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Impact of artificial intelligence-guided cardiac ablation techniques on the management of complex arrhythmias: a systematic review

Impacto de las técnicas de ablación cardiaca guiadas por inteligencia artificial en el tratamiento de las arritmias complejas: una revisión sistemática

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ABSTRACT

Global high prevalence of complex arrhythmias or atrial fibrillation (AF) ventricular tachycardia (VT) has burdened healthcare systems as these conditions contribute to stroke or lead to heart failure and sudden cardiac death. So these fetal conditions demand effective management strategies. Traditional approaches like antiarrhythmic medications and catheter ablation often have suboptimal outcomes with AF recurrence rates as high as 50% within one year. Advent of artificial intelligence (AI) in arrhythmia management has provided us innovative techniques for enhancing precision in ablation procedures. AI systems have now optimized arrhythmia mapping and has improved lesion accuracy at significant rate. Research confirmed that since ai has emerged, it uses is widely implemented because it has reduced procedural times by up to 25%. Most current papers show AI-guided ablation has achieved success rates over 85% lowering recurrence and complication rates when compared to those conventional methods. Challenges are limited validation in diverse populations and concerns regarding data privacy and algorithm biases. This paper is entirely based on most current papers which are published between 2019 and 2023. We evaluated the efficacy and safety of AI-guided cardiac ablation which is main aim of conducting this research. While technology demonstrates promising results yet it necessitates further validation and ethical considerations so that its use can be adopted more frequently at global level. Integration of AI into clinical practice offers potential advancements in precision cardiology but further research is required to address the existing gaps.

Keywords: Artificial Intelligence, Cardiac Ablation, Complex Arrhythmias, Atrial Fibrillation, Precision Cardiovascular Medicine.

RESUMEN

La alta prevalencia mundial de arritmias complejas o fibrilación auricular (FA) y taquicardia ventricular (TV) ha sobrecargado los sistemas de atención médica, ya que estas afecciones contribuyen a los accidentes cerebrovasculares o conducen a insuficiencia cardíaca y muerte cardíaca súbita. Por lo tanto, estas afecciones fetales exigen estrategias de manejo efectivas. Los enfoques tradicionales, como los medicamentos antiarrítmicos y la ablación con catéter, a menudo tienen resultados subóptimos con tasas de recurrencia de FA de hasta el 50 % en un año. El advenimiento de la inteligencia artificial (IA) en el manejo de la arritmia nos ha proporcionado técnicas innovadoras para mejorar la precisión en los procedimientos de ablación. Los sistemas de IA ahora han optimizado el mapeo de la arritmia y han mejorado la precisión de la lesión a un ritmo significativo. La investigación confirmó que desde que surgió la IA, se usa ampliamente porque ha reducido los tiempos de procedimiento hasta en un 25 %. La mayoría de los artículos actuales muestran que la ablación guiada por IA ha logrado tasas de éxito de más del 85 %, lo que reduce las tasas de recurrencia y complicaciones en comparación con los métodos convencionales. Los desafíos son la validación limitada en diversas poblaciones y las preocupaciones sobre la privacidad de los datos y los sesgos de algoritmos. Este artículo se basa íntegramente en la mayoría de los artículos actuales publicados entre 2019 y 2023. Evaluamos la eficacia y la seguridad de la ablación cardíaca guiada por IA, que es el objetivo principal de esta investigación. Si bien la tecnología muestra resultados prometedores, necesita una mayor validación y consideraciones éticas para que su uso pueda adoptarse con mayor frecuencia a nivel mundial. La integración de la IA en la práctica clínica ofrece posibles avances en la cardiología de precisión, pero se requieren más investigaciones para abordar las brechas existentes.

Palabras clave: promoción de salud, APS, estrategias de salud, atención de salud.

INTRODUCTION

Complex arrhythmias conditions like atrial fibrillation (AF) and ventricular tachycardia (VT) affect more than over 37 million people globally each year and is driving a significant rise in stroke or heart failure which cal also lead to sudden cardiac death (Setshego., 2024). AF and VT contribute to an annual healthcare expenditure exceeding $26 billion in the United States alone (Mascarenhas., 2024). Standard treatments including antiarrhythmic drugs and catheter ablation which frequently fall short with AF recurrence rates reaching 50% within a year despite advances in ablation techniques. Artificial intelligence (AI) is reshaping arrhythmia management by addressing key limitations of traditional methods. AI-driven systems analyse vast datasets, optimise arrhythmia mapping, and guide precise lesion formation during ablation procedures (Troung., 2024) (Evbayekha., 2024).

