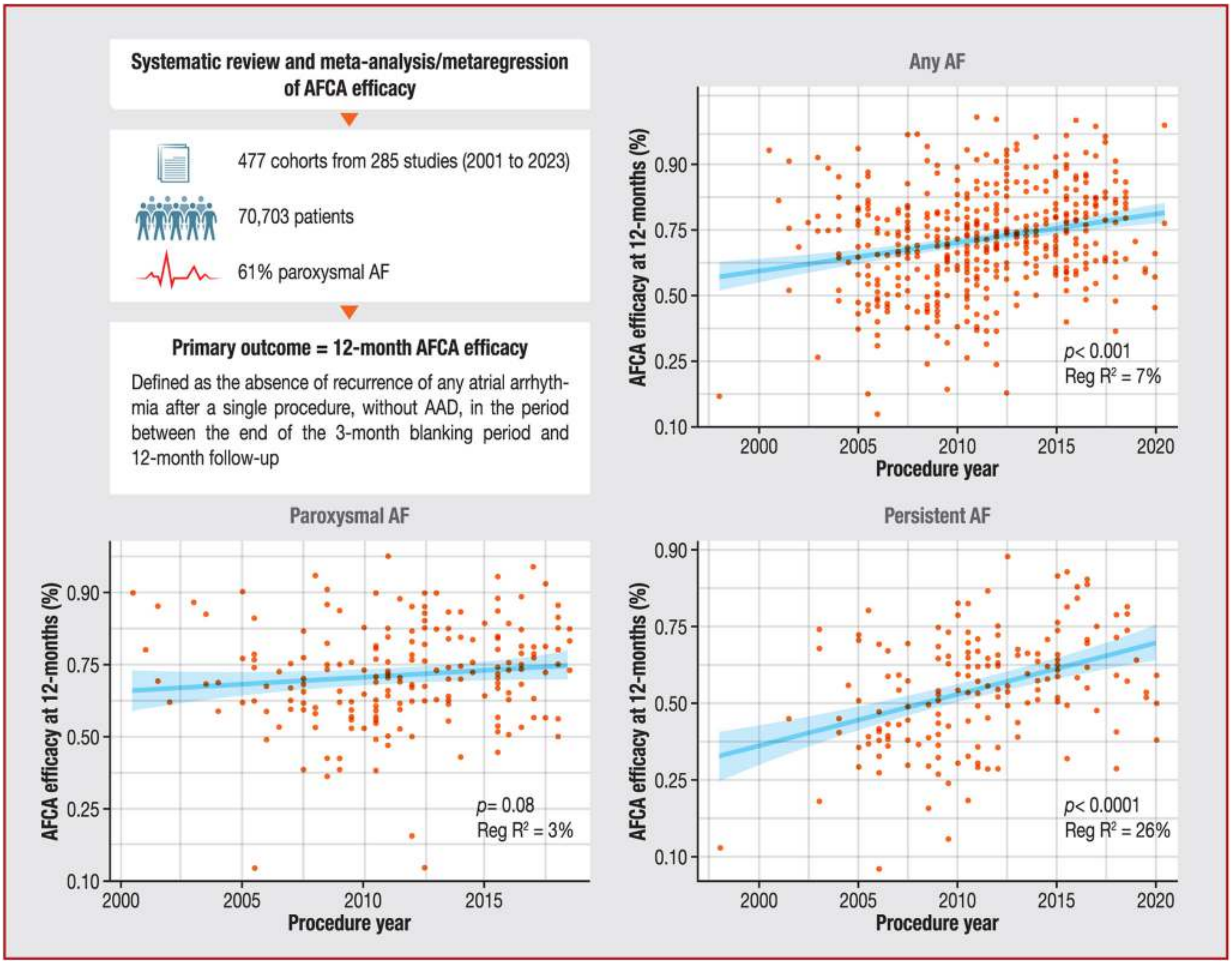
The transient improvement in the early years (i.e. before 2010) in persistent AFCA efficacy can be explained by several phenomena. Firstly, persistent AFCA can be challenging in terms of left atrial anatomy (dilatation, fibrosis), and we hypothesize that it is more likely to depend on operator experience. As a consequence, this phenomenon might have been overcome by the learning curve, to reach a plateau phase in the later years. Secondly, because of tissue scarring, durable PVI is harder to obtain in patients with persistent AF [29]. As a consequence, patients with persistent AF who had AFCA might have been more inclined to benefit from the advances in terms of catheter technology [30].

5.1. Strengths and limitations

Our work is a comprehensive review and meta-analysis of more than 20 years of published clinical data, which allowed us to measure the evolution of AFCA efficacy in a way that it is only feasible when studies have a structured follow-up and clear outcome definition. Indeed, exclusion of large population-based studies (e.g. registries) was necessary because of the aforementioned limitations. As a consequence, the external validity of our findings regarding real-life practice might be limited, especially in the era of integrated AF management. We found heterogeneity in the estimation of the primary outcome, which limits the interpretation of the result; this is probably a consequence of the variety of study designs and populations. However, we performed a generalized linear mixed model with meta-regression to explore this heterogeneity, and a significant amount was explained by co-factors. We did not access patient-level data, which might have refined the effects of said co-factors on the success rate.

6. Conclusions

Our meta-analysis, including more than 70,000 patients, found a minor but significant improvement in AFCA efficacy over the past two decades. This effect was mainly driven by an improvement in the early years (i.e. until 2010) in persistent AF cohorts. This large meta-analysis followed the definition of AFCA success proposed in the latest expert consensus statement, allowing reliable assessment of AFCA efficacy over time. New techniques providing better atrial lesion durability and new tailored ablation strategies are needed to further improve overall outcomes following AFCA (Central Illustration).



Central Illustration. Temporal trends in atrial fibrillation catheter ablation (AFCA) efficacy. Results of relative chances are expressed as relative increase/decrease based on the mean probability of success estimated from the main analysis (66% success). AAD: antiarrhythmic drug; AF: atrial fibrillation; Reg: regression analysis.

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None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.acvd.2025.10.330.

Disclosure of interest

The authors declare that they have no competing interest.

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