NEW CRITERION TO ESTIMATE THE VENTRICULAR RELAXATION TIME CONSTANT (τ)

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Abstract- Left ventricular relaxation time constant (τ) has been widely used in analysis of ventricular diastolic function. A new criterion to detect the ending point of isovolumic relaxation period (IRP) for the estimation of τ in the left ventricular pressure waveform was developed. The proposed method is based on the pattern classification of mean square error between the original and the reconstructed pressure waveforms. We verified the performance of the new method using over 20,000 beats obtained from 96 patients. It showed that the proposed method provides more stable and accurate estimation results. The developed method is now being used in clinical application of real-time analysis of left ventricular diastolic function during cardiac catheterization procedure.

KEYWORDS: Cardiovascular system, Left ventricular relaxation time constant, Left ventricular diastolic function, Cardiac dynamics, Real-time signal processing.

INTRODUCTION

Over the several decades, special attention has been given to the analysis of left ventricular diastolic function, because left ventricular diastolic dysfunction has been recognized as an important primary cause of heart failure [1], [2]. Among many parameters, the diastolic relaxation time constant, τ, which represents the time constant of exponential decay of ventricular pressure during isovolumic relaxation period has been recognized as golden standard to be compared with in verifying the suitability of newly proposed variables [3], [4]. In estimating τ, detection of the ending point of IRP is very important because the estimation result is highly sensitive to it. There exists, however, no generally accepted rule to define it. In this paper we tackle this problem and propose a new algorithm to detect the ending point of IRP for real-time τ estimation.

Weiss et al proposed that left ventricular pressure during isovolumic diastolic period can be modeled as an exponential function [5]. They quantified left ventricular relaxation rate by fitting the time course of the isovolumic pressure fall beginning at the time of dP(t)/dt negative peak and lasting through the mitral valve opening with the exponential function of time.

$$P(t) = P_0 e^{-\frac{t}{\tau}} \tag{1}$$

where P_0, t, τ are pressure at dP(t)/dt negative peak, time after dP(t)/dt negative peak and time constant of isovolumic left ventricular pressure fall, respectively.

Equation (1) was further modified to take into account the effect of unequal end-systolic and equilibrium volumes by incorporating the term, P_∞, which is the pressure to which ventricle would relax if the ventricle were held at its end-systolic volume and allowed to relax completely [6].

$$P(t) = \left(P_0 - P_\infty\right)e^{-\frac{t}{\tau}} + P_\infty \tag{2}$$

Other methods for determination of τ have been proposed such as polynomial fitting [7]-[10].

It is relatively easy to compute τ in Equation (1); taking the natural logarithm of both sides of equation yields a linear relation between ln$P$(t) and t, with a slope of $-1/\tau$. Although incorporation of P_∞ in Equation (2) improves the accuracy with which it describes relaxation, the presence of P_∞ complicates the calculation of τ because the natural logarithm of both sides of Equation (2) no longer yields a linear relation between pressure and time. Yellin et al determined the absolute asymptote of left ventricular pressure decay, P_∞ , to be -7.3 ± 3.3 mm Hg [11]. They went on to show that the simplified assumption of a zero asymptote, $P_\infty=0$, generated similar values for τ to the true nonzero asymptote. Thus, in practical point of view, Weiss et al's original model can still be used as a reasonable measure of how quickly the ventricle relaxes. And we will follow their model in this study.

Ending point of IRP is the point just before mitral valve opens because filling in ventricle after mitral valve opening violates isovolumic assumption. Paulus et al proposed a criterion to define the ending point of IRP [4]. They set it as a point at which left ventricular pressure had decayed to a value that equaled previous beat's end-diastolic pressure plus 5 mm Hg. But their criterion has two limitations. First, as Fig. 1 depicts, τ varies widely according to the position of the ending point of IRP. So, it is somewhat crude just to plus 5 mm Hg to left ventricular end-diastolic pressure. Second, as Fig. 2 presents, in certain patients, many beats are unable to

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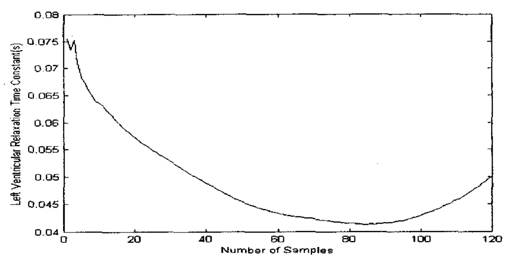


Fig. 1. Typical change of τ as the ending point of IRP moves from the negative peak point of dP(t)/dt by one data point. τ varies widely according to the location of the ending point of IRP.

