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**Review Article**

# Zero-fluoroscopy versus fluoroscopy-guided catheter ablation in ventricular arrhythmia: A systematic review and meta-analysis

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## Abstract

Catheter ablation has been the go-to treatment for ventricular arrhythmia, with traditional fluoroscopy-guided and non-zero fluoroscopy (NZF) catheter ablation posing high radiation risk for operators and patients. Zero-fluoroscopy technique offers elimination of radiation risk; however, its efficacy and safety in ventricular arrhythmia patients are not well explored. The aim of this study was to systematically evaluate the effectiveness, safety, and feasibility of zero-fluoroscopy ablation on ventricular arrhythmia patients. This study only included relevant studies comparing zero-fluoroscopy and NZF in ventricular arrhythmia ablation that were identified from Scopus, PubMed, and ScienceDirect (up to June 20, 2024). The quality of the study was assessed using the ROBINS-I tool, and the meta-analysis was conducted using a random-effect model. Out of 383 studies found, nine cohort studies were included with 1.408 patients. There was no significant difference in the acute procedural success rate of the zero-fluoroscopy and NZF (relative risk: 1.01; 95%CI: 0.95–1.07; $p$=0.69), with a similar recurrence rate ($p$=0.88; for four studies; n=374), and comparable procedural time (mean difference: -19.22 minutes; 95%CI: -41.16–2.72; $p$=0.09). Adverse events such as pericardial effusion, pseudoaneurysm, and hematoma were similar between zero-fluoroscopy and NZF. Overall, zero-fluoroscopy catheter ablation has demonstrated non-inferiority as a treatment option for ventricular arrhythmia ablation. As zero-fluoroscopy eliminates radiation risk without compromising procedural efficacy, zero-fluoroscopy has the potential to become a widely adopted approach for catheter ablation in ventricular arrhythmia.

**Keywords**: Ablation, efficacy, safety, ventricular arrhythmia, zero-fluoroscopy

## Introduction

Ventricular arrhythmias (VA) represent a significant clinical challenge due to their strong association with significant morbidity and mortality [1]. Globally, the prevalence of VA has been reported at 51.86 per 100,000 individuals, with the incidence rising with age and frequently coexisting with underlying cardiac conditions such as ischemic heart disease, heart failure, and cardiomyopathy [2]. The pathophysiology of VA involves aberrant electrical activity within the ventricles, which can lead to life-threatening arrhythmias such as ventricular tachycardia and ventricular fibrillation, necessitating immediate and effective intervention [1,3].

Catheter ablation has emerged as the standard therapeutic approach for VA, particularly in cases of recurrent or drug-refractory arrhythmias. Among the various modalities, radiofrequency



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ablation remains the most commonly employed technique, demonstrating efficacy in suppressing arrhythmogenic foci and improving long-term outcomes [4,5]. Traditionally, fluoroscopy has been the primary imaging modality for catheter guidance during ablation procedures, offering real-time visualization of intracardiac structures and catheter positioning. However, despite its utility, fluoroscopy presents limitations, including exposure to ionizing radiation, which poses potential risks to both patients and operators [6,7]. Prolonged radiation exposure has been linked to an increased risk of malignancies, cataracts, and radiation-induced skin injuries, necessitating the implementation of radiation-reduction strategies in electrophysiological procedures [8,9].

To address these concerns, zero-fluoroscopy (ZF) ablation has gained traction as an alternative approach, aligning with the as low as reasonably achievable (ALARA) principle to minimize radiation exposure [9,10]. This technique leverages electroanatomical mapping (EAM) systems, such as CARTO and EnSite NavX, along with adjunctive imaging modalities like intracardiac echocardiography, to enable real-time catheter navigation without fluoroscopic guidance [11]. Additionally, pre-procedural integration of cardiac magnetic resonance imaging and computed tomography enhances the anatomical accuracy of ablation strategies, facilitating improved procedural precision [12]. Despite its potential advantages, the adoption of ZF ablation remains a topic of ongoing debate. Several studies have demonstrated that ZF techniques effectively reduce radiation exposure without compromising procedural success or safety outcomes [13-15]. Evidence suggests that in atrial fibrillation ablation, ZF approaches have shown comparable efficacy to conventional fluoroscopy-guided procedures, prompting considerations for broader clinical application [16]. However, concerns persist regarding the feasibility of ZF in complex VA cases, where the absence of direct fluoroscopic visualization may increase procedural difficulty and the risk of complications [17-19].

Given the growing interest in radiation-free electrophysiology procedures, a comprehensive evaluation of ZF ablation in VA treatment is needed. Therefore, the aim of this study was to assess the effectiveness, safety, and feasibility of ZF techniques by synthesizing existing clinical data. By providing a detailed appraisal of current evidence, this study sought to elucidate the potential benefits and limitations of ZF ablation in VA management and offer evidence-based recommendations for its clinical implementation.

# Methods

## Study design and protocol registration

This systematic review and meta-analysis adhered to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) reporting guidelines to ensure methodological rigor and transparency [20]. The study protocol was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD42024558605.

