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Method for noninvasive estimation of left ventricular end diastolic pressure based on analysis of heart wall vibration

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Indexing terms: Cardiology, Wavelet transforms

The authors present a new noninvasive method for measurement of the left ventricular (LV) end diastolic pressure by combining Mirsky's method and the experimentally derived relationship among the elasticity of the LV wall, the LV sizes and the LV instantaneous mode-2 eigenfrequency. The LV instantaneous eigenfrequency is selectively determined from the time-frequency distribution obtained by applying the wavelet transform (WT) to the nonstationary vibration on the heart wall.

Introduction: LV pressure is a significant parameter needed for the clinical diagnosis of heart diseases. In particular, the knowledge of the LV end diastolic pressure is usually needed to assess LV function in clinical settings. However, the LV end diastolic pressure, the normal value of which lies between 5 and 12mmHg, cannot be obtained from the blood pressure measured at the brachium artery. Thus, invasive catheterisation is essential in measuring the LV pressure of the patient. Although the accuracy of this measurement has been confirmed, such catheterisation is difficult to apply at the bedside. Therefore, a noninvasive technique for measurement of LV end diastolic pressure is desirable.

Honda *et al.* [1] thoroughly investigated Advani and Lee's complex equation [2], which describes the relationship among LV internal radius r [m], LV wall thickness h [m], vibration mode n, elasticity of LV wall, eigenfrequency f_n [Hz] and myocardial density ρ [kg/m^3]. This equation does not include pressure, which means that myocardial elasticity can be calculated without any information about pressure.

Based on the dimension analysis, Honda *et al.* [1] have derived the simple relationship among Young's modulus E of the LV wall, LV internal radius r, LV wall thickness h, myocardial density ρ, and LV instantaneous mode-2 eigenfrequency f_2. The coefficient A of this relationship is described by a function of h/r and has been determined experimentally [1]. By assuming the value of a myocardial density in this relationship, the elasticity E of the shell is noninvasively estimated without measurement of LV inner pressure when r, h and f_2 are measured. Conversely, Mirsky determined the elasticity of the ventricle based on ventricle sizes and LV pressure [3].

In this Letter, by combining the experimentally derived relationship and Mirsky's equation, we propose a new noninvasive method of estimating LV end diastolic pressure based on ventricle sizes, r and h, and the mode-2 eigenfrequency f_2 of the ventricular wall vibration. However, it is essential to determine instantaneous mode-2 eigenfrequency f_2 because the ventricular wall vibration is nonstationary. Therefore, we introduce the WT procedure into the determination of LV instantaneous mode-2 eigenfrequency f_2, so that the LV end diastolic pressure is successively determined.

Determination of instantaneous LV pressure p(t) from the eigenfrequency $f_2(t)$: The LV pressure $p(t)$ is obtained from the instantaneous eigenfrequency $f_2(t)$ of the ventricular vibration $s(t)$ by combining the derived dimension analysis and Mirsky's method as follows.

From the dimension analysis and Advani and Lee's equation, the ventricular wall vibration at the end diastole is approximated by the free vibration of an elastic spherical shell, and the relationship between the elasticity E [Pa] of the ventricular wall and the eigenfrequency $f_2(t)$ of the mode-2 vibration is described experimentally by [1]

$$r f_2(t) = A(h/r)\sqrt{\frac{E}{\rho}} \tag{1}$$

where the coefficient $A(h/r)$ is a function of h/r and is independent of elasticity. The value of $A(h/r)$ has been determined as ~0.344 when $h/r = 0.3$, which corresponds to the ratio of the standard left ventricle. In Honda's experiment, the values of $A(h/r)$ are determined for various values of h/r, and it is found experimentally that $A(h/r)$ does not highly depend on the values of h/r.

By assuming a myocardial density ρ of 1.02×10^3 [kg/m^3], and using the value of $A(h/r) = 0.344$ for the typical case of $h/r = 0.3$, eqn. 1 is approximated by

$$E = 8.7 \times 10^4 r^2 f_2(t)^2 \tag{2}$$

It is noteworthy that pressure is not required to obtain the elasticity E in eqn. 2.