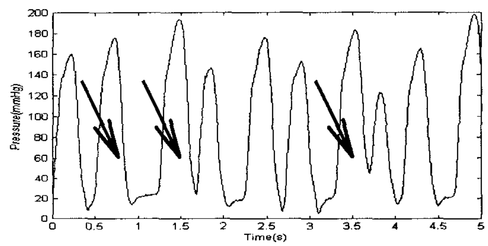


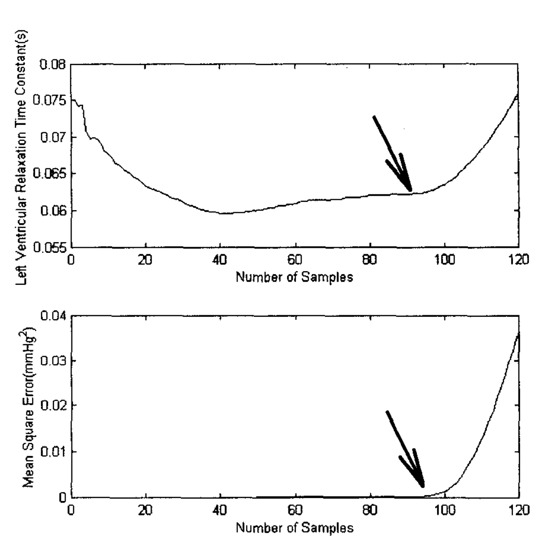
Fig. 2. Pressure waveform of atrial fibrillation patient. Three arrows indicate missed beats in detecting the ending point of IRP using Paulus et al's method.

locate the ending point with their criterion. Thus, it is necessary to define a new objective criterion to find the ending point of IRP.

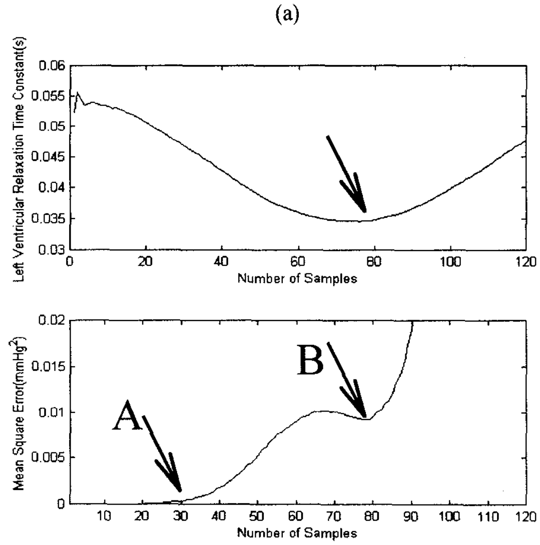
Herein we propose a new criterion to find the ending point of IRP based on the pattern classification of mean square error profile. Practical implementation of this algorithm will be provided and real-time application will also be discussed.

METHODS

We propose the mean square error criterion as an objective method to obtain the ending point of IRP. Moving the ending point of IRP from the starting point of isovolumic diastolic period by one data point, we calculated τ and reconstructed pressure waveform using Equation (1). Then we calculated mean square error between the original and the reconstructed pressure waveform for all data points used in calculation. We obtained about 20,000 beats of pressure waveform from 96 patients who were undertaken cardiac catheterization procedure in Seoul National University Hospital. Pressure data were acquired by Lab-PC-1200 (National Instruments) sampled at 600 Hz. We analyzed all of these pressure waveforms and revealed that mean square error pattern can be classified into two groups. Typical characteristics of one-step and two-step increasing patterns of mean square error profile are shown in Fig. 3(a) and Fig. 3(b), respectively. We named them mono-exponential and double-exponential, respectively.



(a)



(b)

Fig. 3. (a) Mono-exponential case. It shows one-step increase of mean square error. Lower arrow indicates the ending point of IRP. (b) Double-exponential case. It shows two-step increase of mean square error. Between two arrows indicated in lower graph, arrow B indicates the ending point of IRP. τ begins to increase at the point of the detected ending point of IRP in both cases.