## Eligibility criteria

This study evaluated the feasibility, efficacy, and safety of ZF in VA ablation by comparing it with conventional fluoroscopy-guided ablation or the non-zero fluoroscopy (NZF) approach in VA ablation. Studies that align with our research question, as detailed in our patient, intervention, comparator, and outcomes (PICO) framework, were incorporated. The PICO of the study was: patient (P): patients who underwent ablation for VA; intervention (I): ZF catheter ablation; comparator (C): NZF catheter ablation (conventional ablation); and outcomes (O): (a) acute procedural success rate; (b) recurrence rate; (c) procedural duration; and (d) safety profiles. Studies that fulfilled the following requirements were included: (1) non-randomized studies that directly compare the use of ZF and NZF for VA ablation; and (2) patients undergoing catheter ablation due to VA, such as ventricular tachycardia and premature ventricular contraction (PVC). The exclusion criteria included: (1) review articles, letters, comments, case reports, and case series; (2) observational studies that did not compare the use of ZF and NZF in VA patients; (3) irretrievable full-text publications; or (4) articles not published in English.

### Search strategy

A systematic literature search was conducted as of June 20, 2024, using three major electronic databases: Scopus, PubMed, and ScienceDirect. The search strategy was designed to identify relevant studies on ZF ablation for VA. Search terms included combinations of keywords to ensure comprehensive retrieval of the articles. The following search terms were used: ("Ventricular arrhythmias" OR "Ventricular arrhythmia" OR "Ventricular tachycardia" OR "Ventricular fibrillation" OR "Premature ventricular contraction" OR "Ventricular tachyarrhythmia") AND ("Ablation" OR "Isolation") AND ("Fluoroless" OR "Zero fluoroscopy").

### Data extraction

Two independent investigators (CDT and ARKR) conducted abstract and full-text screening using Rayyan software, adhering to predefined inclusion and exclusion criteria. Any discrepancies were resolved by a third investigator (II) through discussion and consensus. From each eligible study, the following data were systematically extracted: (1) first author; (2) study design and geographic location; (3) year of publication; (4) total number of patients and mean age for ZF and NZF groups; (5) type of VA assessed; (6) three-dimensional (3D)-EAM system utilized; (7) origin of the VA; (8) 3D-EAM approach and ablation access; and (9) study outcomes.

### Outcomes

In this study, the efficacy and safety of ZF in VA ablation were assessed with four essential outcomes. Short-term evaluations were observed with the acute procedural success rate, defined as the absence of any instances of PVC or ventricular tachycardia for a period exceeding a minimum of 15 minutes after the last application of radiofrequency ablation. Long-term evaluations were observed with the VA recurrence during the follow-up period of each study. The procedural time between the two approaches, measured from patient preparation until the removal of equipment, was also assessed. Safety parameters were assessed by observing the adverse events (AE) that occurred during the course of the procedure and reported in the studies.

### Quality assessment

The risk of bias in non-randomized studies was assessed using the ROBINS-I tool, which evaluates potential bias across seven domains that may influence study outcomes. Two independent investigators (KM and EAB) systematically assessed each study, categorizing the risk of bias as low, moderate, serious, or critical [21]. Discrepancies in assessments were resolved through discussion, with a third investigator (RM) providing arbitration when necessary.

### Statistical analysis

The statistical analysis was conducted using R Studio version 4.4.1 (Posit PBC, Boston, USA) and STATA version 17 (Stata Corp, Texas, USA). The $I^2$ statistic was employed to assess heterogeneity, with thresholds of 25%, 26–50%, and >50% representing low, moderate, and high heterogeneity, respectively. Considering the variability between studies, the meta-analysis was conducted using a random-effect model. Effect sizes were reported as mean differences (MD) with 95% confidence intervals (CI). In cases where meta-analysis was not feasible due to data variability, *p*-values were combined by inputting the one-sided *p*-values into R Studio. The resulting combined *p*-value data were visually represented in an albatross plot generated within R Studio. Publication bias was qualitatively assessed using a funnel plot and quantitatively evaluated through Egger's regression analysis in STATA version 17.

## Results

### Study selection process

The initial database search identified 383 potentially relevant articles from peer-reviewed sources, as depicted in (**Figure 1**). After removing 50 duplicate records, the titles and abstracts of 333 articles were screened, leading to the selection of 36 articles for full-text review. Following the full-text assessment, 27 articles were excluded based on predefined eligibility criteria. Nine studies met the inclusion criteria [17,18,22-28], comprising three prospective [17,23,26] and six retrospective cohort studies [18,22,24,25,27,28].

## Characteristics of included studies

Nine studies were included in this meta-analysis [17,18,22-28], all of which utilized radiofrequency ablation as the primary treatment modality. Each study employed advanced 3D-EAM using either the CARTO or EnSite NavX system, with only two studies explicitly reporting the use of intracardiac echocardiography in the ZF procedure [24,27]. All included studies reported that the ZF approach was performed with a fluoroscopy time of 0.0±0.0 minutes and a fluoroscopy dose of 0.0±0.0 mSv. The ZF procedures were exclusively conducted by certified electrophysiologists, with fluoroscopy available as a backup if required. Patients who underwent conversion from ZF to NZF during the ablation procedure were excluded from the final analysis. The anatomical origin of VA targeted for ablation varied across studies. In the ZF approach for VA originating from the right heart chamber, right ventricular outflow tract (RVOT) mapping was systematically performed as the initial step in all nine studies [17,18,22-28]. Among the seven studies addressing ablation in the left heart chamber, six utilized the retrograde transaortic approach for mapping and catheter access [17,18,22-24,28]. In contrast, a study specified a differentiated approach, employing transseptal access for VA originating from the septal and anterior regions of the left ventricle while using the retrograde transaortic approach for VA arising from the left ventricle outflow tract (LVOT) and aortic root [27]. Additionally, all studies reported discontinuing anti-arrhythmic drugs for at least five half-lives before the ablation procedure. A detailed summary of the baseline characteristics and procedural aspects of the included studies is presented in (**Table 1**).

