

Methods for analyzing signal characteristics of stable and unstable rotors in a realistic heart model

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Abstract

Atrial fibrillation is a common irregular heart rhythm. Until today there is still a need for research to quantify typical signal characteristics of rotors, which can induce atrial fibrillation. In this work, signal characteristics of a stable and a more unstable rotor in a realistic heart model including fiber orientation were analyzed with the following methods: peak-to-peak amplitude, Hilbert phase, approximate entropy and RS-difference. In this simulation model the stable rotor rotated with a cycle length of 145 ms and stayed in an area of 1.5 mm x 3 mm. Another more unstable rotor with a cycle length of 190 ms moved in an area of 10 mm x 4 mm. In a distance of 2 mm to the rotor tip, the peak-to-peak amplitude decreased significantly, whereas the RS-difference and the approximate entropy were maximal. The rotor center trajectories were detected by phase singularity points determined by the Hilbert transform. We showed that more unstable rotors resulted in more amplitude changes over time and also the cycle length differed more. Furthermore, we presented typical activation time patterns of the Lasso catheter centered at the rotor tip and in different distances to the rotor tip. We suggest that cardiologists use a combination of the described methods to determine a rotor tip position in a more robust manner.

1. Introduction

There is still a need for research because the mechanisms of the most common cardiac arrhythmia atrial fibrillation (AF) have not been completely understood [1]. It is known that rotors can lead to AF [2] and they are found in low-voltage areas [3] [4]. But rotors are not often detected by physicians and therefore the central question is, which methods for analyzing signal characteristics near the rotor tip should be used to find rotors in a more robust manner. The presented simulation study offers new possibilities for reliably detecting rotors during AF.

2. Methods

2.1. Simulation setup

The simulation model of the left (LA) and the right atrium (RA) with included fiber orientation consisted of 263 x 328 x 283 voxels with edge length of 0.33 mm [5]. The Courtemanche-Ramirez-Nattel model [6] adjusted to chronic AF was used and monodomain simulations were performed with the parallel solver acCELLerate [7]. An unstable rotor was initiated near the right superior pulmonary vein [8] and in the right atrium a stable rotor resulted. Furthermore, intracardiac signals with a sampling rate of 1000 Hz were computed by forward calculation using the finite element method.

2.2. Rotor trajectory determined by Hilbert phase

With the signal $x(t)$ and the complex analytical signal $z(t)$ [9] the phase was calculated, compare following equations.

$$z(t) = x(t) + jH(x(t)) \quad (1)$$

$$\varphi(t) = \arctan\left(\frac{\text{imag}\{z(t)\}}{\text{real}\{z(t)\}}\right) \quad (2)$$

The rotor tip position was defined as point, which was surrounded by points with increasing phase values from $-\pi$ to $+\pi$ [9].

2.3. RS-difference and peak-to-peak amplitude

The RS-difference [10] was defined as

$$\frac{|R| - |S|}{|R| + |S|} \quad (3)$$

R was the amplitude of the positive peak and S symbolized the negative peak of an unipolar signal. The peak-to-peak amplitude was defined as

$$|R| + |S|. \quad (4)$$

2.4. Approximate Entropy

Near the rotor tip the signals were more irregular. The regularity of signals could be determined with the approximate entropy (ApEn) [11]. In simulation studies, this method was used to find rotor centers [12] with used standard parameters ApEn (2, 0.1, 500).

2.5. Activation time pattern and cycle length coverage

In this work, the geometry of the commonly used circular mapping catheter Lasso (Biosense Webster, Diamond Bar, USA), which consists of 10 electrodes in a circle, was projected on the endocardial surface. The first and the last local activation time (LAT) were determined by the steepest negative slope in the unipolar signals with the first and last electrode having activation. The cycle length coverage (CLC) was defined as [13]

$$CLC = \frac{\text{last LAT} - \text{first LAT}}{\text{cycle length}}. \quad (5)$$

3. Results

3.1. Rotor trajectory from phase maps

The stable rotor with a cycle length of 145 ms stay in an area of 1.5 mm x 3 mm near the tricuspid valve; another more unstable rotor moved in an area of 10 mm x 4 mm with a cycle length of 190 ms near the right superior pulmonary vein, compare Fig. 1.

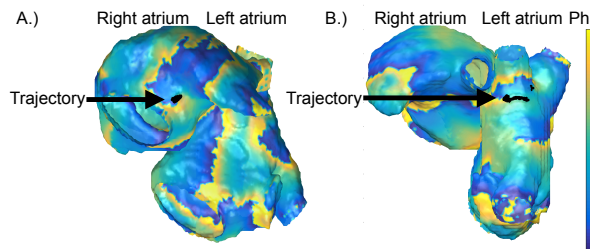


Figure 1. A.) The stable rotor was located in the RA near the tricuspid valve, B.) The more unstable rotor was located in the LA near the right superior pulmonary vein.

