Learning cardiac activation maps from 12-lead ECG with multi-fidelity Bayesian optimization on manifolds

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Motivations

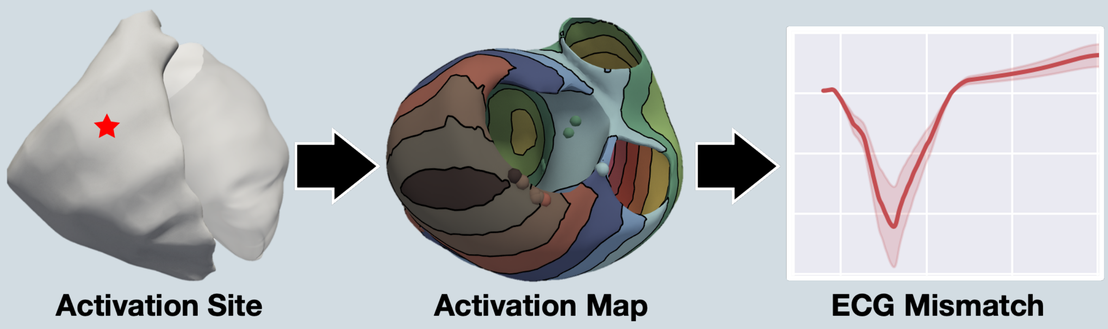
Ectopic activity in the heart can trigger deadly arrhythmias. The localization of the ectopic foci or earliest activation sites (EASs) is therefore a critical information for cardiologists in deciding the optimal treatment.

Precision cardiology aims at creating a digital twin of the patient's heart. Here, we focus on the problem of identifying an ectopic activation in the heart non-invasively, only by using the 12-lead ECG and imaging data.

In this work, we formulate the identification problem as a global optimization problem, by minimizing the mismatch between the ECG predicted by a cardiac model, when paced at a given EAS, and the observed ECG during the ectopic activity.

Methods

ECG in-silico model



▶ **Ectopic focus**

We model the ectopic focus as a single point on the endocardium.

▶ **Conduction velocity**

We consider anisotropic conduction: that is, propagation velocity is faster in the fiber direction.

Moreover, we model a fast endocardial layer mimicking the Purkinje network.

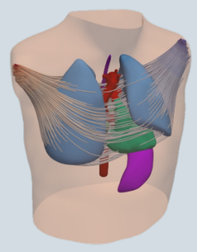
▶ **Activation map**

We solve the anisotropic eikonal equation to extrapolate the activation map in the tissue, given an ectopic focus and the conduction velocity.

The computer model is fast: takes only 0.4 s to compute the map in the biventricular model, at 1 mm resolution.

▶ **ECG simulation**

With activation at hands, we construct a transmembrane potential in the whole heart, just by shifting an action potential at the right timing.
The ECG is simulated by solving the bidomain model in the torso. given the transmembrane potential. The computation is feasible thanks to the lead field approach.



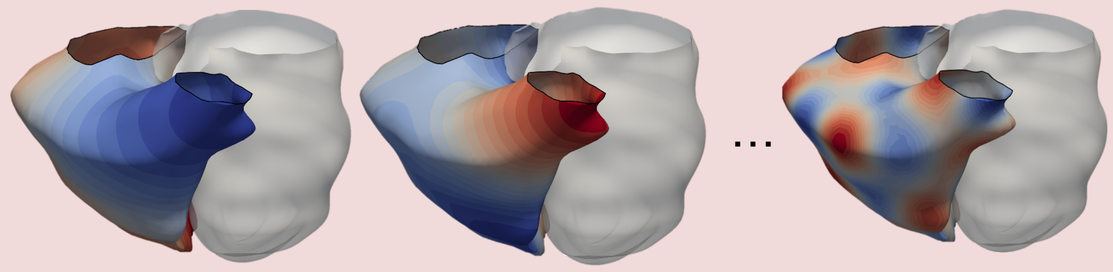
▶ **ECG mismatch**

The obtained ECG can be compared to a given patient ECG during an extrasystole.
Therefore, we can quickly estimate the how far we are from the true source of the extrasystole by testing multiple points.