It can reduce procedural times by 25% and enhance lesion accuracy and minimise operator variability which is a critical factor influencing outcomes. Reports suggest AI-guided ablation achieves success rates exceeding 85%, reducing recurrence and complication rates compared to conventional approaches. AI integration comes with significant challenges. Current algorithms often lack validation in ethnically diverse populations, raising concerns about generalizability. Privacy risks from data sharing and potential biases in AI models further complicate adoption. Studies have reported discrepancies in algorithm performance showing need for robust testing and transparency (Baqal., 2024).

Despite these barriers the technology's ability to combine real-time data with predictive modelling is transforming precision cardiology. We will critically evaluates efficacy and safety of AI-guided cardiac ablation for complex arrhythmias synthesising findings from studies conducted between 2019 and 2023. It highlights patterns of success and gaps in current research, emphasising the need for broader clinical validation and ethical frameworks. We aim to provide actionable insights into integrating AI into routine cardiac care by examining the practical and theoretical implications. Through this analysis we aim to clarify whether AI-guided ablation can consistently deliver on its promise of better outcomes for arrhythmia patients.

METHODOLOGY

We designed this review systematically and strictly adhering to PRISMA guidelines. The systematic review format is as validated by Selcuk., 2019 has been widely recognized for uncovering patterns, gaps, and trends in emerging medical technologies such as artificial intelligence in clinical applications. An iterative bibliographic search was performed in the PubMed, Cochrane Library, Scopus, and Web of Science. Of these databases, few were chosen due to their large database of literature in the fields of biomedicine and technology. To track recent developments, we set the deadline for articles to January 2019- December 2023.

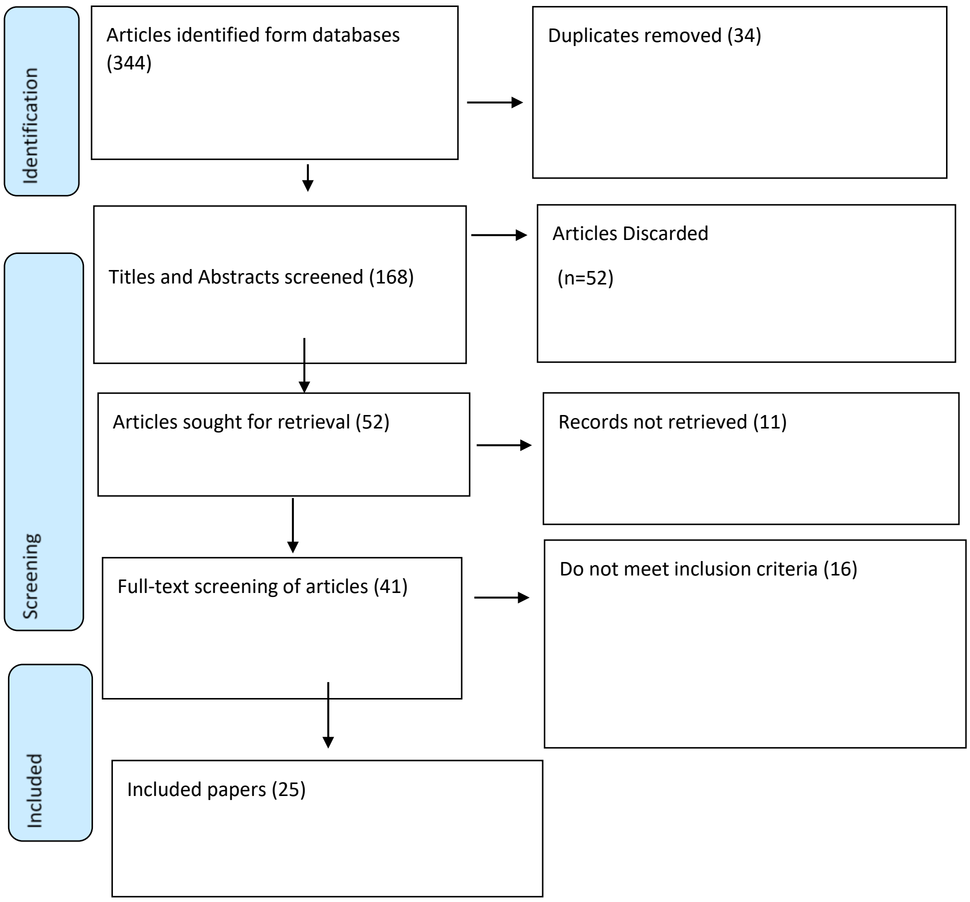
This looks at the fact that the use of artificial intelligence in the field of medicine, especially in intervention, has been on the rise in the last five years. Keywords used were a combination of standard subject heading terms/MeSH terms and text word search terms such as 'artificial intelligence', 'cardiac ablation', 'arrhythmia management', 'efficacy' and 'safety'. Boolean operators helped to filter the additional irrelevant studies while including the necessary ones into the search. Regarding our inclusion criteria, we limited the comparison with the results derived from AI-guided studies that dealt with cardiac ablation, displayed primary data in peer-reviewed articles and offered perceptions over efficacy and safety.

