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Technical Note

Non-invasive estimation of human left ventricular end-diastolic pressure

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Abstract

Sato et al. (Electronic Letters 32, 949–950, 1996) reported that one can obtain a non-invasive estimate of left ventricular (LV) pressure at around end-diastole in an isolated canine preparation. In this study we examined whether this method can be applied to humans. Using the method proposed by Kanai et al. (IEEE. Trans. UFFC, 43, 791–810,1996), we detected small amplitude LV vibration from an ultrasonic pulse Doppler signal reflected from the interventricular septum in five patients (44–63 y.o., male;4, female;1). We measured the oscillation frequency of the LV wall through the wavelet transform of small amplitude LV vibration, and calculated LV pressure at around end-diastole from the values of oscillation frequency, internal radius and wall thickness using Mirsky's equation. The estimated LV pressures at around end-diastole were similar to end-diastolic pressure measured directly by cardiac catheterization. These results show the possibility that this method allows for the non-invasive estimate of LV pressure at around end-diastole, and furthermore provides the basis for future clinical applicability of this technique. © 1998 IPEM. Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

Information on end-diastolic pressure is essential when one considers the presence or absence of clinical symptoms in hypertrophic cardiomyopathy patients or patients with heart failure. However, the only method to determine this pressure is via cardiac catheterization. Therefore, if one were to be able to estimate end-diastolic pressure non-invasively, it would be a valuable tool for evaluating the clinical status of patients.

Sato et al. reported that one can estimate left ventricular (LV) end-diastolic pressure non-invasively in an isolated canine heart preparation [1]. The parameters required for the estimation are the oscillation frequency (termed "eigenfrequency" in the previous reports [1,2]), internal radius and wall thickness of LV. The principle of the estimation is described in the next Section 2. Sato et al. obtained a direct recording of LV wall vibration by suturing a miniature vibration sensor on the LV wall, and measured the oscillation frequency. The difference between the estimated pressure and the measured one obtained by catheter micromanometer was less than 2–3 mmHg. Their results suggest the possibility that if one could non-invasively obtain the oscillation frequency of LV wall through the chest wall, one would be able to estimate LV pressure at around end-diastole in humans.

Kanai et al. reported a new method for detecting small amplitude vibration of an object (heart, large arteries, etc.) from the body surface by processing the ultrasonic Doppler pulse signals reflected from the object [3]. Their method enables us to measure the oscillation frequency of the LV from the precordium. In this study, we exam-

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ined whether one can obtain a non-invasive estimate of human LV pressure at around end-diastole.

2. Methods

2.1. Principle

The principle of the estimation is as follows: Advani-Lee's equation enables us to estimate LV myocardial elasticity when the values of internal radius, wall thickness and the oscillation frequency of spheroidal deformation of LV are provided [2,4]. In the present study, we used the simplified expression of the equation proposed by Honda et al. [2] as

$$E = 8.7 \times 10^4 a^2 f^2 \qquad (1)$$

(E: myocardial elasticity, a: internal radius, f: oscillation frequency). Mirsky proposed an equation which describes the relationship between myocardial elasticity, the values of internal radius, wall thickness and end-diastolic pressure [5] as expressed by the following:

$$E = 3390(1 + \frac{V_w}{V} \frac{a^2}{a^2 + (a+h)^2})(1 + \alpha V)\sigma_m \qquad (2)$$

(E: elasticity, V: LV volume, V_w: LV wall volume, $\sigma_m = (V/V_w) \times (1 + (a+h)^3/2R^3)P(t)$ (a: internal radius, h: wall thickness, $R = a + h/2$, $P(t)$: LV pressure)). It is noteworthy that Advani-Lee's equation does not include LV pressure and that LV myocardial elasticity can be calculated without any information on pressure. Combining Eqs. (1) and (2), one can estimate myocardial elasticity using Advani-Lee's equation when the values of internal radius, wall thickness and oscillation frequency are measured. Assuming that Advani-Lee's elasticity is identical to Mirsky's elasticity, one can estimate LV pressure from the values of internal radius, wall thickness and myocardial elasticity using Mirsky's equation (Fig. 1). The parameters required to estimate LV end-diastolic pressure are internal radius, wall thickness and oscillation frequency of the LV wall.

