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Electroacoustic Tomography Guided Nanosecond Pulsed Field Ablation: A Simulation Study

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ABSTRACT

Pulsed field ablation (PFA) is a promising non-thermal method for treatment of atrial fibrillation that works by inducing irreversible electroporation in cardiac tissue. The procedure is designed to avoid heat damage. However, longer (microsecond) pulse durations can still generate thermal effects. Nanosecond pulses can deliver the necessary electric field much faster, reducing the risk of heating and potentially improving spatial precision and treatment safety. Currently, PFA is an open loop process which does not allow for real time lesion visualization. The lack of real time visualization significantly limits the capabilities of this procedure, leading to incomplete electroporation, and an increase in the likelihood of arrhythmia and the need for repeat procedures. This work presents an initial simulation framework which is aimed at closing the loop and providing real time feedback. The electric field distribution was simulated with a simplified circular catheter with alternating current and ground segments in COMSOL. Biphasic +700 V/ -700V pulses of 100 ns were applied to a homogeneous cardiac tissue domain. Electric energy density was exported at the midpoint of the active pulse window to be imported into a 3D k-Wave acoustic model. The resulting pressure fields were predicted by numerically modeling an electro-acoustic tomography (EAT) process. The time reversal reconstructions generated from these simulations offer a first step towards demonstrating the feasibility of detecting PFA induced lesions. These results are an initial step towards developing a closed-loop PFA system that can deliver nanosecond pulses while simultaneously monitoring lesions, with the overarching goal of making ablation procedures more precise and consistent.

Keywords: Pulsed Field Ablation (PFA), Electro-Acoustic Tomography (EAT), Atrial Fibrillation, Ablation Monitoring

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1. INTRODUCTION

Atrial fibrillation (AF) affects approximately five million people in the United States alone and about 1-2% of the general population worldwide, with that number expected to double in the coming decades ^[1-4]. This places AF as the most common type of cardiac arrhythmia across the globe ^[3]. AF has been linked to significantly increased risk of stroke, heart attack, and other major cardiac events ^[5]. As a result of the prevalence and seriousness of AF, catheter-based ablation methods have emerged as a main form of treatment ^[3]. These ablation methods involve creating targeted lesions in myocardial tissue to disrupt the disorganized electrical impulse and reset the heart's rhythm ^[3].

Conventional ablation methods which include radiofrequency and cryothermal ablation, rely on thermal energy which can cause damage to surrounding structures and tissue ^[6-11]. Though these methods are effective, thermal approaches result in limited safety and consistency ^[11, 13]. Pulsed-field ablation (PFA) is a method that uses microsecond electrical pulses to damage the cell membrane and cause irreversible electroporation leading to cell death ^[9-11]. This method has gained attention as an alternative to the conventional thermal ablation methods.

Although the procedure is designed to avoid heat damage, longer (microsecond) pulse durations can still generate thermal effects ^[11]. Nanosecond pulses can deliver the necessary electric field much faster, reducing the risk of heating and potentially improving spatial precision and treatment safety. Currently, PFA is an open loop process which does not allow for real time lesion visualization. Despite advances in ablation technology and methods, long term treatment success is still limited significantly by incomplete lesion formation which leads to arrhythmia recurrence ^[12,13]. This underscores the importance and need for improved monitoring of the ablation procedure as the lack of real time visualization significantly limits the capabilities of this procedure. Incomplete electroporation increases the likelihood of arrhythmia

recurrence, leading to repeat procedures required in approximately 40–50% of cases [12, 21]. Electroacoustic tomography (EAT) offers a method to directly visualize the applied electric field by capturing the acoustic waves generated during ablation [14]. This enables monitoring of ablation efficacy and offers a pathway to more consistent lesion delivery and reduces the need for repeat interventions.

This work presents an initial simulation framework by combining electric field modeling in COMSOL Multiphysics (V 6.3.0.290, COMSOL AB, Stockholm, Sweden) [18] with acoustic propagation modeling in k-Wave MATLAB toolbox [15] to explore potential of closing the feedback loop in PFA procedures. By simulating a simplified 12-segment catheter design, this study aims to establish a foundation for ablation monitoring and ultimately improving the precision and consistency of the procedure.