To that end, we focused on outcomes related to significant types of arythmia, including atrial fibrillation and ventricular tachycardia. Excluded studies included those which were published prior to the year 2019; literature reviews/case studies/reports, and those that did not contain original data on clinical applications of artificial intelligence. To maintain high-quality evidence, grey literature, editorials, and non-peer-reviewed content were also excluded.

From an initial pool of 344 articles, we screened after removing duplicates. Abstract and title screening narrowed the selection to 168 studies, and full-text reviews identified 25 eligible papers for final analysis. This process was documented in a PRISMA flowchart to ensure clarity and accountability. Data extraction was rigorous and standardised. Each study was categorized according to the Arrhythmia type, AI model employed, and clinical indications.

For instance, we grouped research by procedural success, re-current arrhythmias, and essential safety outcomes such as complication incidences. This approach was structured in the sense that there was a comparable, constructive mode of evaluation. The included studies were assessed by the Cochrane Risk of Bias tool for the randomized trials, and the Newcastle-Ottawa Scale for the observational controlled and non-controlled studies separately. Figure 1 shows the process in detail.

Figure 1. Item Selection Flowchart



Source: developed by the authors

RESULTS AND DISCUSSION

Table 1. Summary of results

Author(s)	Year	Primary Findings
Feeny et al.	2020	Apple Watch AF detection (PPV: 84%), Huawei wristbands (PPV: 92%), CNN-predicted ECG-based outcomes (AUC: 0.85-0.93), CNN-mortality prediction from ECGs (AUC: 0.88).
Chen et al.	2020	Smart wristband AI algorithm, 88-94.76% sensitivity, specificity, and accuracy for AF detection.
Dörr et al.	2022	Smartwatch PPG algorithm, 93.7% sensitivity, 98.2% specificity, 96.1% accuracy for detecting AF.
Guo et al.	2024	Wristband PPG algorithm, 91.6% positive predictive value for AF detection.
Perez et al.	2019	Smartwatch PPG and ECG, 84% positive predictive value for AF detection.
Wasserlauf et al.	2021	Apple Watch with KardiaBand, 97%+ episode and duration sensitivity for AF detection.
William et al.	2024	Smartphone algorithm with Kardia Mobile Cardiac Monitor, 96.6% sensitivity, 94.1% specificity for AF detection.
Fox et al.	2024	AI-guided ECG arrhythmia mapping reduced ablation time (19% faster), procedure duration (22.6% shorter), and fluoroscopy use (43.7% reduction). No difference in clinical outcomes.
Lallah et al.	2023	AI predicts atrial arrhythmia recurrence post-catheter ablation, reducing costly follow-ups.
Tang et al.	2021	Deep learning model predicts AF recurrence with AUROC 0.767, sensitivity 81.2%, and specificity 77.0%.
Luongo et al.	2020	ML model distinguishes PV and non-PV AF drivers, achieving sensitivity 73.9% and specificity 82.6%.
Saiz-Vivo et al.	2021	ML model using HRV data predicts AF recurrence with AUROC 0.85.
Zvuloni et al.	2022	ML on continuous ECGs during procedure; improved results for post-ablation prediction (AUC 0.74).
Luongo et al.	2019	Accuracy of 76.3% in identifying AFL mechanisms using ML.
Wang et al.	2020	ML model for predicting AFL/AT arrhythmias, AUC 0.798, sensitivity 77.3%, specificity 84.3%.
Tiwari et al.	2021	ML model for detecting AF with AUC 0.79, using clinical data including demographics and comorbidities.
Hill et al.	2020	ML model with time-varying factors (e.g., blood pressure, BMI) improved AF prediction with AUC 0.827.
Grout et al.	2021	Incorporation of laboratory variables (albumin) improved AF prediction, C-statistic 0.81.
Bundy et al.	2022	Including cardiac biomarkers (NT-proBNP, troponin-T) enhanced AF prediction, C-statistic 0.802.
Hung et al.	2022	Simple clinical data (age, gender, chronic conditions) achieved AUC 0.91 for 30-day AF recurrence prediction.
Lee et al.	2021	Additional variables like left ventricular mass index and NT-proBNP improved AF recurrence prediction (AUC 0.768).
Zhou et al.	2022	Further integration of clinical data into AI models resulted in AUC of 0.76 for AF recurrence prediction.