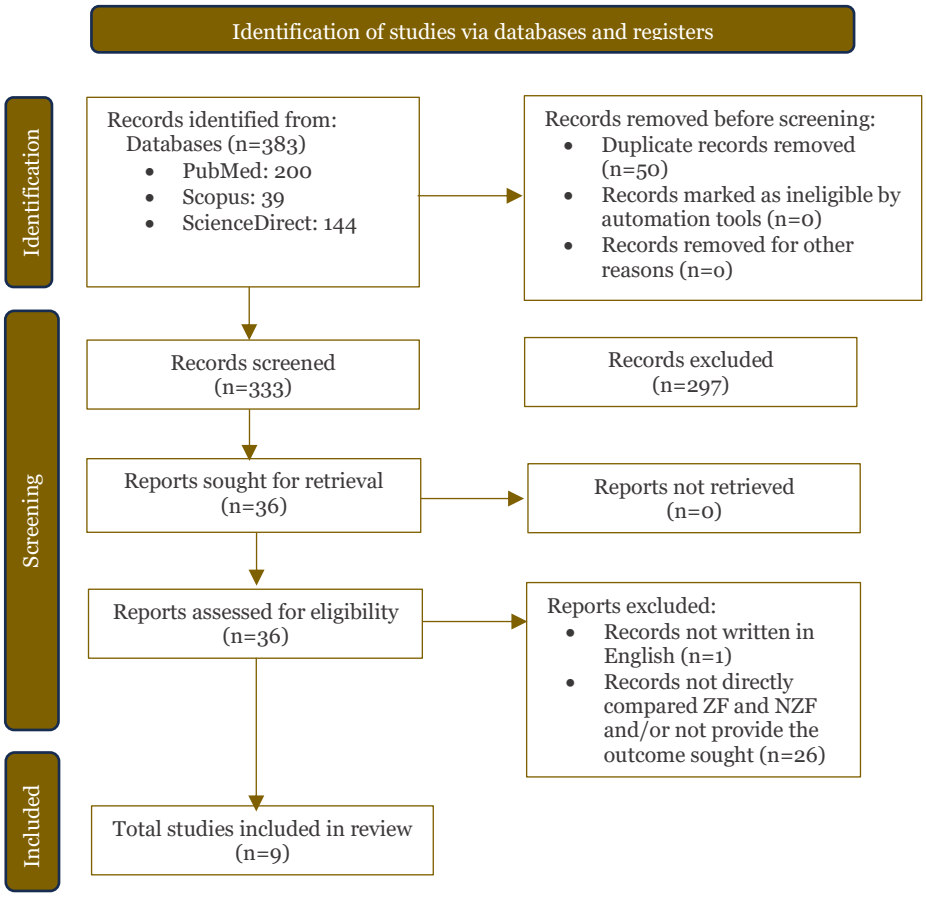


Figure 1. PRISMA flowchart of the study selection process.

## Quality assessment

The ROBINS-I tool was used to assess the quality of included studies, with the detailed results presented in (**Figure 2**). Out of nine studies [17,18,22-28], two studies [23,25] were deemed to have a serious risk of bias, and seven studies [17,18,22,24,26-28] had a low risk of bias. A study was deemed to have a potentially high risk of bias in domain seven due to a lack of focus on reporting effectiveness and safety outcomes [23]. Specifically, the study did not explicitly report procedural duration using numerical data but presented it graphically. This approach rendered

their data on procedural duration ineligible for inclusion in our analysis. Additionally, the study emphasized differences in ablation effectiveness based on origin rather than focusing on the comparison between ZF and NZF techniques. However, it still reported comparisons of acute procedural success rate, recurrence, and safety outcomes. Despite the high risk of bias in this domain, it did not influence our overall results. Another study was also determined to have a high risk of bias because they did not report acute success and safety outcomes separately for the VA subgroup [25]. As a result, their VA-specific data could not be included in the analysis. Nevertheless, these potential biases did not significantly affect the overall findings.