Multi-fidelity Bayesian Optimization

▶ **Gaussian Process Regression on Surfaces**

Each point on the endocardium corresponds to number indicating how close we are to the real ectopic site. We extrapolate the indicator over the whole surface with with Gaussian Process Regression (GPR). In other words, the indicator is a linear combination of basis functions (eigenfunctions) of the Laplace-Beltrami operator.



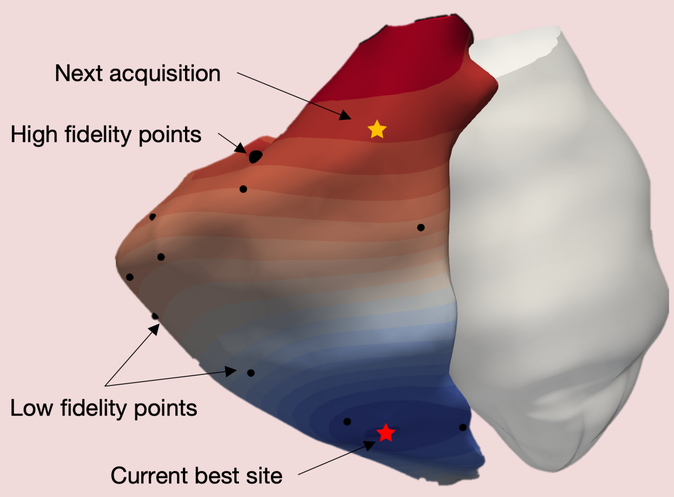
Laplace-Beltrami eigenfunctions

▶ **Bayesian Optimization**

We use active learning to probe the next candidate location. The acquisition function is a trade-off between maximizing the correlation with the surface ECG, and explore regions far from already sampled points.

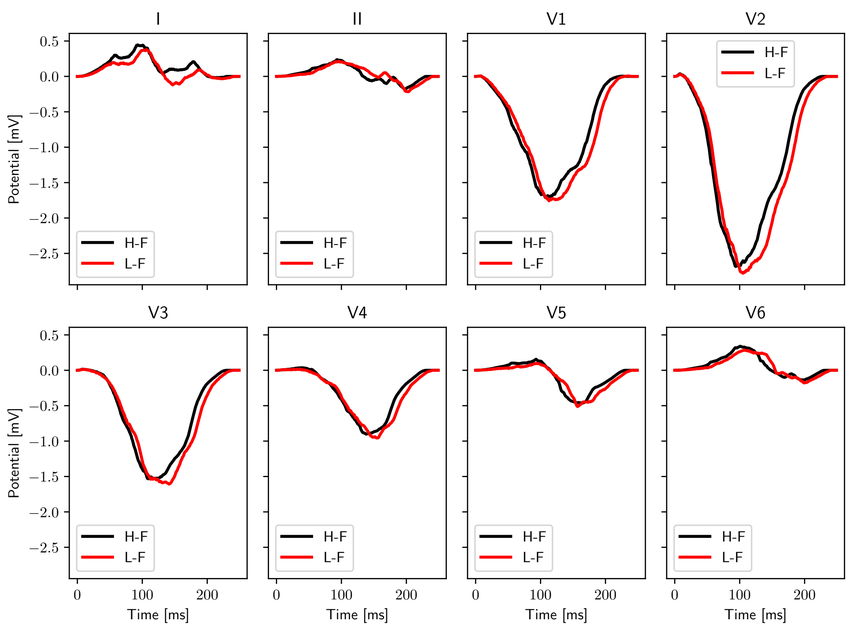
▶ **Multi-fidelity learning**

The high fidelity model is computationally expensive to query. We use a multi-fidelity representation of the indicator, where the correlation with to low fidelity model is exploited so to reduce the computational burden. Many more low fidelity points are acquired than high fidelity points, with a comparable accuracy to the single fidelity approach, but at a fraction of the cost.