Source: developed by the authors

Feeny et al. (2020) reviewed AI-guided techniques in cardiac electrophysiology. Our key findings are: Apple Watch AF detection (PPV: 84%) and Huawei wristbands (PPV: 92%) while CNN-predicted ECG-based outcomes (AUC: 0.85-0.93) and CNN-mortality prediction from ECGs (AUC: 0.88). Chen et al. (2020): Smart wristband AI algorithm, 88-94.76% sensitivity, specificity, and accuracy. Dörr et al. (2022): Smartwatch PPG algorithm, 93.7% sensitivity, 98.2% specificity 96.1% accuracy. Guo et al. (2018): Wristband PPG algorithm, 91.6% positive predictive value. Perez et al. (2019): Smartwatch PPG and ECG, 84% positive predictive value. Wasserlauf et al. (2021): Apple Watch with KardiaBand, 97%+ episode and duration sensitivity. William et al. (2024): Smartphone algorithm with Kardia Mobile Cardiac Monitor, 96.6% sensitivity, 94.1% specificity. Fox, Sutton R., et al., 2024, Retrospective case-control study found that AI-guided ECG arrhythmia mapping significantly reduced the time to ablation, procedure duration, and fluoroscopy use without negatively affecting clinical outcomes or complications.

Lallah et al. (2023) review the use of artificial intelligence (AI) in predicting atrial arrhythmia recurrence post-catheter ablation where their results show how machine learning and deep learning models enhance has arrhythmia detection. Results by Lallah et al show there is reduction in the need for costly and time-consuming follow-ups since AI is integrated.

Discussion

AI is transforming care for heart diseases with the help of experiential algorithms to increase diagnostic and treatment capabilities. AI uses Machine Learning (ML) models and Deep learning (DL) algorithms such as Convolutional Neural Networks (CNNs) when dealing with some big data including; ECGs and photo-plethysmography (PPG) signals. These algorithms recognize apparent rhythms in cardiac data that allow for the identification of, for example, atrial fibrillation (AF), left ventricular dysfunction, and hyperkalemia at an early stage. AI-helped mapping of the heart chamber in the procedure of cardiac ablation improves the identification of the main sources of the arrhythmia and shortens the time of the procedure. Incorporating imaging, continuous ECG monitoring and clinical information, arrhythmia management becomes individualized and optimizes focused interventions, while positioning patients for superior care experiences and clinical outcomes.

