Curve Registration for Study of P-Wave Morphing during Exercise

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Abstract

The P-wave shape analysis remains an interesting objective in various situations. In this paper, the aim is to investigate how the P-wave morphology changes during time-varying effort. To perform this task, a method, Self-Modeling Registration (SMR), derived from the Curve Registration (CR) theory is used. This method permits to link different shapes by mean of time warping functions. First, using the SMR method, significant P-wave shapes are extracted from two ECG records under maximal and graded exercise test where the effort is released abruptly. Then, the selected shapes are linked by warping functions estimated by SMR method. The obtained warping functions show a reversible evolution of the P-wave shape independently of the possible superimposition of the T-wave. To give a physiological explanation of this P-wave morphing, an atrial contribution evolution scenario under exercise is proposed and validated by simulation.

1. Introduction

It is well know that, during exercise, the sympathetic nervous system becomes active in healthy people and this causes an increase in the heart rate, and the duration of the P-wave decreases [1]. This information can be use for classifying healthy patients from pathological ones [1]. In addition to P-wave duration, it could be interesting to study the P-wave shape since it is directly related to the atria activity and could provide us with relevant physiological informations. The shape analysis performed on the P-wave has already been applied for the Atrial Fibrillation (AF) risk detection and gives good results (CinC2003) [2]. In this paper, we are interested in the study of the shape evolution or the morphing of the P-wave during exercise. To perform this task, a method called Self-Modeling Registration (SMR), derived from the Curve Registration (CR) theory is used [3]. This recent method permits to link easily the P-wave shapes in term of time warping functions. Under some hypothesis, these time warping functions allow a precise screening of the P- wave shape. First, in this paper, the CR principles and the SMR algorithm are briefly recalled. Then, a P-wave shape analysis is performed using SMR on two ECG records under maximal and graded exercise test where the effort is released abruptly. According to the results, a reversible P-wave morphing is observed on both ECG records from the beginning of the exercise epoch to the end of the rest epoch. This reversible morphing cannot be explained by the superimposition of the T-wave. To justify physiologically these results, a P-wave morphing model during exercise, based on superimpostion of atria contributions, is proposed. Finally, the study results are discussed and possible research orientations are given.

2. Methods

From the point of view of the CR theory, shape variations among signals are due to time variability around a common structure or a generating shape function. Indeed, CR operation consists in linking different signal shapes by increasing time warping functions to this shape function assuming its existence. These time warping functions represent natural time fluctuations of the generating process [4]. In this application, this hypothesis is coherent with the fact that shape changes of the P-wave, during exercise, are probably due to variations of the atrial contribution timing. To perform CR, different method can be employed. In our study, we choosed a recent CR method, Self-Modeling Registration (SMR). This method estimates the warping functions better than the precedent ones using a semiparametrization [3]. In the next paragraph, SMR algorithm is recalled. According to the CR hypothesis, we can suppose that N signals are generated from the shape function *s(t)* as follows:

$$x_i(t) = a_i s(v_i(t)) + \varepsilon_i(t),\ t \in [0,T], 1 \le i \le N, \qquad (1)$$

where the non-random function *s(t)* is the shape function, v_i are stochastic time warping functions that account for time variability, and a_i and ε_i are stochastic processes that account for amplitude variability. The three stochastic processes are independent. We can write assuming zero mean process for ε_i and $E\{a\} = 1$:

$$E\{x(t)\} = E\{s(v(t))\} \quad (2)$$

which can be approximated, for large N, by :

$$\bar{x}(t) = 1/N \sum_{i=1}^{N} s(v_i(t)) \quad (3)$$

where $\bar{x}(t)$ is the classical average and is different, in general, from *s(t)* [3]. Therefore, the objective of the CR operation is to realign or register the signals to *s(t)*. This signal realignment permits to estimate the time warping functions $(v_i^{-1} = w_i)$ which are not directly observable. Then, an estimated shape function or Structural Average (SA) $\mu(t)$ can be obtained as follows [3]:

$$\mu(t) = 1/N \sum_{i=1}^{N} x_i(\hat{w}_i(t)) \quad (4)$$

In Eq.(4), $\hat{w}_i$ are the estimated warping functions. The signal $\mu(t)$ is a consistent estimator of *s(t)* when the following condition is verified: $1/N \sum_{i=1}^{i=N} \hat{w}_i(t) = t$.