In Mirsky's method [3], conversely, the elastic stiffness E_q [Pa] of the left ventricle is given by

$$E_q = 3990\left(1 + \frac{V_w}{V}\frac{r^2}{r^2 + (r+h)^2}\right)\left(1 + \alpha V + \frac{\beta V}{p(t)}\right)\sigma_m \tag{3}$$

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 the wall volume, respectively, $\sigma_m = V/V_w \times (1 + (r+h)^3/2R^3)\, p(t)$ [Pa] is the stress on the left ventricular and $R = r + h/2$. The coefficients α and β satisfy the relationship of $dp(t)/dV = \alpha p(t) + \beta$. It is found experimentally that β is negligibly small and α is given by $p(t) = 57.32e^{\alpha V}$.

By assuming that E of eqn. 2 is equal to E_q of eqn. 3, the LV instantaneous pressure $p(t)$ is determined from the eigenfrequency $f_2(t)$ obtained based on the following WT analysis, where the internal radius r and the thickness h are easily measured from echocardiography.

Determination of instantaneous mode-2 eigenfrequency $f_2(t)$: It is well known that the wavelet transform, $T_\psi(a, b)$, of the vibration signal $s(t)$ is defined as

$$T_\psi(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} \psi^*\left(\frac{t'-b}{a}\right) s(t')dt' \tag{4}$$

where a and b are, respectively, the scale parameter and shift parameter, * denotes the complex conjugate, and $\psi(t)$ is the analysing wavelet which has to satisfy the following admissible condition:

$$\int_{-\infty}^{\infty} \psi(x)dx = 0 \tag{5}$$

In this Letter, the following Morle's wavelet $\psi_{Morle}(t)$ is employed:

$$\psi_{Morle}(t) = \exp\left(-\frac{t^2}{2} + jmt\right) \tag{6}$$

Since it is well known that $\psi_{Morle}(t)$ satisfies the admissible condition for $m > 5$, $m = 10$ in this Letter. By replacing a and b of eqn. 4 by the inverse of frequency f and the time t, respectively, the time-frequency distribution, denoted by $T'_\psi(t, f)$, of the heart wall vibration $s(t)$ is obtained. The relationship between the elasticity E and the frequency $f_2(t)$ in eqn. 2 holds only for the mode-2 component. However, there are low frequency components <12 Hz with large amplitude owing to heartbeat in the small vibration $s(t)$ on the heart wall. It is therefore necessary to selectively determine the instantaneous mode-2 eigenfrequency $f_2(t)$ from the squared amplitude $|T'_\psi(t, f)|^2$ of the time-frequency distribution.

Thus, the instantaneous eigenfrequency $f_2(t)$ is determined by the frequency corresponding to the maximum peak >12Hz in the resultant $|T'_\psi(t, f)|^2$ at each time t.

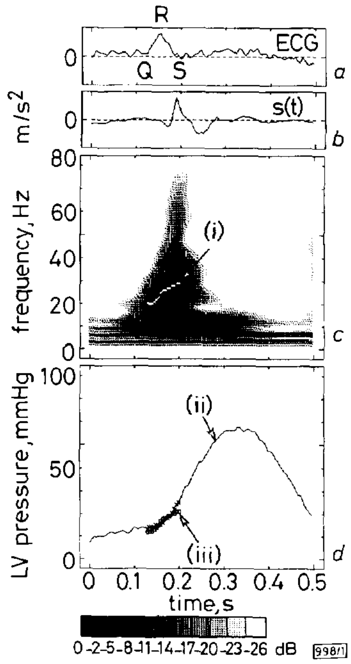

Fig. 1 *Experimental results of extracted canine heart*

a Electrocardiogram (ECG); *b* Analysed small vibration $s(t)$ on LV wall; *c* Estimated mode-2 eigenfrequency $f_2(t)$ around the end diastole, which is superimposed on the normalised time-frequency distribution, $|T'_\psi(t,f)|^2/|T'_\psi(t)|_{max}^2$, obtained by wavelet transform of LV vibration $s(t)$ in *b*; *d* Actual LV inner pressure (——, ×) and estimated pressure (□) at 15 moments in end diastole
(i) Estimated instantaneous mode-2 eigenfrequency $f_2(t)$
(ii) Measured by catheter
(iii) Proposed method