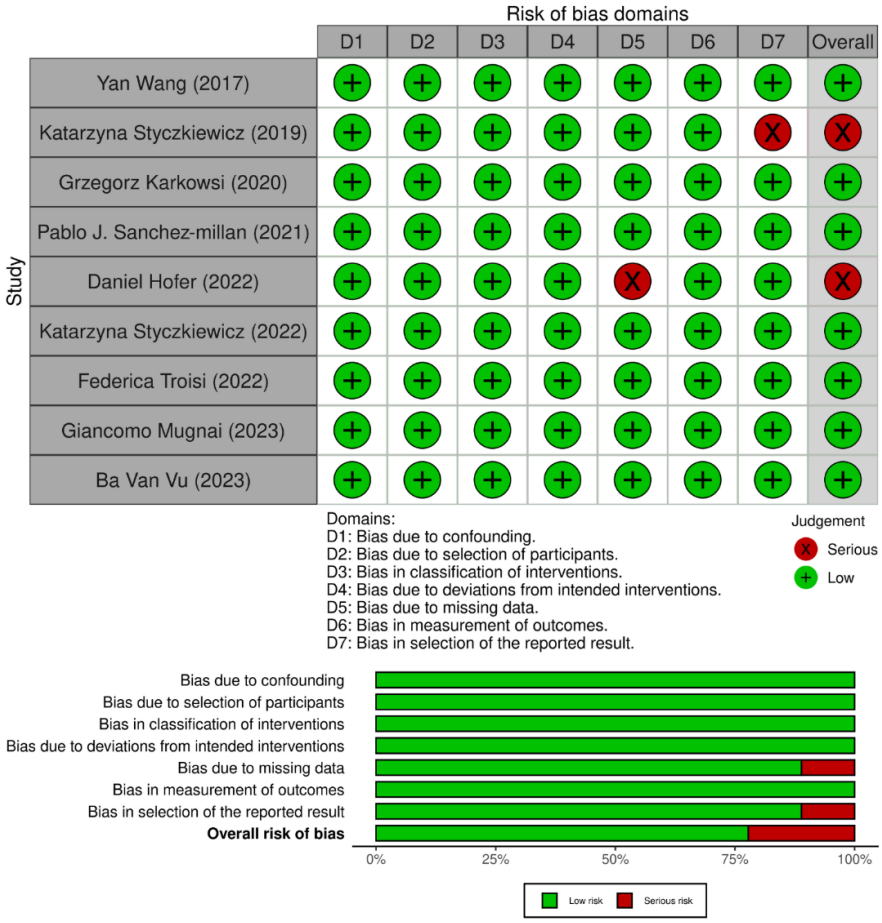


Figure 2. Detailed assessment of risk of bias using ROBINS-I across all studies included in our analysis, 75% were categorized as having low potential risk of bias, ensuring the robustness of the results.

## Acute procedural success

Eight [17,18,23-28] out of nine studies [17,18,22-28] assessed acute procedural success. Study reported a 100% success rate across all ablation procedures, including VA ablation [25]. Five studies observed similar success rate of ZF compared to NZF with not statistically significant: 100% vs 98.2%, $p$=0.32 [26]; 80% vs 50%, $p$=0.36 [24]; 89.8% vs 80%, $p$=0.13 [28]; 100% vs 96%, $p$=0.30 [27]; and 87.5% vs 86.1% [17]. Conversely, two studies found slightly lower acute success rates in ZF compared to NZF, with no significant difference with $p$=0.12 and $p$=0.72 [18,23].

A meta-analysis was performed to evaluate the overall acute procedural success. The pooled analysis showed no significant difference between ZF and NZF with a risk ratio (RR) of 1.01 (95%CI: 0.95–1.07; $p$=0.69) with moderate heterogeneity ($I^2$: 58%). Funnel plot analysis indicated asymmetry, suggesting potential publication bias. However, Egger's regression test did not confirm significant bias or small-study effects ($\beta_0$: 1.46; $p$=0.06). The forest plot summarizing the meta-analysis and sensitivity analysis is presented in (**Figure 3**), with the funnel plot available in **Underlying data.**