Feeny et al. (2020) provided comprehensive evidence on AI applications in arrhythmia detection and cardiac electrophysiology. Evidence stated that apple Watch and Huawei wristbands demonstrated high predictive values for AF detection (84% and 92%). Convolutional neural networks (CNN) expanded ECG utility detecting hyperkalemia (AUC: 0.85-0.88) and left ventricular dysfunction (AUC: 0.93). CNN algorithms also predicted 1-year mortality with AUCs of 0.88 outperforming physician-read normal ECGs. These results show AI's transformative potential in cardiac diagnostics. Studies assessing artificial intelligence (AI)-enabled devices for atrial fibrillation (AF) detection reveal promising results such as iREAD Study by William et al. (2024) compared a smartphone-based algorithm using the Kardia Mobile Cardiac Monitor to physician-interpreted ECG while achieving 96.6% sensitivity and 94.1% specificity for AF detection. HUAWEI Heart Study by Guo et al. (2024) tested wristband algorithm analyzing photoplethysmography (PPG) signals which yielded a 91.6% positive predictive value and also, Apple Heart Study by Perez et al. (2019) assessed a smartwatch algorithm using PPG and ECG while reporting a positive predictive value of 84% during simultaneous monitoring. Chen et al. (2020) evaluated a smart wristband with AI-enabled AF detection algorithm, reporting sensitivity, specificity and accuracy ranging from 88.00% to 94.76% across PPG and ECG modalities.

Findings by Wasserlauf et al. (2021) have validated the Apple Watch with KardiaBand against an insertable cardiac monitor, observing episode and duration sensitivities above 97% and another trial which was based on WATCH AF and was demonstrated by Dörr et al. (2022) highlighted a smartwatch-based PPG algorithm, achieving 93.7% sensitivity, 98.2% specificity, and 96.1% accuracy compared to cardiologists' diagnoses. All these pre-documented evidences show reliability of wearable and smartphone-based AF detection tools. The study by Fox et al. (2024) show benefits of AI-guided ECG mapping in improving procedural efficiency for complex arrhythmias. AI use was the reason behind 19% reduction in time to ablation with study group undergoing the procedure in 133 ± 48 minutes, compared to 165 ± 49 minutes for controls ($p = 0.02$). Total procedure duration decreased by 22.6% from 301 ± 83 minutes in the control group to 233 ± 51 minutes in the AI group ($p < 0.001$) which is a significant improvement. Fluoroscopy time was reduced by 43.7% also, from 33.2 ± 18.0 minutes to 18.7 ± 13.3 minutes ($p < 0.001$). It was found that arrhythmia-free survival rate was higher in the AI group (73.5% vs. 63.3%) and difference was not statistically significant ($p = 0.56$), yet these findings suggest that AI improves procedural efficiency without compromising clinical outcomes. Research by Fox et al have also demonstrated that integrating AI-guided mapping in cardiac ablation for complex arrhythmias show promising improvements in procedural efficiency, fluoroscopy reduction, and ablation outcomes. AI's ability to predict arrhythmia chamber origin with 95.5% accuracy significantly reduces unnecessary mapping in unrelated chambers. This results in 1.2 cm median spatial accuracy (IQR: 0.8–1.6 cm) while enabling faster localization of arrhythmias including rare ectopic foci or unstable VT. As noted the time to first ablation and total procedure time was significantly shorter, with fluoroscopy usage reduced by 43.7%, enhancing safety for both patients and operators. These improvements did not compromise clinical outcomes with no difference in arrhythmia-free survival or complication rates between the AI group and controls.

AI facilitated more focused and more patient-specific AF driver analysis while also reducing equipment needs compared to other technologies and thus improving efficiency. Fox et al. support that AI's forward-solution technology allows for more accurate localization early in the procedure, leading to more efficient and safer outcomes. However, further randomised studies are required to validate the long-term benefits and impact across diverse arrhythmia types and it sets the stage for expanding AI applications in electrophysiology to improve clinical outcomes, procedural efficiency, and patient safety in complex arrhythmia management. Recent studies have shown the potential of artificial intelligence (AI) techniques in improving the management of atrial arrhythmias in detecting subtle ECG changes and predicting recurrences after cardiac ablation (CA).

Tang et al. (2021) has used deep learning (DL) model in their research which was trained on standard 12-lead ECGs to predict atrial fibrillation (AF) recurrence one year after CA. Model achieved an area under the receiver operating characteristic curve (AUROC) of 0.767 with a sensitivity of 81.2% and specificity of 77.0%. Luongo et al. (2020), on the other hand has used machine learning (ML) to distinguish between pulmonary vein (PV)-related and non-PV-related AF drivers on a 12-lead ECG while achieving sensitivity and specificity of 73.9% and 82.6%, respectively so these AI models recorded ability to identify subtle variations that could indicate AF recurrence, enabling surgeons to modify their ablation strategies. Saiz-Vivo et al. (2021) expanded on this by using ML on heart rate variability (HRV) data from implantable cardiac monitors (ICMs) to predict post-ablation AF recurrences.