3.2. Signal patterns of mapping catheter near the rotor tip

A resulting phase map of the stable rotor is depicted in Fig. 2 with a Lasso catheter centered at the rotor tip. The Lasso catheter centered at the rotor tip resulted in a nearly straight line pattern [14] of activation times, see Fig. 3A. In this case the CLC was 85 % of the cycle length. With

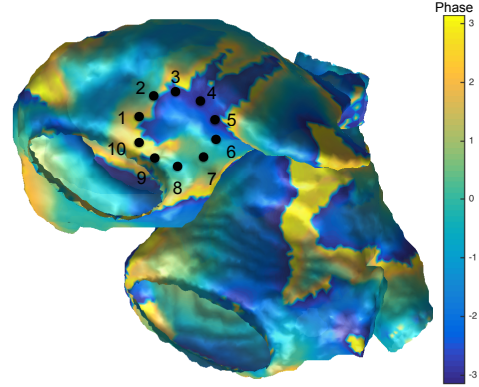


Figure 2. Lasso catheter centered at the rotor tip position in the RA.

a distance between the Lasso catheter and the rotor tip position of 5 mm, the typical line pattern could not be observed, compare Fig. 3B. With increasing distance to the rotor tip the CLC decreased significantly and the LAT pattern became a cosine pattern, which is typically observed at activation wavefronts that pass through the field of the circumferential catheter, compare [15].

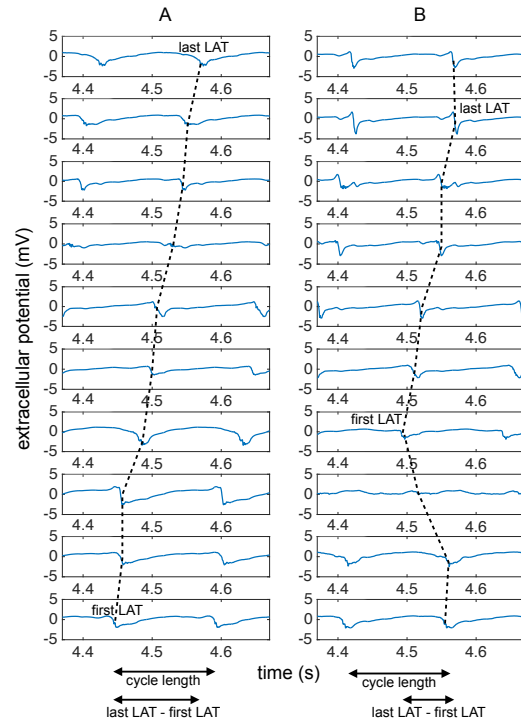


Figure 3. Unipolar signals and LAT pattern of a Lasso catheter A.) centered at the rotor tip, B.) with a distance of 5 mm to the rotor tip. The black line symbolized the LAT pattern.

3.3. Analyzing signal characteristics near the rotor tip

In Fig. 4 the signal morphologies near the stable rotor are shown in a 5 x 5 grid with 2 mm distance around the rotor tip. At the rotor center fractionated signals with small amplitudes were measured. The signal morphologies of the stable rotor were consistent, but the morphologies of the unstable rotor differed over time, compare Fig. 5. Because of the larger area of the rotor tip trajectory, the amplitudes changed over time and also the cycle length differed in the case of the unstable rotor.

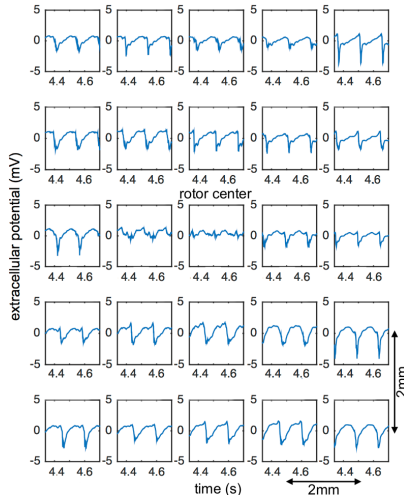


Figure 4. Unipolar signals of the stable rotor from a 5 x 5 grid with 2 mm distance between neighboring signals. The rotor tip position is in the center.

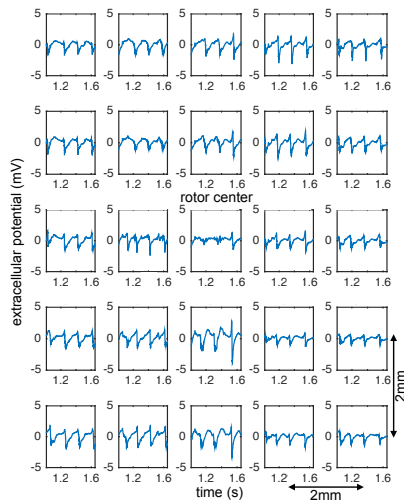


Figure 5. Unipolar signals of the unstable rotor from a 5 x 5 grid with 2 mm distance between neighboring signals. The rotor tip position is in the center.