Experimental results: Fig. 1*a* and *b* shows the electrocardiogram (ECG) and the small vibration $s(t)$, respectively, measured by an acceleration pick-up on the ventricular wall of the an extracted canine heart. Fig. 1*c* shows the time-frequency distribution $|T'_\psi(t, f)|^2$ obtained by the WT of the vibration signal $s(t)$ in Fig. 1*b*, where $|T'_\psi(t, f)|^2$ is normalised by the instantaneous maximum value $|T'_\psi(t)|_{max}^2$ of $|T'_\psi(t, f)|^2$ in the frequency range from 1 to 80Hz. The instantaneous eigenfrequency $f_2(t)$ of mode-2 is determined for the 15 moments at the end diastole from the second peak in $T'_\psi(t, f)|^2$. With the determined $f_2(t)$, the LV pressure $p(t)$ is calculated for each moment t as shown by the squares in Fig. 1*d* from eqns. 1 and 2, where $r = 2.0 \times 10^{-2}$ [m] and $h = 0.6 \times 10^{-2}$ [m] are employed. The resultant LV pressure $p(t)$ almost coincides with the actual one, which is shown by the ×s on the solid line in Fig. 1*d*, directly measured by the catheter in the LV.

Conclusions: In this Letter we have proposed a new method for the measurement of the LV inner pressure based on the sizes and the eigenfrequency of the heart by introducing the wavelet transform into the determination of the instantaneous mode-2 eigenfrequency $f_2(t)$. In the experimental results of the canine heart, by applying the above procedure to the nonstationary heart wall vibrations, resultant estimated LV pressure $p(t)$ almost coincides with the actual pressure around the end diastole, which is clinically significant for assessment of the ventricular function. In these experiments, small vibrations on the ventricular wall were measured by an acceleration pick-up on the wall of the extracted heart; however, these small vibrations can be noninvasively measured from the chest surface by the ultrasonic-Doppler-based method [4] recently developed in our laboratory, even when large motion caused by the heart beat is superimposed on the small vibrations. By combining these two methods, noninvasive measurement of the ventricular pressure can be realised in the near future for the clinical diagnosis of heart diseases .

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Automatic switching synchronisation of serial and parallel avalanche transistor connections

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Indexing terms: Phototransistors, Circuit theory, Switching circuits

150A/10ns current pulses across a low ohmic resistive load (1 Ω) were obtained using Marx-type serial connection of the stages with the parallel connection of a few avalanche transistors in each stage. The automatic feedback allows perfect time synchronisation of the switching process in all the transistors.

Introduction: One of the most popular ways to obtain high current pulses in the nanosecond range nowadays is to use avalanche transistors (see [1]). This allows a maximum current amplitude typically up to 60A with a rise time of 3ns across the low ohmic load to be obtained. One quite promising way is to use a novel GaAs thyristor [2], which provides current pulses of >100A and has a rise time in the subnanosecond range. The main problem here is that such a component is not commercially available.

The simplest parallel connection for avalanche transistors creates significant problems in the time synchronisation of the switching process, since if one of the transistors is switched the voltage across all the transistors decreases. This makes the switching of the other transistors problematic, or at least their switching time delay increases significantly.

The purpose of this work is to present a scheme for both serial and parallel connection of avalanche transistors that allows automatic synchronisation of the switching processes in any device. It leads to a significant increase in current amplitude with the same rise time, that is inherent in a single transistor.

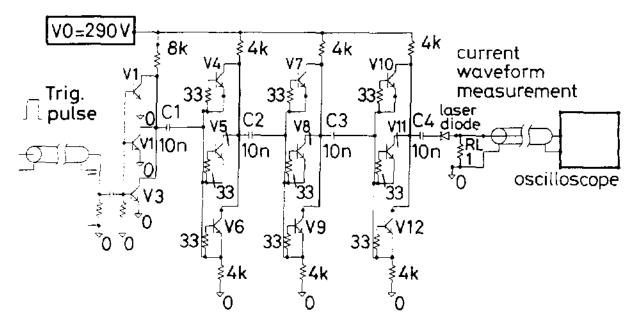

Fig. 1 *Schematic principle of serial and parallel connection of avalanche transistors*

Laser diode is shown as an example of application
Transistors V_1–V_{12}: FMMT 415

The scheme principle is shown in Fig. 1. This circuit is actually a current switch that supplies a low resistance element (e.g. a laser diode). Let us first assume perfect switching synchronisation of all the avalanche transistors and analyse the operation of the scheme in this case. We will then discuss the intrinsic feedback that allows synchronisation, provided that a low-resistance load is used. The