Arrows in Fig. 3(a) indicates the ending point of IRP where the mean square error starts to increase rapidly with slope larger than 0.0002(mmHg^2/data point). This rapid increase of error means that isovolumic assumption is violated because of ventricle filling caused by mitral valve opening. Thus, it is reasonable to take that point as the ending point of IRP. Note that τ also begins to increase at that time as the arrow in upper plot of Fig. 3(a) indicates. There are two arrows in mean square error graph of Fig. 3(b).

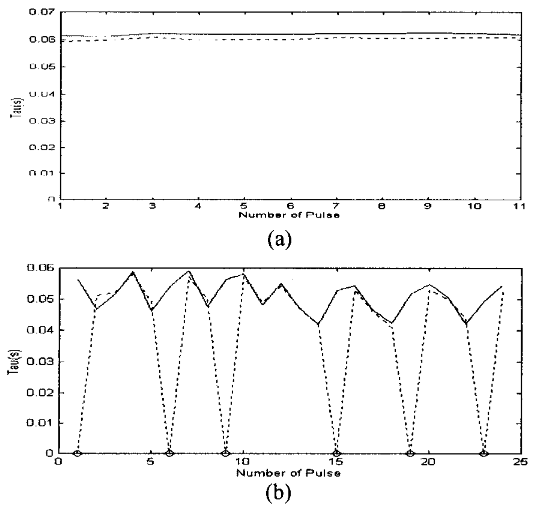


Fig. 4. Comparison between τ obtained from Paulus et al's method and from proposed method. Solid line is for proposed method and dotted line is for Paulus et al's method. (a) uniform τ, (b) variable τ. Small circles indicate missed beats.

Each arrow indicates the point when mean square error starts to increase rapidly with same criterion. Although mean square error already increases to a certain degree at point indicated by arrow A, we took the point indicated by arrow B as the ending point of IRP because τ begins to increase at that point. It is thought to be consistent with mono-exponential case of Fig. 3(a).

Real-time algorithm of estimating τ is given as follows; it consists of two parts of finding starting point and ending point of IRP.

Starting point detection procedure is;

1) real-time data is filtered by 11th order FIR differentiator,

$$h_{diff}(n) = \frac{\cos \pi(n-5)}{n-5} - \frac{\sin \pi(n-5)}{\pi(n-5)^2}, \quad -5 \le n \le 5 \qquad (3)$$

2) noise that is amplified during differentiation is reduced by 11th order lowpass FIR filter with cutoff frequency 50 Hz,

$$h_{low}(n) = \frac{\sin \frac{\pi}{6}(n-5)}{n-5}, \qquad -5 \le n \le 5 \qquad (4)$$

3) starting point is obtained by finding negative peak of differentiated signal.

Ending point of IRP is detected as follows;

4) τ is calculated iteratively as a new data point comes in with predetermined starting point in step 3),

5) reconstruct the pressure waveform applying τ obtained in step 4) to Equation (1),

6) calculate the mean square error between original and reconstructed pressure waveform,

$$E(n) = \frac{1}{n}\sum_{i=1}^{n}\left(P_{orig}(i) - P_{recon}(i)\right)^2 \qquad (5)$$

7) find the ending point of IRP by pattern classification method proposed previously.

RESULTS

Fig. 4(a) and Fig. 4(b) compare the results obtained by Paulus et al's method and newly proposed method. In Fig. 4, solid line corresponds to the newly proposed values and dotted line represents Paulus et al' s values. In case of patient who has uniform τ, two values are very similar [Fig. 4(a)] and Paulus et al's values underestimate our values by approximately 2%. But in other case of patient who has time-varying τ, Paulus et al's criterion misses some beats in detecting τ [Fig. 4(b)].

DISCUSSION

As shown in the results, the proposed method provided more stable estimation results. The only disadvantage of the proposed method is the increased number of calculation due to mean square error calculation. If pressure waveform is sampled at 600 Hz, as in our case, the number of calculation is increased about 100 times. But it does not cause any problem in real-time estimation if we take a iterative algorithm as Chun et al proposed [12]. They solved the equation in a recursive manner and reduced the number of calculation to the same order of Paulus et al's method.

CONCLUSIONS

A new criterion to detect the ending point of IRP for real-time τ estimation was proposed. It shows more reliable performance than current method. Increased number of calculation could be reduced to same order of current method using an iterative algorithm. Whole algorithm has been already implemented in Cath-S-01 polygraph system (Department of Biomedical Engineering, College of Medicine, Seoul National Univ.). The developed method is being used in real-time analysis of ventricular diastolic function during cardiac catheterization procedure.

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