Table 1. Baseline characteristics of included studies

| First author, year | Design study (location) | Type of VA | Total patients of ZF (mean age±SD) | Total patients of NZF (mean age±SD) | 3D-EAM used in the study | Origin of VA | 3D-EAM and ablation access |
|---|---|---|---|---|---|---|---|
| Yan Wang *et al.*, 2017 [17] | Cohort prospective (multi-center; China) | PVC and VT | n=160 (45.6±15.6) | n=321 (45.1±15.2) | EnSite NavX | Not specified/ various (only available as idiopathic VA) | Femoral vein access for VA from right-heart chamber; retrograde trans-aortic for VA originating from left-heart chamber |
| Katarzyna Styczkiewicz *et al.*, 2019 [23] | Cohort prospective (multi-center; Poland; "Electra" registry 2005-2017) | PVC and VT | n=36 (59±6.45) | n=67 (56±6.55) | EnSite NavX | Aortic cusps (LCC (48%); AMC / LCC (26%); LCC/RCC (11%); RCC (9%); NCC (6%)) | Femoral vein access for RVOT mapping, then if no adequate RVOT sites were identified, retrograde trans-aortic for LVOT mapping were conducted |
| Grzegorz Karkowsi *et al.*, 2020 [28] | Cohort retrospective (single-center; Poland) | PVC | n=88 (42±29.26) | n=40 (40±20) | CARTO | RVOT, tricuspid valve region/para-Hisian, aortic cusp, LVOT | Femoral vein access for VA from right-heart chamber; retrograde trans-aortic for VA originating from left-heart chamber |
| Pablo J. Sanchez-Millan *et al.*, 2021 [24] | Cohort retrospective (single-center; Spain) | PVC | n=10 (49±16) | 11 (47±15) | CARTO and EnSite NavX | Aortic sinus cusp | Femoral vein access for RVOT mapping, then if no adequate RVOT sites were identified, retrograde trans-aortic for LVOT mapping conducted |
| Daniel Hofer *et al.*, 2022 [25] | Cohort retrospective (single-center; Swiss) | PVC | n=7 (55±18.1) | n=4 (54±17.8) | CARTO and EnSite NavX | RV | Femoral vein access |
| Katarzyna Styczkiewicz *et al.*, 2022 [18] | Cohort prospective (multi-center; Poland; "Electro" registry 2012 - 2018) | PVC and VT | n=62 (56±8,875) | n=32 (53±7) | EnSite NavX | Aortic sinus cusp | Femoral vein access for RVOT mapping, then if no adequate RVOT sites were identified, retrograde trans-aortic for LVOT mapping conducted |
| Federica Troisi *et al.*, 2022 [22] | Cohort retrospective (single-center; Italy) | PVC and VT | n109 (48.7±16.2) | n=231 (62±15.4) | CARTO | Not specified/various | Femoral vein access for VA from right-heart chamber; retrograde trans-aortic for VA originating from left-heart chamber |
| Giancomo Mugnai *et al.*, 2023 [27] | Cohort retrospective (multi-center; international) | PVC | n=104 (51.7±15.8) | n=27 (48.9±16.9) | CARTO and EnSite NavX | RVOT (55.0%); LV (16%); LVOT and Cusps (14.5%); RV (9.2%); AMC (5.3%) | Femoral vein access for VA from right-heart chamber; transeptal antegrade for VA originating from septal and anterior site of LV; retrograde trans-aortic for VA originating from LVOT and aortic root |
| Ba Van Vu *et al.*, 2023 [26] | Cohort prospective (single-center; Vietnam) | PVC and VT | n=53 (52.6±13.4) | n=55 (48.8±14.1) | EnSite NavX | RVOT | Femoral vein access |

3D-EAM: 3D electroanatomical mapping; AMC: aortomitral continuity; LCC: left coronary cusp; LV: left ventricle; LVOT: left ventricular outflow tract; NCC: non-coronary cusp; NZF: non-zero fluoroscopy; PVC: premature ventricular contraction; RCC: right coronary cusp; RV: right ventricle; RVOT: right ventricular outflow tract; SD: standard deviation; VA: ventricular arrhythmias; VT: ventricular tachycardia; ZF: zero-fluoroscopy.

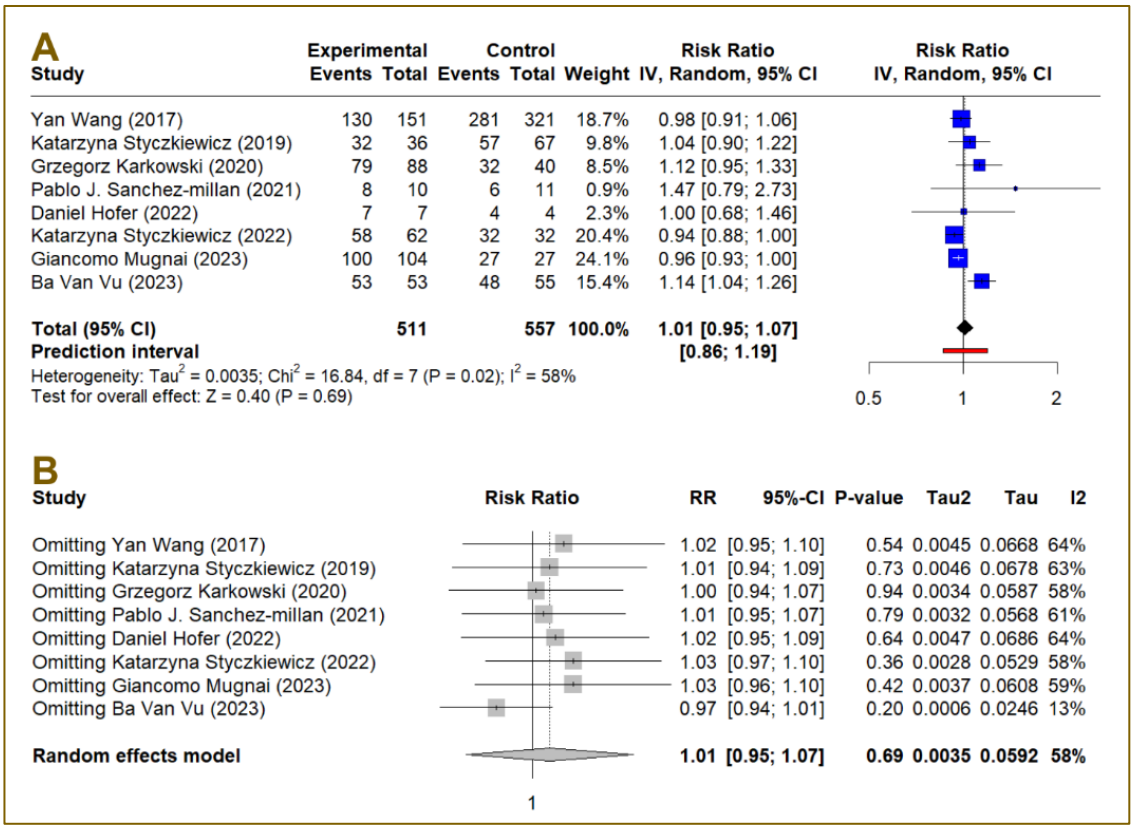


Figure 3. Difference in acute procedural success rate between zero-fluoroscopy (ZF) and non-zero fluoroscopy (NZF). (A) Forest plot using a random-effects model with the Paule-Mandel weighting method, showing no significant difference between ZF and NZF. (B) Sensitivity analysis with the leave-one-out method confirms robustness, with consistent *p*-values and heterogeneity when any single study is excluded.

