A Parameter Sensitivity Analysis on a Virtual Patient Highlights the Impact of Electrical Conductivities on High-Power Cardiac RFA Outcomes

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Background: High-power radiofrequency ablation (HP-RFA) is a minimally invasive technique for treating atrial fibrillation (AF). Computational modelling is increasingly used to simulate ablation and optimize procedural outcomes. However, variability in model parameters can influence lesion formation and limit the reliability of these predictions.

Methods: A 3D patient-specific virtual model was reconstructed from CT imaging data, incorporating detailed anatomical segmentation of the heart, lungs, liver, skin, adipose tissue, and skeletal muscle (Figure 1, Left). The ablation electrode was positioned at the right inferior pulmonary vein, the dispersive return patch was placed on the posterior thorax, and high-power ablation at 90 W was applied. Uncertainty in the electrical conductivity of the left atrial wall (σ_{wall}) and blood (σ_{blood}) was considered.

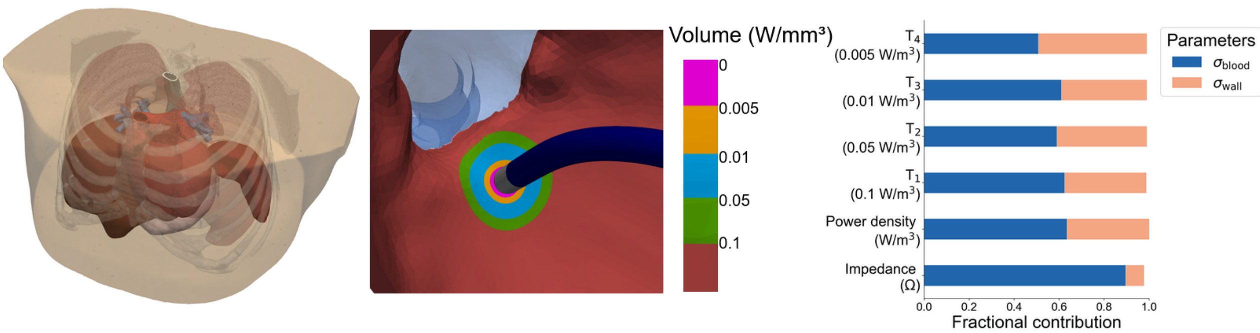

Figure 1: **(Left)** 3D patient-specific computational torso model including all major thoracic organs and tissues. **(Middle)** Power density isocontours near the ablation electrode in the left atrial wall at four threshold levels. **(Right)** Fractional contribution of blood (σ_{blood}) and wall (σ_{wall}) conductivity to impedance and power density across all thresholds.

Results: A surrogate model was constructed using $N = 125$ simulations (with $R^2 > 0.999$ and leave-one-out error below 0.5%) and validated against an independent test set of $N_{\text{test}} = 25$, showing low mean absolute errors (MAE): $0.51\,\Omega$ for impedance, $0.043\,\text{W/mm}^3$ for power density, and below $1.65\,\text{W/mm}^3$ for all volumetric measures (T_1–T_4). The Sobol sensitivity analysis shows a decoupling between global impedance and local tissue power density. Impedance is predominantly governed by blood conductivity ($S_1 = 0.9$), whereas the left atrial wall contributes only 8.3% ($S_1 = 0.08$) to its variance. In contrast, both the blood and the wall play a substantially larger role in power density, with σ_{blood} ($S_1 = 0.63$) and σ_{wall} ($S_1 = 0.42$) respectively.

Conclusion: Our results show that impedance alone is an insufficient indicator of lesion formation during HP-RFA. Since blood conductivity dominates impedance variance, real-time impedance monitoring may mask inadequate energy delivery to the atrial wall, risking under-treatment or localised overheating.