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Editorial

Beyond Fluoroscopy: Intracardiac Echocardiography and Electroanatomic Mapping as the New Foundation for Atrial Fibrillation Ablation

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Fluoroscopy has served as the procedural compass for catheter-based cardiac interventions for decades. From vascular access to transseptal puncture and catheter manipulation, fluoroscopy's two-dimensional representation of intracardiac anatomy has enabled operators to navigate increasingly complex procedures. Despite its enduring role, this technology has not been able to overcome certain limitations, such as the inability to delineate endovascular and endocardial boundaries without contrast, obtain real-time assessment of tissue response to energy delivery, and differentiate adjacent anatomical structures. In electrophysiology (EP), these constraints are particularly important when performing left-sided ablation procedures.

In addition to these technical limitations, the radiation burden associated with fluoroscopy-guided EP procedures represents an underappreciated clinical hazard. Cardiac interventions account for approximately 40% of the cumulative effective radiation dose from all medical sources in the United States, excluding radiotherapy [1], and EP operators may sustain two to three times greater occupational exposure than diagnosticradiologists [2]. Case reports involving brain tumors in interventional cardiologists have demonstrated a left-hemisphere predominance corresponding to the side facing the image intensifier [3], while a survey of catheterization laboratory personnel reported a trend toward a higher overall cancer prevalence among female radiation workers, the majority of these being breast cancers, attributed to inadequate axillary coverage by conventional lead aprons [4]. A safe dose threshold does not exist, and conventional lead apron protection leaves substantial anatomical regions exposed [5].

Major society guidelines now reflect this mounting evidence regarding the detrimental effects of increased radiation exposure. Both the 2023 ACC/AHA/ACCP/HRS atrial fibrillation guidelines and the 2024 EHRA/HRS/APHRS/LAHRS expert consensus on catheter ablation recognize fluoroscopy reduction as an achievable and desirable goal [6,7]. The convergence of these safety concerns with advances in alternative imaging modalities has created the conditions for a paradigm shift in how EP procedures are performed. The progressive reduction of fluoroscopy exposure, culminating in its complete absence during ablation procedures, has been driven by advances in intracardiac echocardiography (ICE) and three-dimensional electroanatomic mapping (EAM). Together, these technologies have transformed techniques used to guide diagnostic procedures and have firmly established the foundation for the next era of atrial fibrillation ablation.

1. Intracardiac Echocardiography

Two-dimensional intracardiac echocardiography (2D ICE) is performed through a catheter equipped with ultrasound crystals capable of broad anterior-posterior and lateral deflection, providing real-time imaging of cardiac structures due to its proximity to the targets of interest. ICE does not require general anesthesia for image acquisition and can be operated directly by the physician throughout the procedure, without dependence on a dedicated imaging specialist [8]. Originally introduced as a complementary technology to facilitate transseptal access, ICE has since demonstrated a much broader set of procedural advantages during arrhythmia interventions, such as the precise anatomical relationships between adjacent structures, accurate navigation of guidewires and catheters, real-time assessment of tissue hyper-echogenicity adjacent to ablation sites as a marker of lesion quality, and early identification of complications such as iatrogenic pericardial effusions and clot formation [9].

Recent advances in ICE-based anatomical reconstruction have further expanded its role in arrhythmia ablations for atrial fibrillation. Integrated platforms, such as CartoSound (Biosense Webster), utilize deep learning algorithms to automatically segment and reconstruct three-dimensional left atrial geometry without reliance on catheter-tissue contact point registration, and have demonstrated feasibility and accuracy in routine clinical settings with correct identification of all major left atrial structures [10]. However, these tools cannot provide all the advantages that EAM provides. Voltage characterization and activation sequence mapping, among other properties, cannot be substituted by ultrasound-derived reconstruction alone.

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Standard views are acquired from the right atrial cavity, but high-definition, near-field images of adjacent structures can be acquired by advanced techniques involving placement of the catheter in all other cardiac chambers, allowing for very detailed anatomical delineation and evaluation of catheter-tissue interaction. This distinction is especially important in complex anatomic structures such as the papillary muscles and the moderator band in the ventricles. Collectively, these capabilities have established ICE as an extremely powerful tool for catheter interventions.

