# Measurement of Local Pulse Wave Velocity in Arteriosclerosis by Ultrasonic Doppler Method

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***Abstract***—This paper presents a new method to measure *local* pulse wave velocity (PWV), which is an index of the hardness in the range of several millimeters on the aortic wall for diagnosis of the early stage arteriosclerosis. Small vibration signals are measured simultaneously at two adjacent points on the aortic wall near the aortic valve by electronically alternating the direction of an ultrasonic beam. Transit delay time of the pulse wave between these two points is determined from the two vibration signals obtained by this *alternating-beam method*. *Local* PWV at a point several millimeters along the aorta is precisely obtained by dividing distance between these points by resultant transit delay time. Such *local* acoustic properties of the blood vessels will prove useful, especially for noninvasive diagnosis of early stage arteriosclerosis.

## I. INTRODUCTION

In this paper, a new method is proposed to measure local pulse wave velocity in the range of several millimeters on the aortic wall. A major concern in the diagnosis of arteriosclerosis has been to develop a noninvasive method for evaluating the hardness of the aortic wall. Since the proposal of PWV as an index for use in diagnosis of arteriosclerosis [1], numerous studies on measuring the PWV have been reported [2],[3],[4],[8]. In the standard method, the PWV is obtained from the difference in arrival time of pressure waves propagating from the carotid artery to the femoral artery [2],[4].

This method, however, has the following three problems. (a) Sounds generated by a pressure wave propagating along the aorta are measured with microphones. Thus, the measurable points are limited to those where the aorta exists near the skin surface and the distance between such points is considerable long, i.e., several hundred millimeters.
(b) The measured sound has a frequency component of 10Hz at the most, and the delay time is determined in the time domain. Thus, the spatial resolution of the local evaluation is limited by the wavelength of the pulse wave, that is, several hundred millimeters.
(c) Furthermore, it is known that there is a large increase of the PWV from near the heart to the femoral artery [6]. Thus, the PWV obtained in the standard method between these distant points shows their average value.

In the early stage of arteriosclerosis, fibrous spots several millimeters in diameter are scattered on the surface of the artery. After growth of these spots, the arterial wall becomes homogeneously hard in the final stage of arteriosclerosis. It is important for early diagnosis, therefore, to measure the local hardness of the surface of the arterial wall. To increase the spatial resolution, it is necessary to measure vibrations due to pulse waves with frequency components up to about 50 Hz.

Therefore, we have developed a new method to noninvasively measure small vibration signals on the heart wall or the aortic wall from the surface of the skin based on the ultrasonic Doppler effect [9].

*Vibrations* of heart walls with small amplitude (about ±100 $\mu$m), up to at least a few hundred hertz are superimposed on the *motion* with large amplitude (about ±15 mm), several hertz due to heartbeat during one cardiac cycle. Thus, there are large fluctuations (about ±10 $\mu$s) in the transit period of an ultrasonic wave traveling from a transducer to an object in the heart and back.

Several methods have been proposed and applied to measure arterial wall *motion* having large amplitudes in which the zero-crossing point of the echo signal from an arterial wall is tracked for each transmitted RF pulse using the phase-locked loop (PLL) technique [5]. In these methods using the PLL circuit, however, only the phase of the received signal is considered and it is easily affected by the additive noise as pointed out in [7]. Thus, with each of these devices it has proven to be experimentally difficult to lock onto and remain locked to the desired echo.

Therefore, we have proposed a method for measur-

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ing small vibrations on various parts of the heart in the frequency range of up to a few hundred hertz [9]. The demodulated signal of the received signal is A/D converted at a high sampling frequency. From the phase of the received echo, small vibration signals are measured noninvasively using ultrasonic Doppler method. In simulation experiments using a water tank to detect small vibrations with amplitudes of 10 ~ 100 $\mu$m on the motion due to heart beat with the amplitude of 10 mm, such signals were successfully detected in the frequency range up to 1 kHz [10].

In the method, however, the object position is determined only from the *magnitude* of received echo. Therefore, we proposed a new method to accurately track the heart/aortic wall movement using both the *phase* and *magnitude* of the demodulated signal to determine the instantaneous position of the wall, from which the velocity is estimated. By this method, small vibrations with amplitudes of 10 ~ 100 $\mu$m on the motion due to heart beat with the large amplitude of 10 mm are successfully detected in the frequency range up to 1 kHz continuously for more than ten beat periods from the chest. From *in vivo* experiments, the proposed method is applied to the detection of small vibrations on the aortic wall near the interventricular septum in man.