Self-Modeling Registration (SMR): The main idea of the SMR method is to model the warping functions as linear combinations of a small number of functions as in following [3]:

$$w_i(t) = t + \sum_{j=1}^{q} \alpha_{ij}\phi_j(t) \quad (5)$$

The component functions ϕ_j are estimated from the signals. They are linear combinations of B-spline basis of order p, then we can write:

$$\phi_j(t) = \sum_{i=1}^{p} c_{j,i}\beta_i(t) \quad (6)$$

The parameters of the signal generation model defined in Eq.(1) can be estimated by integrated least squares minimization as follow:

$$\min F(s,\{a_i\},C,\{\boldsymbol{\alpha}_i\}) = \min \sum_{i=1}^{n} \int_0^T \{x_i(t) - a_i s(v_i(t))\}^2 dt \quad (7)$$

and in another form:

$$\min F(s,\{a_i\},C,\{\boldsymbol{\alpha}_i\}) = \min \sum_{i=1}^{n} \int_0^T \{x_i(w_i(t)) - a_i s(t)\}^2 w_i'(t) dt \quad (8)$$

where C is the $c_{i,j}$ coefficient matrix. The objective function F is minimised by an iterative algorithm, given the estimated warping functions as follows :

$$\hat{s}(t) = \frac{\sum_{i=1}^{n} \hat{a}_i \hat{w}_i'(t)\hat{x}_i(\hat{w}_i(t))}{\sum_{i=1}^{n} \hat{a}_i^2 \hat{w}_i'(t)} \quad (9)$$

In the method, the warping functions are estimated by taking as reference de time axis of $\hat{s}(t)$. In this study, to better show the shape evolution of the P-wave, the time axis reference is changed to the one of another signal (ex. the beginning of the exercise) $x_1(t)$, so we can write:

$$\hat{w}_{i,1} = \hat{w}_i \circ \hat{w}_1^{-1}, 1 \le i \le N, \quad (10)$$

where $\hat{w}_{i,1}$ are the estimated warping functions related to the time axis of $x_1(t)$. In the next paragraph, this time transformation will be applied to all the estimated warping functions.

3. Results

In this application, a couple of young healthy male subjects (A and B) were administered a maximal and graded exercise test on a cycle ergospimeter. After a 5 min. warm-up session, the test consisted of a 8 min. ramp load increase from 60% to 100% VO2max, immediately released abruptly. The ECG was simultaneously recorded. The ECG records obtained are segmented in two parts: exercise part and recovery part. To perform the shape extraction, SMR algorithm is applied on different portions along the selected part after a good parametrization of *p* and *q*. Then, significant P-wave shapes are selected in the exercise and recovery parts for each record and linked together by the algorithm. For the warping estimation, the reference time axis is taken corresponding to the one of the first selected signal for each part.

Record A: The entire ECG record of this patient contains approximatively 2800 beats segmented (250 points) and aligned on the QRS. For the exercise part, 30 signals, averaged on 10 successive beats to reduce noise, are selected from the 350^{th} beat each 50 beats (the end of the exercise is at about the 2200th beat). For the recovery part, 30 signals, averaged on 6 succesive beats, are selected from the 2310^{th} beat each 10 beats. The selected signals contains P-waves sampled on 120 points. The warping functions are estimated with the SMR algorithm for the two parts with q=3 and p=9. The results for each part are presented on figure 1. As it can be seen on the figure, the P-waves are not contaminated by the superimposition of the T-wave. On Fig. 1-a and 1-c, we can observe the selected shapes for the exercise and recovery part respectively. A reversible morphing occurs indicated by the initial shape (P-wave 1) and the final one (P-wave 30). In addition to a reduction of the duration, it consists, as the heart rate increases, of an asymetric evolution of the P-wave shape from a nearly symmetric shape with a flatened top to an asymmetric one with a slow rise, a rapid descent and an important peak. In the recovery part, an inversed shape evolution occurs. This reversible morphing is confirmed by the study of the corresponding warping functions. Indeed, the warping