## Recurrence rate

Out of nine studies reviewed [17,18,22-28], seven studies [17,18,23-25,27,28] reported recurrence rates across different follow-up periods. All seven studies found that recurrence rates in the NZF group were similar to those in the ZF group, although a slightly higher recurrence rate was observed in the NZF group. However, none of these differences reached statistical significance across various follow-up durations: 6-month follow-up (1.9% vs 2.2%) [17], 12-month follow-up (13% vs 19%; $p$=0.79) [27], and long period follow-up of approximately 48.6±16.7 months in the ZF group compared to 49.3±16.3 months in the NZF group (18.2% vs 27.5%; $p$=0.23) [28]. Two studies [18,23] assessed recurrence rates over at least 12 months of follow-up: one study reported no significant difference, with $p$=0.84 [23], while another study did not report the $p$-value [18]. Similarly, another study. [25] noted three VA recurrences in the NZF group over a mean follow-up of 240±180 days, while no recurrences were observed in the ZF group. In contrast, a slightly lower recurrence rate was observed in the NZF group at the 3-month follow-up (30% vs 27.3%; $p$=1.00), though the difference remained non-significant [24].

Due to the variability in follow-up durations, a meta-analysis was not feasible. However, the data were evaluated using the combined $p$-value method, and the direction of effect was assessed using an albatross plot. Three studies [17,18,25] were excluded from the analysis due to missing $p$-values. The combined $p$-value indicated comparable results between ZF and NZF ($p$-value combination of 0.88; four studies). Furthermore, the albatross plot showed no directional preference, with most studies clustered near the center, indicating an overall comparable recurrence rate between ZF and NZF groups (**Figure 4**).

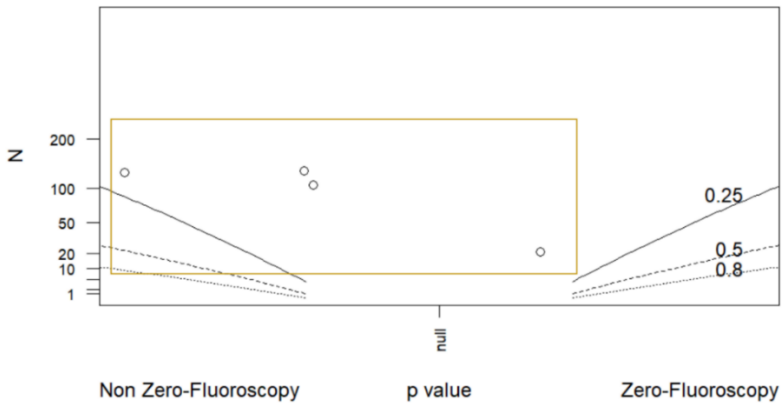


Figure 4. Albatross plot of recurrence rate of the included studies. The distribution of studies (represented by dots) around the center (yellow box) indicates a comparable trend between the two approaches, with no clear directional preference in recurrence rate between zero-fluoroscopy (ZF) and non-zero fluoroscopy (NZF) groups.

## Procedural duration

Among nine studies included [17,18,22-28], eight [17,18,22,24-28] reported procedural time. Six of these studies [17,18,22,27,25,28] observed a shorter procedural duration in the ZF group, with four reaching the statistical significance: 59 min vs 76.7 min, $p$=0.002 [18]; 110.5 min vs 176.9 min, $p$<0.001 [22]; 84.4 min vs 96.6 min, $p$=0.04 [28]; and 100.4 min vs 156.2 min, $p$<0.001 [27]. The remaining two studies [17,25] did not find statistically significant differences: 77.1 min vs 79.9 min [17] and 91 min vs 118 min, $p$=0.27 [25]. In contrast, two studies [24,26] reported longer duration in the ZF group compared to NZF, although this result did not reach statistical significance: 269 min vs 229 min, $p$=0.12 [24]; and 67.9 min vs 62.9 min, $p$=0.34 [26].

A meta-analysis was conducted to assess the average procedural time difference and evaluate the overall consistency of the effects across the included studies. The results indicated that ZF approaches were not significantly associated with a lower procedural time compared to NZF (MD: -19.22; 95%CI: -41.16–2.72; $p$=0.09), with high heterogeneity observed ($I^2$: 94%). Funnel plot analysis revealed asymmetrical distribution, but Egger's regression test (intercept: 1.02; $p$=0.53) suggested no significant publication bias or small-study effect. Sensitivity analysis, using the leave-one-out method, revealed variability in the results. The most substantial change occurred when the study. was excluded, which rendered the $p$-value statistically significant. However, the heterogeneity remained stable regardless of the study excluded, indicating that the overall heterogeneity was not influenced by individual studies. The forest plot for the meta-analysis and sensitivity analysis is presented in (**Figure 5**), while the funnel plot is available in **Underlying data**.