2.2. How to measure oscillation frequency of the LV wall from the precordium

Kanai et al. reported a method to measure small amplitude vibrations from the precordium [3]. Here, we briefly describe the principle. When an ultrasonic transducer generates a 3.5 MHz burst pulse, the ultrasound reflected from an object which is vibrating with a small amplitude produces a phase shift because of the Doppler effect. If the object moves with a large amplitude, a phase shift is also produced by the change of the position of the object. The transducer receives the summation of the above mentioned two phase shifts. When one detects the reflected signal, expressing it with a complex number, one can separate it into the real part and the imaginary part, and can obtain the phase and the amplitude of the reflected signal. One can select the frequencies which received a phase shift by subjecting the detected signal to a low pass filter. One makes a precise tracking of the maximal reflection intensity of the detected signal, identifying the exact time interval of the reflected pulse, and can then follow the large movement of the object to subtract the phase shift caused by the large movement from the detected signal. The essence of estimating the small vibration is to measure the phase difference $\Delta\theta(x;t)$ of the object caused by small amplitude vibration during a short time interval ΔT. The average velocity of the object during the interval ΔT, $\Delta x(t)/\Delta T$, is expressed by the following equation:

$$\frac{\Delta x(t)}{\Delta T} = c_0 \frac{\Delta\theta(x;t)}{2\omega_0\Delta T} \qquad (3)$$

Here, c_0 and ω_0 are the transmission velocity and angular frequency of ultrasonic pulses applied to the chest wall. Adding some improvements to the commonly used echocardiographic apparatus (Sonolayer α, SSH-140A, Toshiba, Tokyo), Kanai et al. developed a tool to detect a miniature vibration of the LV wall from the precordium. This method enables us to detect a small amplitude LV vibration (resolution is about 10 μm) superimposed on the motion of a large amplitude (with an order of mm–cm) produced by the cardiac contraction. Validation experiments proved that this method could clearly detect an amplitude of 20 μm vibration superimposed on a motion with a larger amplitude of 7.5 mm [3]. Using this method, we detected the small amplitude vibration of the LV wall. To determine the oscillation frequency of the LV, we subjected the LV vibration to Morle's wavelet transform. Sato et al. already reported that Morle's wavelet transform could provide the time course of the oscillation frequency of LV in an isolated canine preparation [1]. From the values
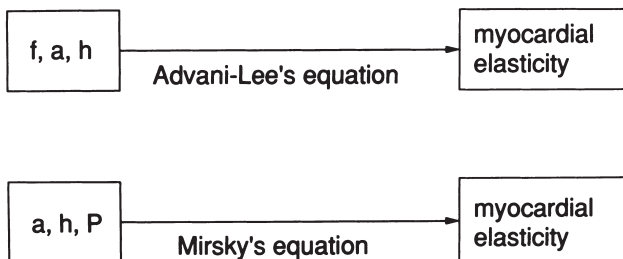

Fig. 1. Schematic illustration of the principle to estimate LV pressure at around end-diastole. Advani-Lee's equation gives the myocardial elasticity when the values of oscillation frequency (f), internal radius (a) and wall thickness are provided. Mirsky's equation gives the myocardial elasticity when the values of internal radius, wall thickness and LV pressure (P) are provided. Thus, if the values of internal radius, wall thickness and myocardial elasticity are provided, one can estimate LV pressure using Mirsky's equation.

of oscillation frequency of the LV, we calculated LV pressures at seven points during a single cardiac contraction (from 15 ms before the R wave of the electrocardiogram to 15 ms after it with 5 ms intervals).

2.3. Subjects

The summarized data for the patients are displayed in Table 1. The patients ranged from 44 to 63 y.o. (male; 4, female; 1), and were between I and II of NYHA classification. During cardiac catheterization, we detected the LV wall motion from the ultrasonic pulse reflected from interventricular septum. All patients showed neither regional reduction of septal wall movement nor marked unevenness of LV wall thickness. The details of the procedure to detect LV wall vibration were described elsewhere [3]. We compared the estimated LV pressure with that obtained by catheter–micromanometer (PC-350A, Millar Instrument).

3. Results

In Fig. 2, a typical example of the detected vibration of the LV wall and its spectral distribution are displayed (patient No. 1 in Table 1). The frequencies ranged from 24–27 Hz. In the lower panel of Fig. 2, the LV pressure estimated by this method and that obtained by catheter micromanometer are displayed. The estimated, calculated pressure was similar to that measured directly by the catheter; the difference was, on average, 6.59 ± 0.14 mmHg (mean ± SEM).