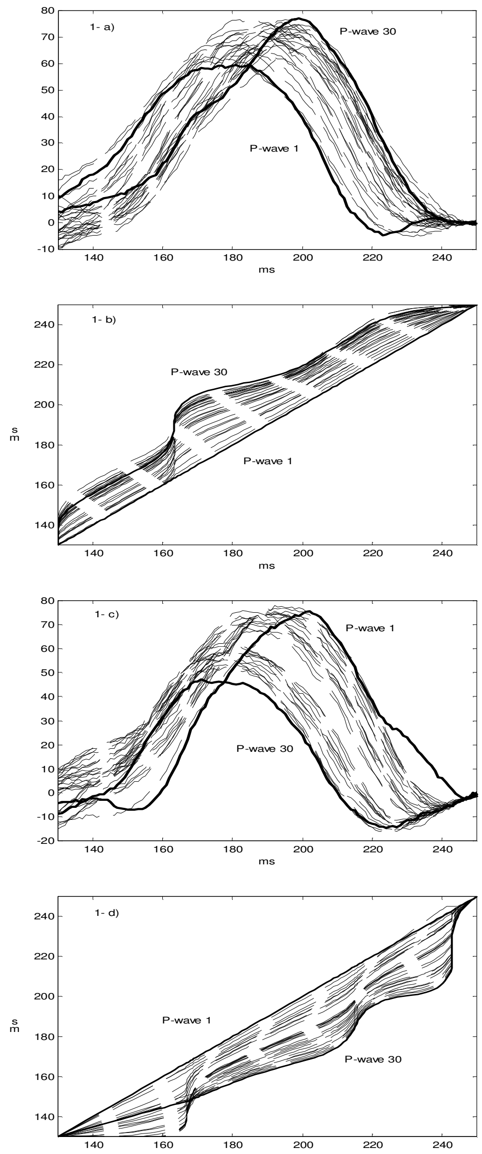

Figure 1. The selected shapes (1-a exercise, 1-c recovery) for the ECG *record A* and theirs corresponding warping functions (1-b exercise,1-d recovery).

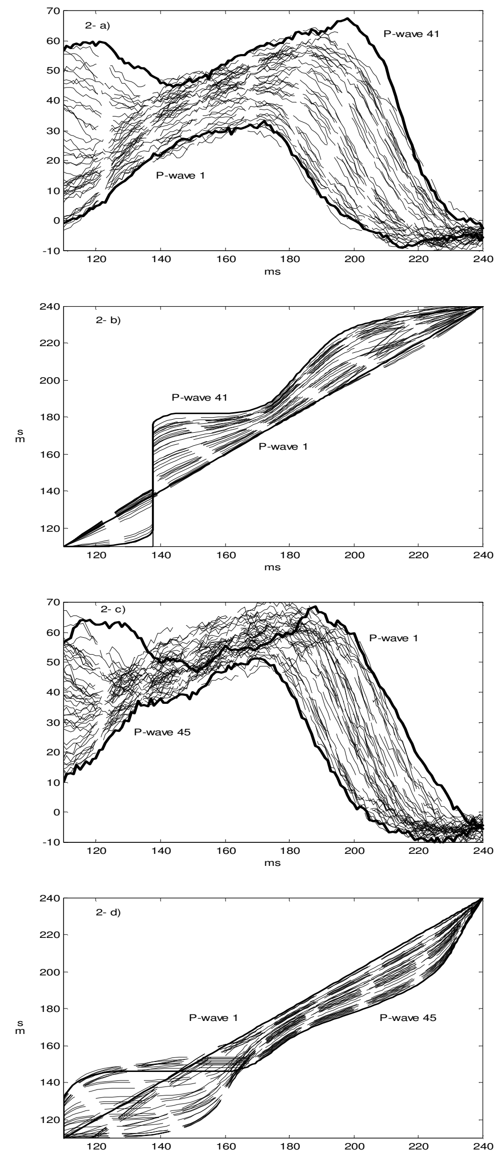

Figure 2. The selected shapes (2-a exercise, 2-c recovery) for the ECG *record B* and theirs corresponding warping functions (2-b exercise,2-d recovery).

functions on Fig.1-d seems to belong to the inverse family of the warping functions on Fig.1-c especially in the segment [160, 220 ms]. The rapid rise before the bump (at 160 ms) in the warping functions generates a time dilatation generating the slow rise and the asymmetry. The flattened part after the bump (at 170 ms) indicates a time compression transforming the flatened top into a peak.

