DEVELOPMENT OF ONLINE MONITORING OF MYOCARDIAC ELASTANCE BY IMPOSING DUAL-FREQUENCY MINUTE VIBRATION

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***Abstract*- It is necessary to determine both ventricular and myocardial mechanical properties for the assessment of cardiac contractility in patients with heart disease. It is important to establish a framework to integrate myocardial properties into ventricular time-varying elastance for understanding the pathophysiology of heart failure. We measured myocardial mechanical properties by imposing minute sinusoidal vibration of different frequencies. Analysis between the amplitude and phase of force relative to those of displacement of at least two frequencies yielded elastance, viscosity, and inertia. Of these, elastance and viscosity were time varying, while inertia was constant during cardiac cycle. Applications of vibration of two different frequencies simultaneously have realized the online monitoring of myocardial properties continuously.**

Keywords*- Myocardial elastance, Material property, Time-varying elastance

I. INTRODUCTION

Ventricular mechanical properties, such as end-systolic and end-diastolic pressure-volume relationships, are of clinical importance as they determine the pump function of the heart. Ventricular properties are, in turn, theoretically considered to be determined by integrating myocardial mechanical properties according to the geometric arrangement of myocardium. It is unsolved, however, to establish a framework to integrate myocardial properties into ventricular properties and vice versa. The methods to measure myocardial mechanical properties remain also limited.

Measurements of myocardial properties are important for understanding the pathophysiology of heart failure because the impaired ventricular properties may result from both abnormalities of myocardium per se and those of myocardial arrangement. Therefore, it is necessary to combine methods to measure both ventricular and myocardial elastance. To approach these problems, we developed a method to measure time-varying elastance, viscosity and inertia of myocardium by imposing minute sinusoidal vibration on myocardial wall. Additionally, by imposing dual-frequency vibration, we developed an online monitoring of myocardial elastance.

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II. METHODOLOGY

A. Model of myocardial mechanical properties

We lumped myocardial mechanical properties into three components, elastance, viscosity, and inertia (mass). We modeled these elements being connected in parallel. As expected from the time-varying nature of ventricular mechanical properties, these elements may be time varying. Elastance, viscosity, and inertia generate force that is proportional to displacement, velocity, and acceleration, respectively. Because the measured force is the sum of these, it follows that

$$F = E \cdot D + V \cdot \frac{dD}{dt} + M \cdot \frac{d^2 D}{dt^2} \tag{1}$$

where F is force, D is displacement, and E, V, and M are elastance, viscosity, and inertia, respectively. Given D = A•sinωt, F is given by

$$F = A \cdot (E - Mw^2) \cdot \sin wt + A \cdot Vw \cdot \cos wt \tag{2}$$

If one knows the amplitude and phase of force relative to displacement, it is easy to determine E-Mω^2 (in-phase amplitude ratio) as well as Vω (orthogonal amplitude ratio). E and M can be separately obtained by combining the measurements at multiple frequencies. The time-varying nature of each element was obtained by analyzing piecewise data consisting of a single sinusoidal wave [1].

B. Animal preparation

In 13 dogs anesthetized with pentobarbital, we isolated heart and perfused it retrogradely with arterial blood from another support dog. We poked myocardial wall according to small-amplitude high-frequency sinusoidal waves by a mechanical stimulator. We selected the amplitude large enough to detect force changes but not too large to depress contractility. We continuously measured the displacement of

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Abstract

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the stimulator probe, and the force that is required for this myocardial displacement using the displacement and force transducers equipped with the mechanical stimulator.

C. Online monitoring by imposing dual-frequency vibration

We have to impose vibration of two different frequencies to uniquely determine E and M. It is quite inappropriate to impose two different vibrations separately, to monitor the changes in mechanical properties continuously, or to examine the rapidly changing mechanical properties such as in the case of arrhythmias.

To circumvent these limitations, we developed a method to impose two different vibrations simultaneously. During the digitization of force and displacement signals, we simultaneously multiplied each signal with each of the imposed sinusoidal wave and then applied digital low-pass filter to obtain the changes in in-phase amplitude ratio. Orthogonal amplitude ratio was similarly obtained by multiplying sinusoidal wave with the same frequency but orthogonal to the original vibration. We examined if this dual-frequency method is capable of measuring mechanical properties as the method of imposing vibrations separately.

III. Results

A. Examination of the frequency range where model describes the myocardial behavior well

In Fig. 1, we plotted the relationship between the in-phase amplitude ratio (vertical axis) and ω^2 (horizontal axis). The model predicts that these are linearly correlated with the slope of –M and the vertical-axis intercept of E. Because the elastance is expected to change cyclically with the cardiac cycle, and the mass of the sampling volume is likely to be relatively constant, linear relations are considered to shift in a parallel manner.

Results of experiments revealed that the relationship between the in-phase amplitude ratio and ω^2 was linear throughout the cardiac cycle, as predicted, if we only focus ω>70 Hz (Fig. 1). The slope was relatively constant with vertical-axis intercept changing according to the cardiac cycle.