The average difference between the calculated pressures and the directly measured pressure for all patients ranged between − 4.63 to 6.59 mmHg, as shown in Table 1. The average difference for all data points was − 0.28 ± 0.79 mmHg. In the lowest two rows in Table 1, LV pressure at the timing of the R wave of the electrocardiogram obtained by the calculation method and direct cardiac catheterization measurement are presented. The calculated pressures were approximately equal to the measured pressure obtained by catheter.
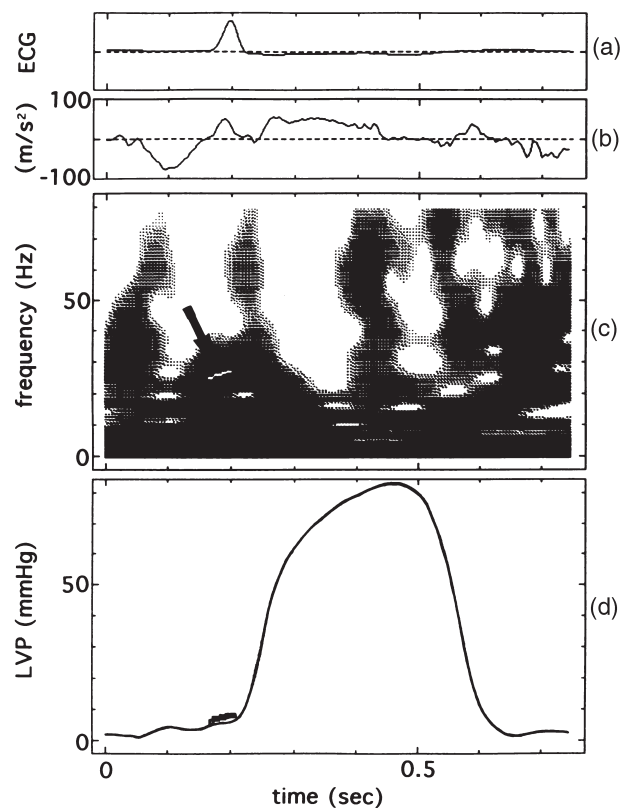

Fig. 2. Results of the experiment. A: electrocardiogram (ECG); B: detected vibration of the LV wall; C: density plot of the power spectrum. The white line in the lower panel indicated by an arrow is the time course of the instantaneous oscillation frequency of the LV wall. D: LV pressure (LVP); solid line: measured by catheter; open square: estimated LVP.

Table 1
Summarized data of the patients

n.o.	1	2	3	4	5	mean
Age	63	60	57	61	44	57
Gender	M	M	M	F	M	
Diagnosis	DCM	MR	DCM and OMI	DCM	DCM	
NYHA	II	I	I	II	II	
ΔP	6.59	2.42	1.41	−4.47	−4.63	−0.28
σ_p	0.14	0.94	0.37	0.38	0.96	0.79
$LVP_{R\ cal}$	13.2	25.6	7.8	23.4	21.3	
$LVP_{R\ measured}$	6.3	22.5	8.7	27.4	25.4	

DCM: Dilated cardiomyopathy; MR: mitral regurgitation; OMI: old myocardial infarction; NYHA: New York Heart Association classification; ΔP: mean difference of pressure (calculation–measured) of seven points at around end-diastole (from 15 ms before the R wave of the electrocardiogram to after 15 ms of it with 5 ms intervals); σ_p: standard error of the difference of pressure at seven points; $LVP_{R\ cal}$: calculated LV pressure at the R wave of the electrocardiogram; $LVP_{R\ measured}$: LV pressure at the R wave measured by catheter.

4. Discussion

In the present study, we showed that it is possible to obtain an approximate estimation of LV pressure at around end-diastole. However, it is difficult to draw definite conclusions regarding the feasibility and the accuracy of the method based on five cases. We have to extend the number of data to more subjects and examine the relationship between the data obtained by the proposed method and that obtained by direct measurement. Several limitations of the present study need to be considered. First, this method assumes that LV is spherical. In the case of an isolated canine heart, the right ventricle and atria were excised and therefore, the LV was nearly spherical during diastole. On the other hand, the human LV in the closed chest is ellipsoidal rather than spherical in shape, based on the consideration of the axis ratio. This may be the underlying cause of the difference between the calculated LV pressure and the direct measurement. Therefore, the model relating LV pressure to LV geometry and stiffness needs to be examined in future for detail to find a suitable model that is applicable to humans. Second, Advani-Lee's elasticity (myocardial elasticity for a spheroidal deformation) may not be equal to Mirsky's elasticity (myocardial elasticity for a spherical volume change). The preliminary examination of canine preparations suggests that Mirsky's elasticity is almost equal, albeit not exactly, to that of Advani-Lee's elasticity. Hence an empirical expansion of Mirsky's elasticity could provide a more precise estimation of LV pressure. Therefore, further examinations are required to determine empirical factors, if any, in humans to expand one equation. Third, there are many factors that may reduce the accuracy of the pressure estimation, such as regional hypo- or akinesis of the LV wall, marked hypertrophy or thinning of the regional wall, pulmonary hypertension, regional difference of myocardial elasticity such as observed in angina pectoris. Future studies, therefore, should focus on the effects of different types of cardiac diseases on the accuracy of non-invasive measurement.

In the present study, we showed that one can obtain an approximate estimate of LV pressure at around end-diastole non-invasively. However, at present, the method requires improvements to allow it to be used in general practical use. Nevertheless, non-invasive measurement of LV pressure at around end-diastole will soon be realized for clinical application in the near future.

5. Conclusion

1. We could measure the oscillation frequency of human LV at around end-diastole.
2. Five cases provided a non-invasive approximation of LV pressure at around end-diastole that was similar but not identical, to directly measured pressure.
3. Further studies employing a larger study group are required to establish the accuracy of the method.

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