Record B: The entire ECG record of this patient contains approximatively 3000 beats treated as patient A record. For the exercise part, 41 signals, averaged on 10 successive beats to reduce noise, are selected from the 535^{th} beat each 45 beats (the end of the exercise is at about the 2600th beat). For the recovery part, 45 signals, averaged on 6 succesive beats, are selected from the 2600^{th} beat each 8 beats. The results for each part are presented on figure 2. The selected signals contains P-waves sampled on 130 points. The same values of p and q are used for the SMR method. We can observe the superimposition of the T-wave that makes possible interpretations more difficult. As it can be seen on Fig. 2.a. and 2.c, the observed reversible P-wave morphing cannot be explained by the presence of the T-wave. Especially for the last part of the signal (over 180 ms), where a flatened part can be observed better than the first record on the warping functions, it corresponds to the generation of the peak and the rapid descent. This point indicates that the same phenomenon occurs in record B as record A.

Simulation: through the presentation of the following model, we try to give a physiological explanation to the P-wave morphing observed on the precedent results. The model consists in the addition of two Gaussian signals representing both atrial contributions. We can write:

$$P_{i,tot}(t) = A_R G_R(\sigma_{i,R}, m_{i,R}, t) + A_L G_L(\sigma_{i,L}, m_{i,L}, t) \qquad (11)$$

with: $\sigma_{i,R} = \sigma_{0,R} - \alpha_i t_i, \sigma_{i,L} = \sigma_{0,L} - \alpha_i t_i,$

$$m_{i,R} = m_{0,R} + \beta_{i,R} t_i, m_{i,L} = m_{0,L} + \beta_{i,L} t_i, 1 \le i \le 30.$$

the parameters values of the model are chosen to equal: $A_R = 10, A_L = 9, \alpha_i = 0.16, \sigma_{0,R} = 19, \sigma_{0,L} = 20, m_{0,R} = 105,$ $m_{0,L} = 75, \beta_{i,R} = 0.4, \beta_{i,L} = 0.6.$

Since the signals are selected linearly in beat number but not in time, to generate the time parameter t_i, we used the following formula: $t_i = \sqrt{150(i-1)}$. We can see the simulated data on figure 3.

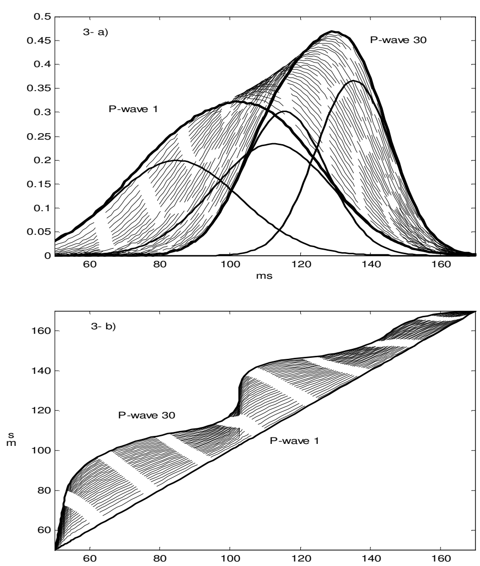

Figure 3. The simulated shapes (3-a) and theirs corresponding warping functions (3-b).

For the simulation purpose, we supposed that the right atrium contribution is slightly more important with a conduction time distribution more narrow than the left one. During exercise, as the heart rate increases, the conduction rate (represented by $\alpha_i t_i$) increases too. In the same time, the distance between both atria contributions decreases due to this conduction rate increase. These time variations produce, in addition to a time duration reduction, the morphing on figure 3. As it is shown, the simulated warping functions mimic in a realistic way the ones presented on figure 1.b. The shape evolution at recovery can be simulated just by time inversion of the presented scenario.

4. Discussion and conclusions

We have proposed a shape analysis of the P-wave based on the study of time warping functions. This method of shape caracterization can provide us useful informations. Using a recent method, the SMR method, for time warping estimation, our study shows that, in addition to a time duration variation, the P-wave shape changes during exercise in a reversible way according to the heart rate variation. This P-wave morphing is, in some cases, difficult to observe due to the superimpostion of the T-wave. To give a physiological explanation of the observed phenomena, we proposed a simulation model of the P-wave during exercise. The main obtained result is that the variation, according to the heart rate, of the conduction rate is an important factor in the P-wave morphing occuring during exercise. For further applications, it may be interesting to better estimate the model parameters using the real data.

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