A New Method for the PP-PR Hysteresis Phenomenon Enhancement under Exercise Conditions

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Abstract

A non-linear relation between PR *and* PP *intervals has been established in a previous work [1] under maximal and graded exercise test as well as under pyramidal exercise where the effort is not released abruptly. This study presents a new method whose aim is to exhibit more clearly the hysteresis behavior of this non-linear relation under graded exercise. After the description of the initial approach, we propose a second one which can provide a better estimation of the* PR *intervals. Moreover pooling the results of these two methods leads to an improvement of the estimation accuracy of PR intervals and then the hysteresis.*

It is well known that a hysteresis behavior exists at AV node's level, between the refractory period and the repolarization period. Besides, the autonomic neural system also acts upon the cardiac activity during an intense effort. Therefore, hysteresis which links the "PR interval vs PP interval" seems not be explained only at the cellular level ; the heart must be viewed in his global context considering the nervous system.

1. Introduction

Some studies on ECG recordings under exercise conditions show that it exists a non-linear relation between PR and PP intervals which exhibits a hysteresis shape, [1], [2]. Actually, for a same value of PP interval in exercise and recovery, the PR interval is extended during the recovery.

We start from the hypothesis that the features of the linear relation which links the PR and PP intervals evaluated under exercise and recovery stages, differs from one stage to the other, [3], [4]. Besides, a hysteresis phenomenon has already been displayed for the animal between the heart period and the atrioventricular conduction time when the animal is stimulated according to a ramp protocol (increase and then decrease in ramp of the heart period). So, for the same value of the heart period, we observe a higher atrioventricular conduction time during the descent of the ramp.

The first part of the paper is devoted to two different approaches whose aim is to exhibit the PR-PP hysteresis under exercise conditions. The first one takes over the works of [1] and is based on the cross-correlation technique in order to determine the delays between the realizations of P waves and a fixed reference P wave. These delays define the PR intervals. The second one is an estimation of the difference between the PR intervals under exercise and recovery for a same value of PP interval. Finally, the results of these two previous approaches are combined in order to obtain a better evaluation of the PR interval by way of a MSE (Mean Square Error) method.

The analysis and moreover the interpretation of heart period series is a difficult task especially under exercise conditions. So, we will show that the AV node properties seem not be sufficient to explain this non-linear relation between PR and PP intervals under exercise. The autonomic nervous system should probably be considered.

2. Methods

ECG recordings are from healthy people. The subjects performed on a cycle ergometer a graded exercise test. Before the study on the ECG recordings, two pre-processing methods permit us to estimate the position of R waves and the P waves detection at best. First, a threshold technique applied on the high-pass filtered and demodulated ECG, refines the estimation of the R waves times of occurrence t_k. Then the use of a polynomial based baseline removal brings to a better detection of P waves. We obtain segments including P waves and the corresponding R waves at t_k.

Introduction

The determination of the P wave, especially during the effort where the T wave catches up the P wave, is particulary difficult. So, we can not measure accurately the PR interval.

The principle is to measure a delay d_k between a realization P_k and a fixed reference P wave.

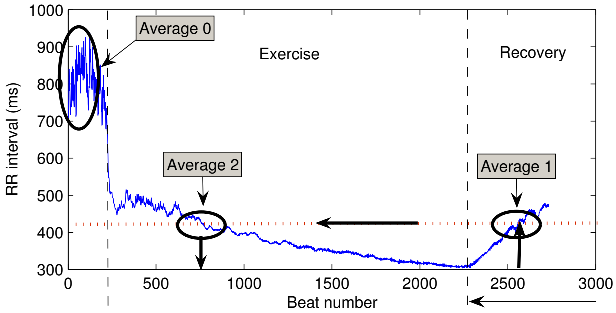

Figure 1. Processing of the second method.

So, for each segment, the PR_k interval is given by :

$$PR_k = K - d_k \tag{1}$$

With the constant K defined as the time delay between the R waves and the fixed reference P wave.