2. Electroanatomic Mapping

Mapping systems, continuously refined since the 1990s, have transformed the operator's ability to understand and treat complex arrhythmia substrates. Its contribution involves four main clinically distinct dimensions:

(1) Detailed anatomic reconstruction by registering catheter position during contact with cardiac tissue, allowing detailed and high-fidelity 3D geometry creation, providing the shell upon which all other functional information will be superimposed [11].

(2) Functional representation of the activation sequence and tissue voltage characterization, allowing detailed understanding of arrhythmia mechanisms and substrates, such as scar tissue and areas with a level of resolution unattainable by fluoroscopy alone [11].

(3) Real-time catheter visualization and navigation within the reconstructed anatomy, replacing the spatial orientation that was previously dependent on fluoroscopic projections [12].

(4) Direct assistance in lesion delivery through integration of catheter-tissue contact force data, minimizing the risk of perforation associated with excessive force while ensuring adequate lesion delivery. Lesion tagging allows for continuous, overlapping lesions, thus preventing gaps in ablation lines [13].

Mapping hardware has evolved in parallel, from single-tip, point-by-point acquisition toward dedicated multi-electrode array catheters, with closely spaced, small surface area electrodes that reduce far-field contamination and improve resolution of low-voltage tissue, allowing thousands of electrograms to be collected within minutes when paired with automated annotation and filtering algorithms. Multipolar and omnipolar electrogram configurations have now been introduced to overcome the directional dependence on conventional bipolar recordings, enabling wavefront-independent voltage assessment and real-time visualization of conduction vectors [13].

3. Zero-Fluoroscopy Era

The combination of ICE and EAM provides all the necessary tools required for performing diagnostic and interventional EP procedures without fluoroscopic assistance [12]. This transition does require a structured learning curve, as it demands a reorientation from fluoroscopic references to these new image modalities. This shift is supported by robust clinical evidence. In a 5-year retrospective analysis of 500 patients undergoing near fluoroless catheter ablation, Razminia et al. [12] demonstrated that complete fluoroscopy elimination is feasible, safe, and reproducible, reporting a 1.6% complication rate and outcomes comparable to fluoroscopy-guided benchmarks [12]. Furthermore, fluoroscopy-guided ablation has been identified as an independent predictor of both pulmonary vein reconnection and recurrence of arrhythmias. In a multicenter prospective study, fluoroscopy-guided cases showed an 8.5-fold increased odds of pulmonary vein reconnection when compared to ICE-guided PFA ablation, demonstrating that the imaging modality used for catheter guidance clearly improves lesion durability [14].

These new imaging capabilities take on additional significance in the treatment of atrial fibrillation. Inadequate catheter-tissue contact and discontinuous lesion sets are principal drivers of pulmonary vein reconnection and recurrence of arrhythmias [14]. Near-field left-atrial ICE positioning directly addresses issues with contact, which is crucial for pulsed field ablation (PFA) catheters that lack direct contact force sensing [14]. In addition, automated EAM lesion tagging allows assessment of interlesion spacing, helping operators identify potential gaps in lesion coverage along the intended ablation line [13]. This combination does not merely replace fluoroscopy; it adds superior anatomical resolution and real-time tissue feedback, which is unavailable through radiation-based imaging [15]. Translating these principles into a standardized, reproducible clinical framework is the central contribution of the HALO protocol, which applied mandatory left-atrial ICE contact verification and EAM-enforced overlapping 4 mm lesion tags. In 192 consecutive patients undergoing fluoroless AF ablation with either PFA or radiofrequency ablation (RFA), lesion strategy and technique were found to be critical determinants of ablation success in addition to the selection of the energy source [16].

The rapid adoption of PFA further underscores the role of structured ICE and EAM-guided workflows to ensure durable ablation outcomes. In the future, multicenter validation of standardized fluoroless workflows will be essential to establish reproducibility across institutional settings. The continuous refinements of supporting technologies suggest that the elimination of fluoroscopy may soon represent not just an exceptional capability, but will become an expected standard procedure during ablations for atrial fibrillation.

Author Contributions

GPS and CMT conceived the editorial. GPS contributed to the drafting of the manuscript, and revised it in response to reviewer and editor comments. CMT contributed to the drafting of the manuscript and revised it in response to reviewer and editor comments. Both authors

have read and approved the final manuscript and agree to be accountable for all aspects of the work.

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During the preparation of this manuscript, ClaudeAI (Anthropic) and ChatGPT (OpenAI) were used for language refinement and spelling checks. Following the use of these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the manuscript.

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