Noninvasive estimation of left-ventricular end-diastole elasticity by analysing heart wall vibrations

H. Kanai, S. Nakaya, H. Honda and Y. Koiwa

A new noninvasive method was previously presented for the measurement of the left ventricular (LV) end-diastolic pressure (EDP) by combining Mirsky's method and the experimentally derived relationship. The eigenfrequency was determined by applying a short-time Fourier transform to the velocity signal on the human heart wall which is transcutaneously measured *in vivo* by the phased tracking method using ultrasound. In the Letter the authors estimate the elasticity of the heart wall for several human patients.

Introduction: Left ventricular (LV) pressure and its elasticity are significant parameters necessary for the clinical diagnosis of heart diseases. In particular, knowledge of the LV end-diastolic pressure (EDP), P_{ED}, is usually needed to assess LV functioning in clinical settings; a noninvasive method to measure this was previously presented [1]. The eigenfrequency was found by using a short-time Fourier transform to the velocity signal on the human heart wall [2] which is measured transcutaneously *in vivo* by the phased tracking method [3] using ultrasound. However, the LV EDP, the normal value of which lies between 5 and 12mmHg, cannot be obtained from the blood pressure measured at the brachial artery. Furthermore, the LV end-diastolic elasticity (EDE) E_{ED} cannot be noninvasively measured. To measure the LV pressure of a patient, invasive catheterisation is essential. Although the accuracy of this measurement has been confirmed, such cardiac catheterisation is difficult to apply at the bedside. Therefore, a noninvasive technique for measuring of LV EDP, P_{ED}, and its elasticity, E_{ED}, is needed.

Based on dimension analysis and Advauni and Lee's equation [4], by assuming that the LV wall vibration at the end-diastole is approximated by the free vibration of an elastic shell, Honda *et al.* [5] have experimentally derived a simple relationship between Young's modulus E [Pa] of the LV wall, the LV internal radius r [m], the LV wall thickness h [m], the myocardial density ρ [kg/m^3], and the LV instantaneous mode-2 eigenfrequency f_2 [Hz] as follows:

$$r \cdot f_2 = A\left(\frac{h}{r}\right)\sqrt{\frac{E}{\rho}} \quad \text{[m/s]} \qquad (1)$$

where the coefficient $A(h/r)$ is a function of h/r and is independent of elasticity. From Honda's experiment [4], the values of $A(h/r)$ are determined for various values of h/r and it is experimentally found out that $A(h/r)$ does not strongly depend on the values of h/r. By assuming a myocardial density ρ of 1.02×10^3 [kg/m^3], eqn. 1 is approximated by

$$E = 1.02 \times 10^3 \frac{1}{A\left(\frac{h}{r}\right)} r^2 f_2^2 \quad \text{[Pa]} \qquad (2)$$

It is worth noting that the elasticity E of the shell is noninvasively estimated without measuring the LV EDP when r, h, and f_2 are measured.

In Mirsky's method [6], on the other hand, the LV elastic stiffness E_Q [Pa] is given by

$$E_q = 399\left(1+\frac{V_w}{V}\frac{r^2}{r^2+(r+h)^2}\right)\left(1+\alpha V+\frac{\beta V}{P_{ED}}\right)\sigma_m \quad \text{[Pa]} \qquad (3)$$

where $V = 4\pi r^3/3$ [m^3] and $V_w = 4\pi((r+h)^3 - r^3)/3$ [m^3] are the internal and wall volumes, respectively, $\sigma_M = V/V_w \times (1 + (r+h)^3/2R^3)P_{ED}$ [Pa] is the stress on the LV wall, and $R = r + h/2$. The coefficients α and β satisfy the relationship $dP_{ED}/dV = \alpha \cdot P_{ED} + \beta$. It is experimentally found that β is negligibly small and α is given by $P_{ED} = 57.32e^{\alpha V}$.

By assuming that the E of eqn. 2 is equal to the E_Q of eqn. 3, the LV EDP P_{ED} is determined from the eigenfrequency f_2 of the LV wall vibration, where the internal radius r, and the thickness h, are easily measured by echocardiography. The LV wall vibration $y(t)$ is transcutaneously measured by the novel phased tracking method [3] developed in our laboratory using ultrasound. By applying a short-time Fourier transform to the resultant $y(t)$, its eigenfrequency f_2 is determined at the end-diastole. At the same time, the LV EDE E_{ED} is obtained from eqn. 2.

In vivo experimental results: Fig. 1*a* and *b* show a typical example of the electrocardiogram (ECG) and the vibration $y(t)$, respectively, on the LV side of the interventricular septum (IVS) measured by the phased tracking method of a 60 year old male patient (A) with mitral regurgitation (MR). By referring to the cross-sectional B-mode image, the direction of the ultrasonic beam is set so that the beam is perpendicular to the IVS during the measurement. Fig. 1*c* shows the time-frequency distribution of $y(t)$ of Fig. 1*b*. The instantaneous eigenfrequency f_2 of mode 2 is determined for the five instants at the end-diastole. With the determined f_2, the LV EDP P_{ED} is calculated for each instant t as shown by the squares in Fig. 1*d* using eqns. 2 and 3. The resultant pressure estimate, $\widehat{P_{ED}}$, closely coincides with the actual value, P_{ED}, which is shown by the solid line in Fig. 1*d*, directly measured by a catheter in the LV. In the other four patients and three young healthy subjects, the same procedure was applied, the results being summarised in Table 1; catheterisation was not used in the healthy subjects. The average difference between $\widehat{P_{ED}}$ and P_{ED} ranges from –4.6 to 3.6mmHg, which is sufficiently small.