Then from t_k and d_k, it is easy to calculate PP_k using the expression :

$$\begin{aligned} PP_k &= RR_k + PR_k - PR_{k+1} && (2) \\ &= t_{k+1} - t_k + d_{k+1} - d_k && (3) \end{aligned}$$

So, an empirical relation $PR_k = f(PP_k)$ can be drawn for all k. If a hysteresis exists, for a given RR value, the PR corresponding to the exercise and the recovery stages should be significantly different. It introduces two relations in function of RR values : PR_{ex} during exercise and PR_{rec} during recovery. Then, the hysteresis phenomenon is characterized as the difference :

$$\Delta(RR) = PR_{ex}(RR) - PR_{rec}(RR) \tag{4}$$

Then, the determination of PR intervals can be addressed using two approaches. The first one determines the delays d_k in exercise and recovery stages whereas the second one specifies the value of the difference Δ for each RR interval.

First approach : measure of the delays d_k

For the estimation of the d_k, and so for the PR_k intervals (1), the method chosen is the cross-correlation using a fixed reference P wave which is for exemple the average of the 100 first P waves (Average 0 on the fig.1), [1],[2]. The delay d_k is the lag corresponding to the cross-correlation maximum.

Second approach : measure of the difference Δ

For a same value of a RR interval under exercise and recovery conditions, in case of lack of the hysteresis phenomenon, the two PR intervals corresponding to the exercise and recovery stages, should be nearly similar and synchronous. This comparison assumes that the P wave's shape doesn't vary a lot during graded exercises and that the R waves fiducial points can be correctly determined. In order to get rid off the shape variability from the beginning to the end of the exercise, the P waves will be compared for the same corresponding RR values.

The figure 1 shows the second approach's principle. We follow the beat numbers decreasing from the end of the recording and the moment when the exercise is maximal. For each beat number, we take the RR value and we make two averages of small sets of P waves : one corresponding to the exercise stage (Average 2) and the second one (Average 1) to the recovery for this value of RR interval. The use of the cross-correlation technique produces an estimate of the delay Δ (4) between the two average signals but also a measurement of their likeness. Finally, this Δ is a difference between the d_{ex} at exercise and the d_{rec} at recovery for the same RR value.

Pooling the previous results

The first approach estimates the relation between PR and PP intervals during exercise and recovery stages. The second approach provides Δ which correspond to the difference between the PR intervals for the two stages for a fixed RR value. Our goal is to use the information available in the data to estimate at best the PR intervals. We consider 3 observations containing noise:

$\widetilde{PR}_{ex}$: PR interval during exercise (first approach)
$\widetilde{PR}_{rec}$: PR interval during recovery (first approach)
$\widetilde{\Delta}$: the time between PR_{ex} and PR_{rec} (second approach)

We assume that the noises δ, n_{ex} and n_{rec} are uncorrelated stationary white noise processes. Since the unknown variables are PR_{ex} and PR_{rec}, the model for each RR interval can be written as following:

$$\begin{pmatrix} \widetilde{\Delta} \\ \widetilde{PR}_{rec} \\ \widetilde{PR}_{ex} \end{pmatrix} = \begin{pmatrix} -1 & 1 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} PR_{rec} \\ PR_{ex} \end{pmatrix} + \begin{pmatrix} \delta \\ n_{rec} \\ n_{ex} \end{pmatrix} \tag{5}$$

We annotate the matrix A as :

$$A = \begin{pmatrix} -1 & 1 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{6}$$

Then, the MSE (Mean Square Error) optimal solution of a such problem with independent noises is given by :

$$\begin{pmatrix} \widehat{PR}_{rec} \\ \widehat{PR}_{ex} \end{pmatrix} = A^{\sharp} . \begin{pmatrix} \widetilde{\Delta} \\ \widetilde{PR}_{rec} \\ \widetilde{PR}_{ex} \end{pmatrix} \tag{7}$$