## Safety outcomes

Of the nine studies included [17,18,22-28], seven studies [17,18,22-24,27,28] reported on safety outcomes, with no deaths observed either peri-procedurally or post-procedurally during the follow-up period. Pericardial effusion (PE) was reported in four studies [17,22,24,28], with no significant difference between the ZF and NZF approaches. Specifically, study documented one case of PE in the ZF group and two in the NZF group [17]. Another study. [24,28] reported only one case of PE in the ZF group, with none in the NZF. Troisi *et al.* reported only one case of PE in NZF with none in ZF [22]. Pseudoaneurysm was reported in two studies: one study reported one case in ZF and two cases in NZF [17], while another study only observed one case in ZF [28]. Hematomas were also reported in two studies [27,28]. Mugnai *et al.* [27] only observed two hematomas in the ZF group with none in the NZF, whereas Karkowski *et al.* [28] observed two hematomas in the NZF group with none in the ZF. Additionally, other adverse effects, including arteriovenous fistula [17], pneumothorax [17], hemothorax [17], atrioventricular block [23], pericarditis [28], coronary spasm [18], and femoral dissection [22] were only reported by a single study with none of them reported significantly higher in the ZF group.

A meta-analysis of adverse effects reported by multiple studies revealed no significant difference in the risk of PE, pseudoaneurysm, or hematoma between the ZF and NZF approaches. The full results of the meta-analysis are presented in (**Table 2**). These findings demonstrate the overall safety of the ZF approach, supporting its clinical reliability.

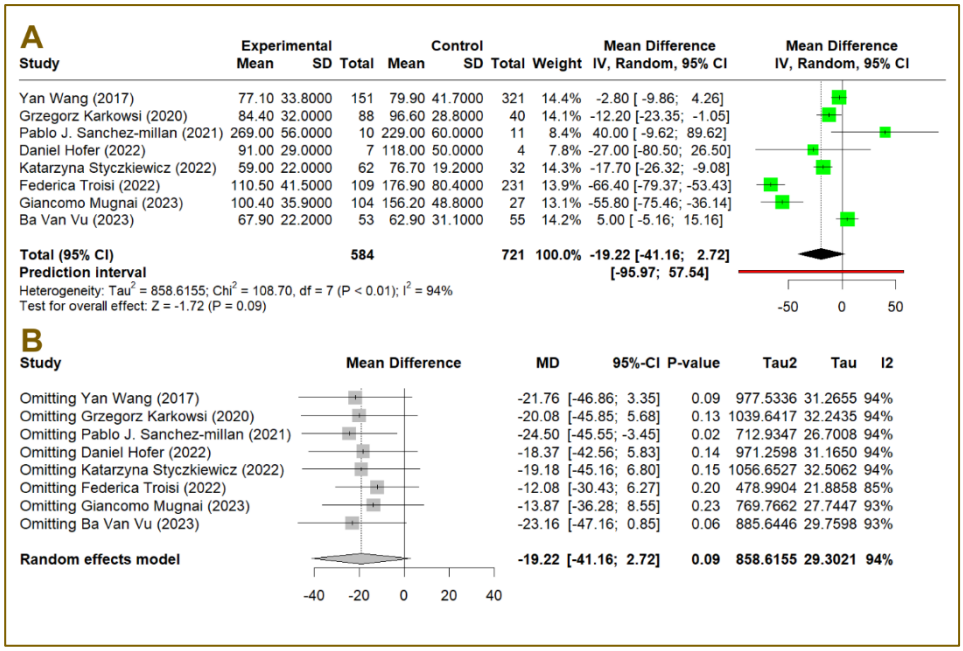


Figure 5. Difference in procedural duration between zero-fluoroscopy (ZF) and non-zero fluoroscopy (NZF). (A) Forest plot from the meta-analysis using a random-effects model with Paule-Mandel weighting, demonstrating non-significant results. (B) Sensitivity analysis using the leave-one-out method, highlighting variability in results. The exclusion of study. revealed a significant reduction in procedural time, while overall heterogeneity remained unchanged, indicating that the findings were not influenced by individual studies.

Table 2. Meta-analysis of adverse events in zero-fluoroscopy (ZF) and non-zero fluoroscopy (NZF) approaches

| Adverse events observed | Pooled RR (95%CI) | $I^2$ Higgins | $X^2$ | *p*-value |
|---|---|---|---|---|
| Pericardial Effusion [17,22,24,28] | 1.32 (0.31; 5.62) | 0% | 0.52 | 0.71 |
| Pseudoaneurysm [17,28] | 1.17 (0.17; 7.89) | 0% | 0.02 | 0.87 |
| Hematoma [27,28] | 0.35 (0.03; 4.74) | 34% | 1.51 | 0.43 |

All meta-analyses were conducted with a random-effect model with the Paule-Mendel weighting approach. All analysis showed non-significant/comparable result.