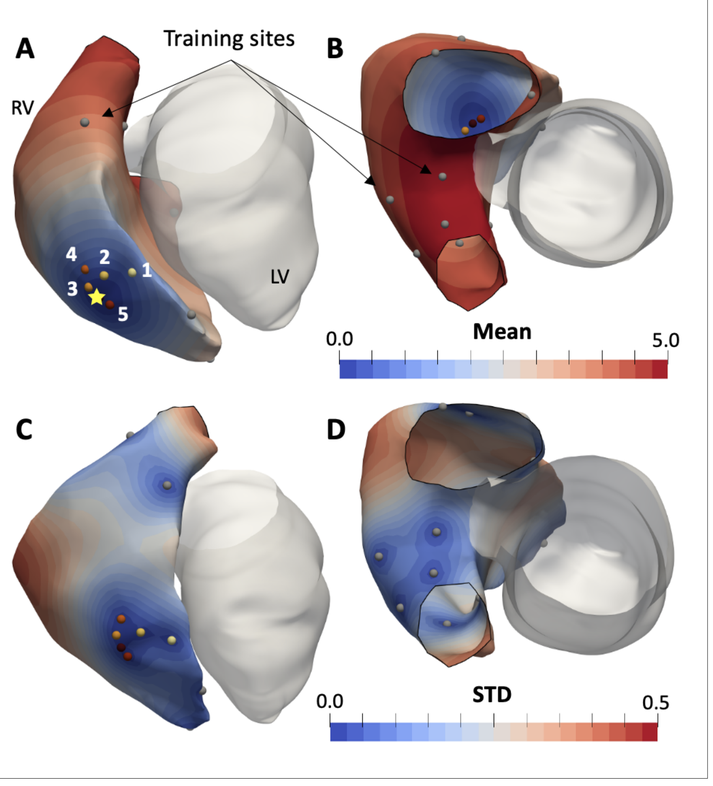


Results

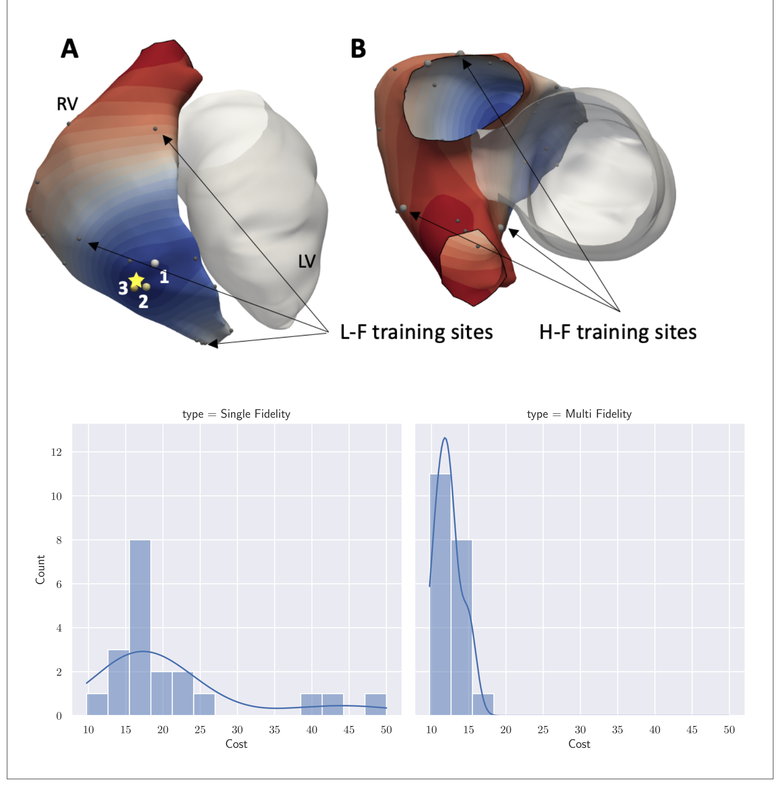
ECG correlation



Single fidelity



Multi fidelity



Final Remarks

In summary, we have presented a novel methodology to identify the EASs from non-invasive signals in cardiac electrophysiology. We hope this method will enable more precise interventions to treat cardiac arrhythmias.

Pezzuto, S. *et al.* Reconstruction of three-dimensional biventricular activation based on the 12-lead electrocardiogram via patient-specific modelling. *EP Europace* **23,** 640–647. doi:10.1093/europace/euaa330 (2021)

Pezzuto, S. *et al.* Learning cardiac activation maps from 12-lead ECG with multi-fidelity Bayesian optimization on manifolds. *IFAC-PapersOnLine.* arXiv: 2203.06222 (2022). accepted

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