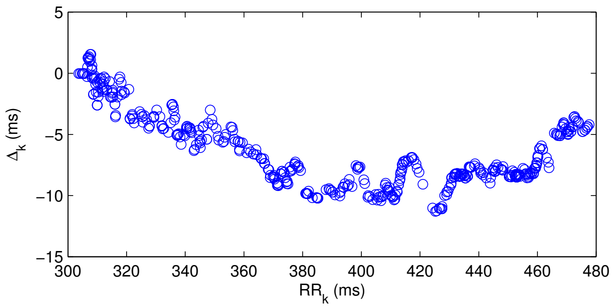

Figure 2. Δ_k = f(RR_k)

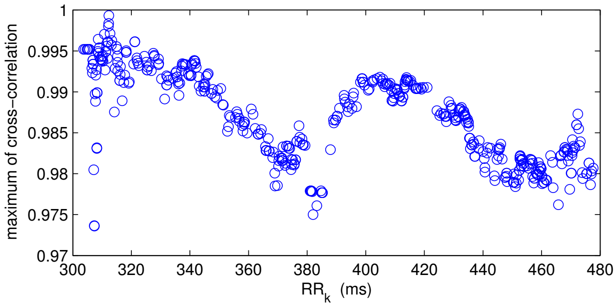

Figure 3. Maximum of cross-correlation

with $A^\sharp$ the pseudoinverse matrix of A:

$$A^\sharp = (A^t C^{-1} A)^{-1} A^t C^{-1} \tag{8}$$

As we do not have informations on the noises for all observations, we consider the covariance matrix C as identity matrix.

3. Results

For ECG recordings under exercise tests, a non-linear relation between PR and PP intervals exists. In a previous work [1],[2] with the first approach, it has been established that the hysteresis phenomenon exists between PR and PP intervals as it is shown in fig.4. Actually, thanks to the data given by the equations (1) and (2), this relation can be revealed.

Besides, an improvement of this method has been tried building a wave of reference which evolved on the time in order to take care of the waves'form. But it did not give better results. In fact, we obtained a saturation of the PR interval at the end of the effort. This problem probably come from errors due to the fact that the reference moves leading to a loss of absolute time reference.

With the second approach, we get a new delay, Δ_k for each RR record allowing the display of the hysteresis phenomenon as a negative bell curve presented on fig. 2. As the Δ_ks represent the difference $PR_{ex} - PR_{rec}$, the

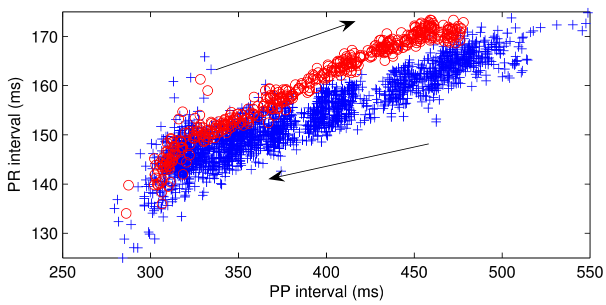

Figure 4. PR_k = f(PP_k) during Exercise (+) and Recovery (○) with the first method.

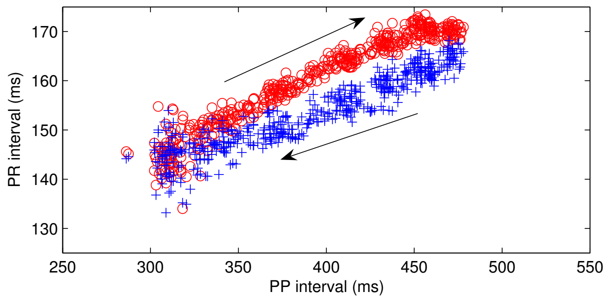

Figure 5. PR_k = f(PP_k) during Exercise (+) and Recovery (○) after pooling the results of the two previous methods.