The relationship between the orthogonal amplitude ratio and ω was also linear and the slope increased during systole (data not shown). This indicates that myocardial viscosity is also time varying.

B. Validation of time-varying myocardial elastance

We obtained myocardial elastance and mass as a function of time in cardiac cycle from the changes in intercept and slope. Fig. 2 summarizes the pooled changes in elastance (upper panel) and in inertia (lower panel). Viscosity increased in systole and decreased in diastole, similar with elastance (data not shown).

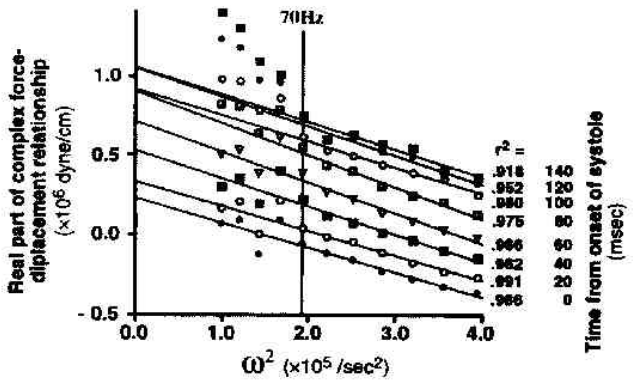

Fig. 1. The relationship between the in-phase amplitude ratio (real part of complex force-displacement relationship) and square of vibration frequency (ω^2) for different time from onset of systole

We compared time-varying myocardial elastance with the simultaneously measured time-varying ventricular elastance; these changes correlated well. The maximal myocardial elastance increased with dobutamine, and decreased with propranolol. It was relatively insensitive to the changes in preload. Regional ischemia decreased myocardial elastance only in ischemic area.

C. Online monitoring by imposing dual-frequency vibration

Fig. 3 illustrates an example of comparison between ventricular and myocardial time-varying elastance measured with dual-frequency vibration. These elastance values correlated well throughout a cardiac cycle, indicating the capability of online time-varying elastance measurement.

Fig. 4 shows the correlation between myocardial end-systolic elastance obtained by dual-frequency method and ventricular elastance. Correlation between these were better than correlation between elastance obtained by imposing vibration separately.

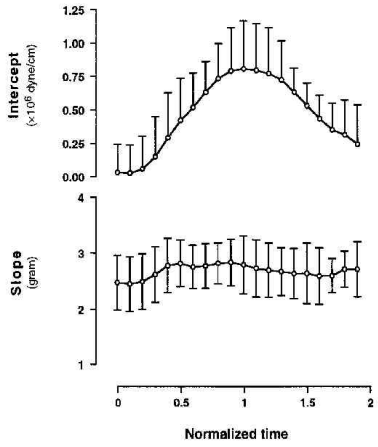

Fig. 2. Changes in elastance and inertia within a cardiac cycle determined by intercept and slope of the relation between in-phase amplitude ratio and square of vibration frequency.

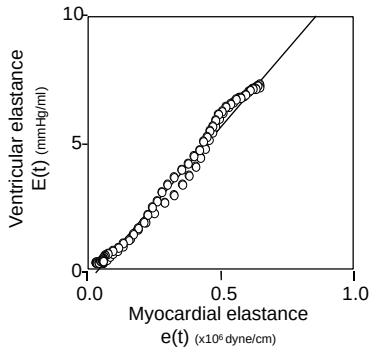

Fig. 3. Ventricular and myocardial time-varying elastance measured with dual-frequency vibration.

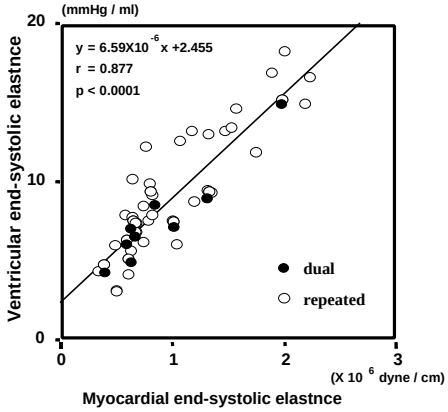

Fig. 4. Correlation between myocardial end-systolic elastance obtained by dual-frequency method and ventricular elastance, and between elastance obtained by imposing vibration separately and ventricuar elastance.

IV. Discussion

The results of this study indicate that myocardial elastance can be measured by imposing sinusoidal minute vibration of at least two different frequencies on myocardial wall. The myocardial elastance, thus obtained, showed desired characteristics, such as being a material property, time-varying nature with cardiac cycle, contractility dependence, independence of loading condition, manifestation of regional property.

Additionally, myocardial elastance can be obtained by imposing dual-frequency vibration (i.e., imposing vibration with two different frequencies at the same time) instead of imposing them separately. This enabled one to develop online monitoring device of myocardial elastance. Because separation of two vibrations and analysis of amplitude and phase is realized with application of digital filters, one can obtain elastance data only with delay of digital filters.

V. Conclusion

In summary, we developed a method to measure myocardial elastnance by imposing minute vibration. Introduction of dual-frequency vibration enabled one to measure elastance online.

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