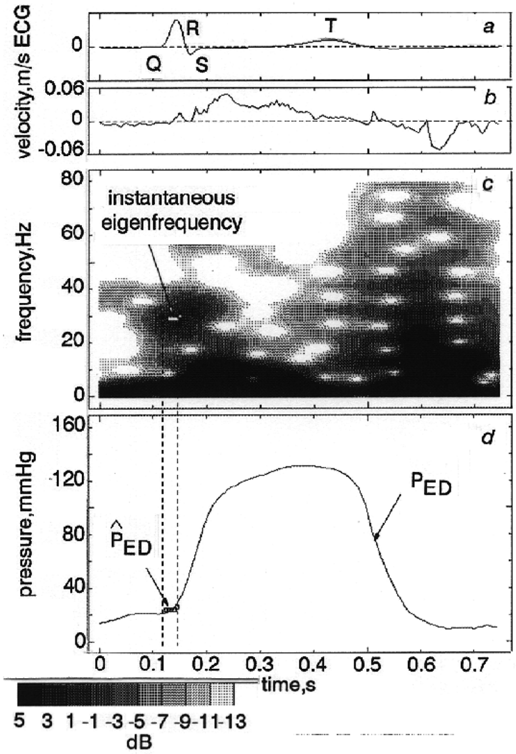

Fig. 1 *In vivo experimental results for 60 year old male patient* (*A*)

a Electrocardiogram (ECG)
b Vibration signal $y(t)$ on IVS
c Estimated mode 2 eigenfrequency f_2 around end-diastole, which is superimposed on time-frequency distribution, obtained by short time Fourier transform of $y(t)$
d Actual LV EDP, P_{ED} and estimated P_{ED}, $\widehat{P_{ED}}$ at five instants in end-diastole

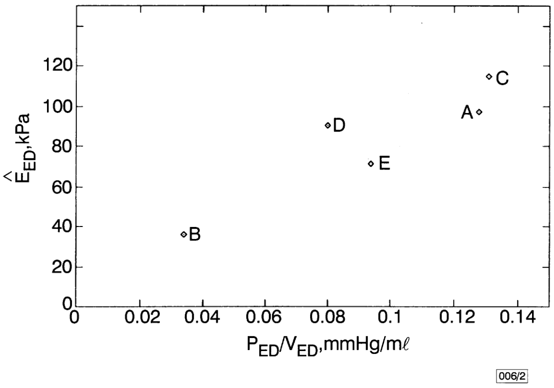

Fig. 2 *Correlation between estimated LV EDE* $\widehat{E_{ED}}$ *[kPa] and ratio,* P_{ED}/V_{ED} *[mmHg/ml], for five patients in Table 1*

The LV EDE E_{ED} of eqn. 2 is presented in the lowest row of Table 1. According to the LV elastic stiffness, E_M, obtained in the *in vitro* experiments [6], the average value of E_M is 24.6 ± 2.2kPa for 13 healthy subjects, and 134.8 ± 2.1kPa for six patients with congestive cardiomyopathy. Also in Table 1, for the patients with dilated cardiomyopathy (DCM), MR, or old myocardial infarction (OMI), the LV EDE estimates are similarly increased, that is, the passive chamber compliance is decreased; in patient (B), a diuretic was applied and it would be effective.

Table 1: *In vivo* experimental results for five patients and three healthy subjects

	Patients					Healthy		
Age	60	57	61	44	63	25	25	21
Diagnosis	MR	DCM-OMI	DCM	DCM	DCM			
Gender	male	male	female	male	male	male	male	male
Subject ID	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
LV volume V_{ED} [$m\ell$]	179	268	229	310	137	85	97	85
LV radius r_{ED} [mm]	35	40	38	42	32	22	23	22
LV wall thickness h_{ED} [mm]	12	8	12	12	9	11	10	12
h_{ED}/r_{ED}	0.34	0.20	0.32	0.29	0.28	0.5	0.43	0.55
$A(h/r)$	0.346	0.343	0.345	0.344	0.343	0.348	0.347	0.349
Eigenfrequency f_2 [Hz]	30	16	30	24	28	27	24	23
Actual EDP P_{ED} [mmHg]	23	9	30	25	13	–	–	–
EDP estimate $\widehat{P_{ED}}$ [mmHg]	26	8	28	21	17	13	11	10
Error ΔP [mmHg]	2.3	–1.2	–3.6	–4.6	3.6	–	–	–
EDE estimate $\widehat{E_{ED}}$ [kPa]	96	36	114	89	71	30	26	22

The ratio P_{ED}/V_{ED} [mmHg/ml] of the LV EDP P_{ED}, directly measured by the catheterisation, to the LV end-diastolic volume V_{ED}, measured by angiocardiography, has been employed to evaluate the cardiac function. Fig. 2 shows the relationship of the estimates $\widehat{E_{ED}}$ and the ratio P_{ED}/V_{ED} for the five patients in Table 1. There is a correlation between them.

Conclusions: In this Letter, we have proposed a new method for estimating the LV EDE based on the sizes and the eigenfrequency of the LV obtained by the transcutaneous measurement of vibrations on the LV surface and their spectral analysis to determine the instantaneous mode-2 eigenfrequency. These *in vivo* experimental results indicate that the elasticity noninvasively estimated in this Letter will become an effective parameter for the evaluation of the heart function.

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