bell curve is negative meaning that the hysteresis is clockwise. Actually, for the smallest RR_k, i.e. when the exercise is maximum, we can observe that the Δ_k is zero. Thus the difference between PR_{ex} and PR_{rec} for a same RR, increases then decreases. The Δ_k should be zero too for the largest RR_k but our ECG recordings are not enough long in recovery. The cross-correlation method is very current for the P wave detection. When the correlation is perfect and in the not noisy case, the coefficient of cross-correlation is equal to 1. The detection is considered acceptable when this coefficient is greater than 0.75 [5]. Figure 3 shows the coefficients of cross-correlation corresponding to the Δ_ks estimation. Thus, this method is more robust than the previous one because we are not interested in the PR interval itself but in the relative position of P waves for the two stages. An other version of this method where the RR intervals on the fig.1 was preliminarily smoothed, has been tried and we can notice some better results for many subjects with it.

Thanks to the pooling of the previous results, the MSE optimal solution for the system (5) is given by the equation (7). Figure 5 shows the relation between the PR and PP intervals corresponding to this solution. The hysteresis is more pronounced and points'dispersion reduced than the ones of the first method presented on fig. 4.

4. Discussion and conclusions

It has been demonstrated that a non-linear relation between PR and PP intervals exists under graded exercise test.

Since changes of the width of P waves in ECG recordings do not appear clearly, we assume that this hysteresis phenomenon is not explained at the sinus node and auricular's levels.

Besides, it is well known that a hysteresis behavior exists at AV node's level, between the Action Potential Duration (APD) and the Diastolic Intervals (DI) at the ventricular myocytes'level when the nervous system is not considered [6], [7]. Actually, when the repolarization period increases, the refractory period grows and when the repolarization period decreases, the refractory period decreases too but more slowly. So if we consider the PP interval as the Cycle Length, which is defined by the relation CL = APD + DI, we increase the PP intervals in order to simulate the exercise then the recovery stage by decreasing them and we follow the hysteresis curve given by Wu et al. [6]. Then, we observe for a same value of PP interval, i.e. a same value of CL, a refractory period longer during the recovery than during the exercise. In accordance with the hysteresis phenomenon at ventricular myocytes'level, we notice a counter-clockwise hysteresis between the PR and PP intervals, i.e. a positive's bell curve. This is the contrary of the hysteresis curve that we obtain from the ECG recordings on fig.4. Besides, the autonomic neural system also acts upon the cardiac activity during an intense effort. Therefore, hysteresis which links the "PR intervals *vs* PP intervals" seems not be explained at the cellular level ; the heart must be viewed in his global context considering autonomous driving.

Moreover, the sympathetic and parasympathetic influences on the sinusal node and the atrioventricular node seem be different [5] even independent [8].

Besides, few studies [9], [10], show that the atrioventricular conduction time, PR interval, decreases then the cardiac period i.e. RR interval increases. This "basal" state can be the expression of the protection of the ventricles. However, we observe the contrary state under exercise : PR interval decreases when RR interval decreases. Then, we can suppose that it exists a balance between this two states due to the different influences of the sympathetic and parasympathetic nerves on the two nodes. When the exercice begins, the parasympathetic influence withdraws whereas the sympathetic one increases. Then, it can be suppose that at the end of the effort, at recovery's beginning, there is a quick come back to the "basal" state and it can explain the lengthening of the PR intervals during recovery. Nevertheless, there is no yet study on this subject and the test'protocols for tests on human are difficult.

The physiological understanding of the hysteresis phenomenon should carry out a better knowledge of the atrioventricular node's intrinsic properties and in particular, the fatigue effect witch has been showed in animals [4].

Also, if the hysteresis phenomenon is understood, it could be introduced in pacemakers' algorithms and then will improve the patient's life.

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