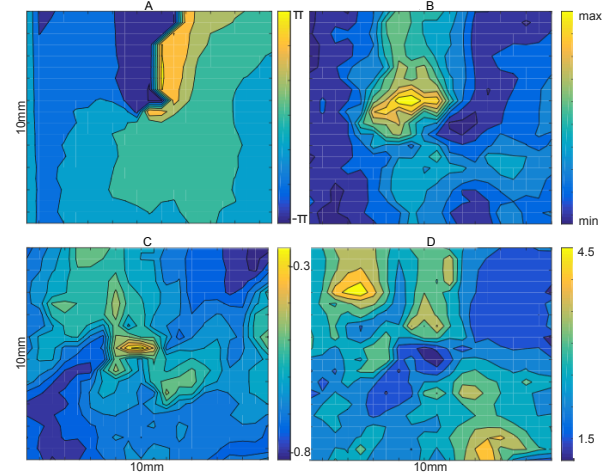


Figure 6. Area of 10 mm x 10 mm around the stable rotor tip. A.) Phase map, B.) ApEn map, C.) RS-difference map, D.) Peak-to-peak voltage map: low voltage < 1.5 mV at rotor tip (deep blue).

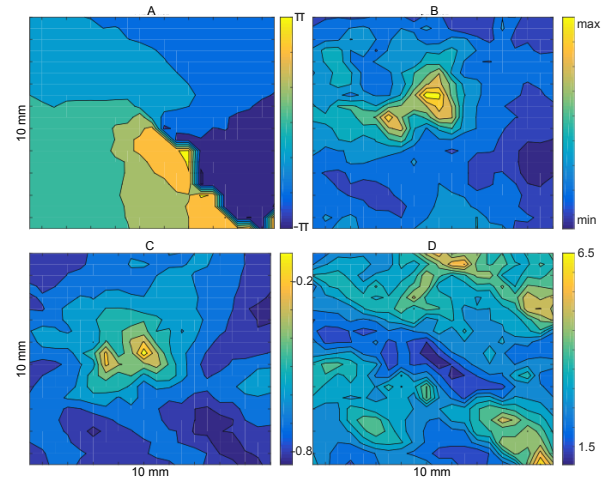


Figure 7. Area of 10 mm x 10 mm around the unstable rotor tip. A.) Phase map, B.) ApEn map, C.) RS-difference map, D.) Peak-to-peak voltage map: low voltage < 1.5 mV at rotor tip (deep blue).

In the area of 10 mm x 10 mm around the rotor tip, compare Fig. 6 and Fig. 7, the peak-to-peak amplitude decreased significantly whereas the ApEn was maximal near the rotor tip. The position of phase singularities were calculated using the Hilbert transform. The RS-difference was maximal at the stable rotor, but at the unstable rotor the RS-difference differed also. In a distance of about 2 mm to the rotor tip, fractionated signals with small amplitudes were measured and therefore the LAT and similarly the phase could not be clearly determined.

4. Discussion

This is the first signal analysis known to the authors of differences of signal characteristics between a stable and an unstable rotor in a realistic 3D simulation model. On the one hand, amplitude- based methods like peak-to-peak amplitude, ApEn or the RS-difference were useful for the signals in a distance of about 2 mm to the rotor tip. We could demonstrate that in this area, there is a significantly decreasing peak-to-peak amplitude towards the rotor tips. This correlation is in agreement with clinical studies [4] [13] and with simulations in a 3D patch [14]. But decreasing amplitudes could also originate from inhomogeneous tissue, like fibrotic tissue or increasing distance between electrodes and tissue. Furthermore, the ApEn increased significantly in this area near to the rotor tip for stable and unstable rotors. Also the RS-difference increased near to the rotor tip, but only for the stable rotor. On the other hand, LAT- based methods, like the signal patterns and CLC were well suited, if the mapping catheter was centered at the rotor tip. Furthermore we showed the differences of signal characteristics of stable and unstable signals. In the case of the unstable rotor the cycle lengths and the behavior of the amplitudes changed more over time. The limitations of this simulation study are, that the results are demonstrated in a simulation model without various distances between the virtual electrode and the tissue, without anchoring in fibrotic tissue and without noise. Until today, standard 3D mapping systems do not have the option to display rotors and their trajectories. From the simulation results, we suggest that cardiologists and device manufactures might use combinations of the described methods and characteristics to find rotors in a more robust manner and to determine how stable the rotor is.

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