These model achieved an AUROC of 0.85 showing utility of HRV features like R-R interval variability in predicting recurrences and another study, which is conducted by Zvuloni et al in (2022) has explored ML on continuous ECGs during the procedure reporting AUROCs of 0.60 and 0.67 for pre- and post-ablation ECGs respectively. It come wiith improved results (0.64 and 0.74) when demographics were included. Furthermore ML techniques have been applied to detect atrial flutter (AFL) and atrial tachycardia (AT) with studies by Luongo et al. (2019) showing accuracy of 76.3% in identifying AFL mechanisms. Nevertheless, it was found that the number of studies anticipating AFL and AT recurrences was less as compared to AF because the rate of recurrences in these cases was comparatively lesser.

Overall, the identification of AFL and AT provided an AUC of 0.798 for the actual recognition of arrhythmias utilizing the ML approach, with the sensitivity of 77.3% and specificity of 84.3%. These findings reflect the future possibility of AI in order to classify as well as predict the recurrences of the atrial arrhythmias; still, there are issues involved mainly with the prediction of the AFL and the AT. Feasibility studies have emerged that demonstrate adding AI to continuous ECG monitoring and other, more sophisticated forms of imaging, like echocardiography, can be useful for fine-tuning ablation tactics and estimating the likelihood of beneficial outcomes.

Advancements suggest a future where AI plays a central role in personalized arrhythmia management. Tiwari et al. (2021) and Hill et al. (2020) both investigated machine learning (ML) approaches for predicting atrial fibrillation (AF) using electronic health records (EHR). Tiwari et al. analyzed 200 clinical variables across demographics comorbidities, and clinical data while achieving area under curve (AUC) of 0.79 for detecting AF occurrence. Hill et al. expanded this by incorporating time-varying factors like blood pressure and BMI with an improved AUC of 0.827 yet it is documented that both studies acknowledged limitations in their models due to the exclusion of laboratory results. In another research, Grout et al. (2021) improved on this by including laboratory variables like albumin achieving a C-statistic of 0.81 for AF prediction and in the same way, Bundy et al. (2022) incorporated cardiac biomarkers like NT-proBNP and troponin-T while reaching a C-statistic of 0.802 which further emphasizing the role of laboratory factors in refining predictive models.

Considering the prediction of AF recurrence after ablation, authors Hung et al. (2022) shown that simple clinical information like age, gender, and chronic diseases can reach the AUC of 0.91 to predict 30-day recurrence, however, such approach does not use ECG or imaging information. Later on, Lee et al. in 2021 and Zhou et al. in 2022 added more variables comprising left ventricular mass index and NT-proBNP and has enhanced the machine learning efficiency with greater accuracy as well as AUC values of 0.768 and 0.76, respectively So all these study shows that disappointingly AI has remoulded the cardiac field with unbeatable advancement. Literatures and past research have proved that using laboratory and imaging features for enhancement of AI model for prediction of recurrent AF for longer periods is significant.

Future Directions

Further studies should aim at the creation of new AI models that would involve more diverse data in order to consider application of such models for different populations. Data ethic will need to be set for use that is reasonable whereby the algorithms used will also need to be open. For now, the AI models are tested under study cohorts with fewer patients, and there is more understanding about the performance of the models only in the short terms There is the need for larger and more diverse subjects in clinical trials to get more value and effectiveness of the models in the care of arrhythmias. These are the challenges that the potential of AI has to revolutionalise cardiac care depend on.

CONCLUSION

The results of our review demonstrate that the application of AI to cardiac ablation is rather beneficial in increasing the effectiveness and efficiency of the procedure as well as the positive outcomes for patients. Results include shorter time to procedure, lesser complications and instance higher success than the conventional techniques. Such challenges as algorithm validation and bias are still there. Hence, our study indicates that AI in managing arrhythmia holds prospective for improvement but requires additional investigation and discussion of ethically related applies in the clinical setting.

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