2. METHODS

2.1 COMSOL Multiphysics Simulation

A simplified version of the PulseSelect Medtronic pulsed field ablation catheter [20] was built within COMSOL Multiphysics (V 6.3.0.290, COMSOL AB, Stockholm, Sweden) [18] to simulate the electric field distributions within cardiac tissue. The simplified catheter consisted of 12 equally spaced segments arranged circularly, with 6 alternating current and ground electrodes. The remaining segments were left inactive. The cubic block representing heart tissue measured at 30mm x 30mm x 20mm (width x depth x height). The catheters electrode ring was constructed with an inner radius of 10mm and outer radius of 10.25mm allowing for each segment to have a radial thickness of 0.25mm. The base segment was defined as a parametric curve.

The catheter was positioned in the center of the tissue block to ensure it was fully surrounded by simulated heart tissue. The catheter material was defined as cobalt alloy (properties from COMSOL materials library), and the surrounding block's medium was modeled as homogeneous cardiac tissue using COMSOL's built in parameters [16]. The Electric Currents physics interface was used for the electric field distribution. Biphasic nanosecond pulses were applied to the active electrodes with an amplitude of +700 V followed immediately by -700 V with each phase lasting 100 ns [18, 20]. This simulates one single pulse with a duration of 200 ns as a preliminary data.

Meshing was performed using a free tetrahedral mesh applied to all domains with a global element size set to “finer” for improved resolution of the field gradients near the electrodes. A minimum element size of 0.08 mm was applied, and the complete mesh consisted of 398270 domain elements, 22110 boundary elements, and 2496 edges. The finalized geometry has 13 domains, 66 boundaries, 108 edges and 56 vertices (Figure 1).

The electric energy density was recorded for all elements at the temporal midpoint of the pulse's active window ($t=100\text{ns}$) which corresponded to the end of the positive phase and before the onset of the negative phase. This was chosen to capture peak field deposition without averaging over time for acoustic modeling. The exported data was saved for direct import into k-Wave.

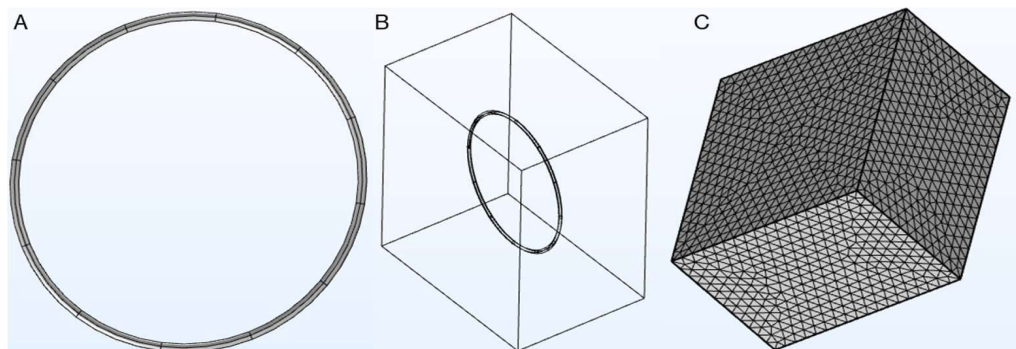


Figure 1. Geometry and mesh of the simplified pulsed field ablation catheter model. (A) Circular catheter with 12 equally spaced segments. (B) Catheter positioned centrally within the cubic heart tissue domain (C) Free tetrahedral mesh applied for electric field simulation.

2.2 K-wave Simulation

The electric energy density (J/m^3) was exported from COMSOL at the pulse midpoint ($t=100\text{ns}$) and imported into MATLAB voxelized onto a 3D cartesian grid as the initial pressure distribution (p_0) in k-Wave (v 1.4) [15]. The computational domain was set as $60\text{ mm} \times 60\text{ mm} \times 100\text{ mm}$ with grid spacing of 0.5 mm . The propagation medium was modeled as water with uniform acoustic properties (speed of sound = 1500 m/s , density = 1000 kg/m^3). A region of interest which contained the non-zero COMSOL field values was identified and centered within the simulation domain. A 16×16 matrix array sensor with 256 elements total was positioned on the z face of the domain to record forward propagated wavefield. Each sensor element was square and evenly placed, with a center frequency of 1 MHz and 100% fractional bandwidth. The forward simulation was run using the `kspaceFirstOrder3D` solver. The recorded time series was then used in a time reversal reconstruction by keeping the same medium and grid properties, except for the grid spacing which was chosen to be larger (0.75 mm) to avoid inverse crime. The reconstructed initial pressure field was visualized as maximum intensity projections (MIPs) along the xy , xz , and yz planes for qualitative assessment.

