Supplemental Material

Data S1.

In-silico P-wave simulation

The computation of the surface P-wave comprised several steps, detailed below. Briefly, the surface potential of a given lead resulted from Green's reciprocity formula with a combination of a fixed action potential (AP) shape, the activation map and the lead field. The action potential shape was computed using the cable theory with a detailed model for the dynamics of the ionic channels. The activation map was obtained from a 3-D propagation or eikonal model. Finally, the lead field resulted from the Poisson's equation in the torso. In mathematical terms, denoting by $U(\xi)$ the AP shape, by $\tau(x)$ the activation map and by $Z_k(x)$ the lead field for some lead $k = 1, \dots, 12$, the surface P-wave $V_k(t)$ read as follows:
$V_k(t) = \int_0^\infty U'(t-\xi) \int_{\tau^{-1}(\xi)} G_{in} n \cdot \nabla Z_k(x) \, \mathrm{d}\sigma(x) \, \mathrm{d}\xi$,where $\tau^{-1}(\xi)$ is the activation front at time ξ, that is the set $\{x \in \Omega: \tau(x) = \xi\}$, and n is the normal direction in the propagation direction.

Action potential model

The AP was simulated on a 1-D, 5 cm long fiber strand with the monodomain equation coupled with the Skibsbye model for the ionic currents.[20] The fiber conductivity was 1.5 mS/cm and the surface-to-volume ratio was 1000 cm^{-1}. A stimulus was applied in a 1-mm region on the left side of the fiber to trigger a propagation of the AP from left end towards the right end. The average conduction velocity was evaluated by taking the difference in activation time at 1 cm and 4 cm divided by the distance. Finally, the AP shape was extracted from the transmembrane potential at $x = 2.5$ cm.

Propagation model

The activation map $\tau(x)$ was simulated using the eikonal equation, which simulated the spread of an activation front from a selected origin and with given spatially varying, direction-dependent conduction velocity encoded in a tensor $D(x)$. Mathematically, the equation reads:

$$\begin{cases} \sqrt{D(x)\nabla\tau \cdot \nabla\tau} = 1, \\ \tau(x_0) = 0. \end{cases}$$

The earliest activation site x_0 was located in the sinoatrial node region. The conduction tensor was set as
$D = \frac{\theta^2}{\beta} G_{in}(G_{in} + G_{ex})^{-1} G_{ex}$where β was the myocyte surface-to-volume ratio and G_{in} and G_{ex} were respectively the intra- and extra-cellular electric conductivity. The scaling parameter θ was extrapolated from the 1-D simulation and estimated as follows:
$\theta = CV \cdot \sqrt{\beta\sigma^{-1}}$,where parameters were as in the previous section.

Lead field computation

Twelve lead fields were computed, one for each lead of the 12-lead ECG. Each lead field solved the following problem in the whole torso (with zero-flux boundary conditions at the chest): $-\nabla \cdot (G \nabla Z) = \begin{cases} -1 & at negative electrode, \\ +1 & at positive electrode, \end{cases}$ where $G = G_{in} + G_{ex}$ was the bulk conductivity. The bulk conductivity in the torso was heterogeneous, with distinct values in the blood, lungs, myocardium, skeletal muscles and skin. Furthermore, skeletal muscle and myocardium were assumed anisotropic.