## Discussion

The ZF technique is a novel and revolutionary method in catheter ablation, which significantly eliminates the fluoroscopy utilized during the VA ablation procedure [22,29]. The elimination of fluoroscopy use is pivotal, as previous studies have demonstrated that both patients and operators are at an increased risk of radiation exposure associated with the traditional NZF method [30]. The risk of cataracts, dermatologic injury, malignancy, and genetic defects is particularly concerning for operators who perform numerous procedures over their careers, leading to substantial cumulative doses [31-34]. Moreover, there is an increasing radiation risk in pediatric and pregnant patients [34]. Therefore, the ZF technique offers the elimination of these substantial hazards, facilitating more effective control of VA [35].

From the findings of our study, the ZF approach has an equal result in both efficacy and safety parameters. This finding highlights that the advancement of the mapping technique has successfully delivered ZF as the new viable option, considering the dangerous side of radiation exposure [15,36]. The advancement of 3D-EAM has been pivotal in the success of the ZF approach. The mapping of the right atrium combined with intracardiac echocardiography has delivered a new approach to performing transeptal puncture, which facilitates the mapping and

ablation of VA in the left heart chamber [37,38]. However, in several scenarios, such as patients with cardiac devices or complex left-sided VA, particularly arising from LVOT or aortic root, our included study predominantly used the retrograde trans-aortic approach [24]. While fluoroscopy may be necessary in extremely complex cases, such as tortuous vascular anatomy or significant variability in the aortic root [39,40], efforts should still be made to minimize its dose as much as possible. Notably, our included studies demonstrated that all of the procedures in ZF were done without the use of fluoroscopy [17,18,22-28]. This emphasizes the critical role of advanced operator skills in ensuring efficacy and safety in ZF VA ablation, particularly in complex cases [41,42].

In this study, we also underscore that the recurrence rates for both ZF and NZF were also comparable. This finding may be attributed to the recurrence rate being significantly correlated with the ablation site's inadequate energy penetration and poor proximity to arrhythmia foci. The VA origin is firmly associated with the insufficient proximity to foci [26,43]. Thus, VA that originates from the left ventricular summit is reported to be challenging to ablate completely, requiring additional ablation [43]. Study also demonstrated that VA originating from the septal anterior distal and septal posterior proximal ventricular sites had a higher recurrence rate [26]. This finding is suspected to be due to the deep anatomical foci location, anatomical complexity of the septal region, and heterogeneity of tissue substrate within the septal region; hence, the mapping may be harder [44]. The unclear mapping will contribute to inadequate penetration of energy and an invalid site of ablation. Multi-foci ablation also enhances the difficulty of completing VA ablation since the operator needs to target all foci in the ventricle [4,45]. Moreover, the etiology of VA may link to a higher recurrence rate with ischemic etiology, which may generate a more profound and wide site of VA, thus adding more challenging complete ablation [46].

While our overall findings were aligned with a previous meta-analysis [13], our study elaborated that the procedural duration of ZF vs NZF in VA was comparable. This result may be attributed to several factors. First, there are higher complexities and additional procedural steps in VA ablation, such as retrograde trans-aortic puncture or intricate mapping of deep ventricular structures, which is unnecessary in other types of arrhythmias. Second, we believe that VA ablation duration varies across VA origins. For instance, VA arising from aortic sinus cusps sometimes requires a longer duration to perform due to the proximity to vital structures such as coronary arteries which need careful navigation and ablation [4,24,47]. This fact mainly affects our result, as in sensitivity analysis, when we exclude. [24], the *p*-value becomes significant. Third, it is believed that operator experiences and skills were the main issues, as more experienced operators, particularly those who can integrate 3D-EAM and intracardiac echocardiography, will contribute to a shorter duration of the procedure [41,42].

While the results of this meta-analysis are promising, several limitations should be acknowledged. The heterogeneity among included studies and differences in operator experience and technology used could impact the generalizability of the findings. We noted that this study does not differentiate between types of VA, particularly PVC and ventricular tachycardia. We also could not differentiate the VA etiology, as ischemic VA typically requires significantly longer ablation times compared to non-ischemic VA. Future recommendations should focus on the establishment of a standardized protocol for ZF VA ablation, with particular emphasis on determining the appropriate use of the transeptal or retrograde trans-aortic approach. Additionally, studies assessing cost-effectiveness, operator experiences, and quality-of-life improvements associated with ZF techniques would provide valuable insights for healthcare decision-making.

## Conclusion

ZF catheter ablation has demonstrated non-inferiority as a treatment option for various types of VA in general, offering comparable acute success rate, recurrence rate, and AE to traditional NZF methods. While the efficacy and safety outcomes between ZF and NZF were similar, the ZF approach presents a significantly lower radiation risk without compromising procedural efficacy. As experience and technology continue to evolve, ZF has the potential to become a widely adopted approach for catheter ablation in VA management. The adoption of ZF techniques requires

investment in technology and operator training but holds promise for improved patient safety and management of VA, which might enhance health outcomes for both patients and operators.

### Ethics approval

Not required.

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### Competing interests

All the authors declare that there are no conflicts of interest.

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### Underlying data

Derived data supporting the findings of this study are available from the online digital repository (dx.doi.org/10.6084/m9.figshare.28673585).

### Declaration of artificial intelligence use

We confirm that no artificial intelligence (AI) was used at any stage of this work, including data collection, analysis, visualization, or manuscript preparation. The authors conducted all components of this work manually, without the use of AI-based tools.

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