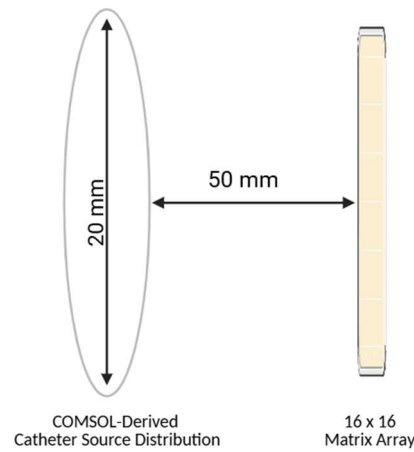


Figure 2. Simulation setup. Schematic of the experimental geometry showing the relative positioning of the COMSOL-derived catheter source (20 mm inner diameter) and the 16×16 matrix ultrasound array, separated by a 50 mm distance.

3. RESULTS

The COMSOL derived electric energy density successfully integrated into k-Wave to simulate forward acoustic propagation and time reversal reconstruction. The initial pressure distribution maintained the spatial arrangement of the catheters active electrodes and showed distinct regions in the domain. The normalized reconstructed field from time reversal showed a high spatial correspondence with the original pressure map (Figure 2). This indicates accurate localization of the energy deposition region.

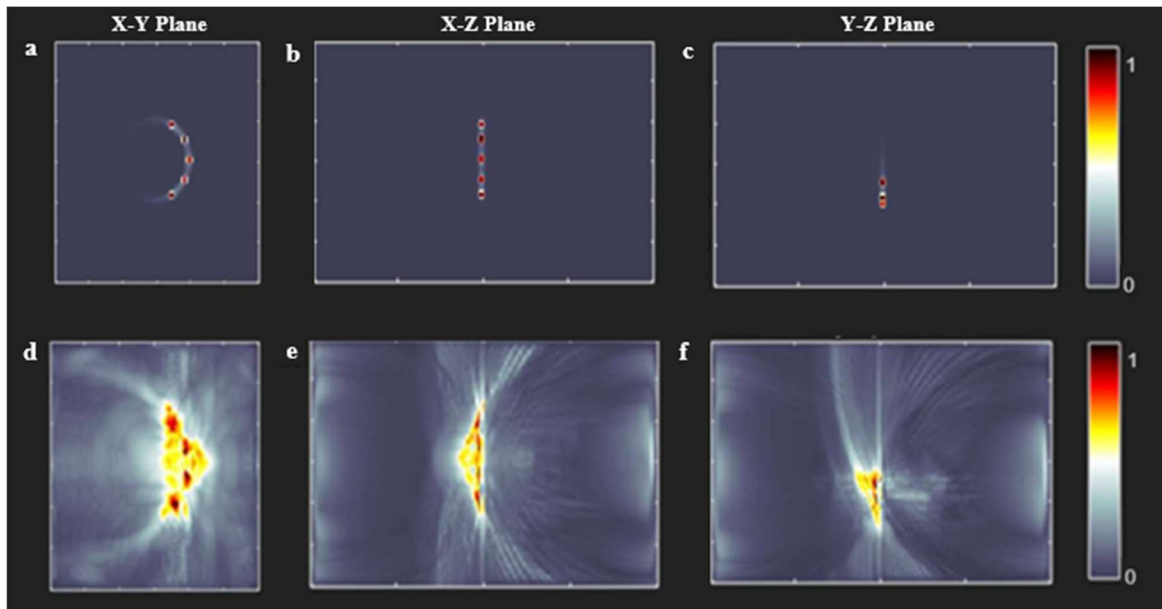


Figure 3. Comparison of initial pressure distribution and time reversal reconstruction. (a–c) Initial pressure distribution (P_0) mapped from COMSOL electric energy density at $t = 100\text{ns}$ shown as maximum intensity projections in the x-y, x-z, and y-z planes. (d–f) Corresponding normalized time-reversal reconstructions obtained from k-Wave simulations, demonstrating spatial correspondence with the original P_0 distribution.

4. CONCLUSIONS

This study introduces a physics-based simulation framework that links COMSOL electric field modeling with k-Wave acoustic propagation to simulate forward and time-reversal wave dynamics driven by PFA. This approach preserves spatial distribution of the catheters active electrodes and allows for an accurate localization of the energy deposited regions. These results highlight the potential of this combined simulation for studying PFA dynamics and present the framework to move toward closing the feedback loop for PFA treatment of atrial fibrillation.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

Liangzhong Xiang has financial interest in SoundDose, Inc., which, however, did not support this work. The remaining authors declare no conflict of interests.

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