Based on these results, this paper proposes a new method for obtaining local PWV by simultaneously measuring small vibrations at two points on the surface of the aortic wall. By the proposed method, high spatial resolution, which is necessary in the evaluation of local hardness, is attained. Using a silicone tube, the dynamic experiments are compared with the static experiments and it is confirmed that the local hardness (Young's modulus) of the vessel wall is also evaluated with high spatial resolution.

By applying the proposed method to *in vivo* experiments, the PWV of the vibration wave transmitted between the two points on the aortic wall is obtained even for the aortic wall near the aortic valve. The distance between the two points is about several millimeters. By measuring the thickness and the radius of the aortic wall, the local elasticity (Young's modulus) is also evaluated for each measurement point. Thus, the proposed method will be effective for local evaluation of the hardness on the aortic wall.

## II. Principle of Measurement of Small Vibration on Aortic Wall[12]

The RF pulses with angular-frequency $\omega_0$ are transmitted at a time interval $\Delta T$ from an ultrasonic transducer on the chest surface. The instantaneous distance $x(t)$ between an ultrasonic transducer and a moving object is given by $x(t) = c_0 \cdot \tau(x;t)$, where $c_0$ is the acoustic velocity and $\tau(x;t)$ is the instantaneous period required for one-way transmission from the object to the ultrasonic transducer. The ultrasonic pulse reflected at the object is received by the same ultrasonic transducer. The phase $\theta(x;t)$ of the demodulated complex signal $y(x;t)$ of the received signal is given by

$$\theta(x;t) = 2\omega_0 \tau(x;t). \qquad (1)$$

The phase difference $\Delta\theta(x;t)$ between the demodulated signals of the succeedingly received signals is given by

$$\Delta\theta(x;t) = \theta(x;t+\Delta t) - \theta(x;t) = \frac{2\omega_0}{c_0}\Delta x(t), \qquad (2)$$

where $\Delta t$ is the received interval of the pulses reflected at the object at a time $t$ and $\Delta x(t) = x(t+\Delta t) - x(t)$ is the movement of the object in the period $\Delta t$ from the time $t$. Thus, the average velocity of the object is determined by

$$\widehat{v}(x;t+\frac{\Delta t}{2}) = \frac{\Delta x(t)}{\Delta t} = c_0 \cdot \frac{\Delta\theta(x;t)}{2\omega_0 \Delta t}. \qquad (3)$$

In this ultrasonic Doppler method, it is necessary to accurately track the position $x(t)$ of the object. When the received signal is A/D converted at a finite sampling interval $T_S$, the reflected signals and their phase values are obtained only for the discrete spatial points, where the spatial resolution $\Delta x_S = T_S \cdot c_0/2$. If the object moves from one discrete spatial point to the boundary of the next one during the period $\Delta t$, phase discontinuity occurs between $\theta(x;t)$ and $\theta(x \pm \Delta x_S; t+\Delta t)$, which introduces considerable large noise in the resultant velocity estimates $\widehat{v}(x;t+\Delta t/2)$.

In this paper, therefore, the complex correlation is introduced in the determination procedure of the object position $x(t)$. Let us define the mean squared difference between the demodulated complex signal $y(x+\tau_x;t+\Delta t)$ and the preceding signal $y(x;t)$ by $\alpha(\beta;\tau_x)$,

$$\begin{aligned}\alpha(\beta;\tau_x) = \ & \textstyle\sum_{x \in R} |c(x+\tau_x;t+\Delta t) - \beta(\tau_x)c(x;t)|^2 \\ & -\gamma(|\beta(\tau_x)|^2 - 1), \end{aligned} \qquad (4)$$

where $\tau_x$ is the movement of the object during the period $\Delta t$ of the succeeding pulses, $\beta(\tau_x)$ is the phase change from $y(x;t)$ to $y(x+\tau_x;t+\Delta t)$, $\gamma$ is the Lagrange multiplier, and $R$ is the range $x \pm \Delta x$ around the previous position $x$, where the above difference is evaluated. The minimum $\alpha_{MIN}(\tau_x)$ of $\alpha(\beta;\tau_x)$ is achieved by

$$\widehat{\beta}(\tau_x) = \frac{r(\tau_x;t)}{|r(\tau_x;t)|}, \qquad (5)$$

where $r(\tau_x; t)$ is the cross correlation between $y(x; t + \Delta t)$ and $y(x; t)$. Letting us denote $\widehat{\tau}_x$, by which $\alpha_{MIN}(\widehat{\tau}_x) = \alpha(\widehat{\beta}; \widehat{\tau}_x)$ takes the minimum, the average velocity in Eq. (3) is given by

$$\widehat{v}(x; t + \frac{\Delta t}{2}) = c_0 \frac{\angle \widehat{\beta}(\widehat{\tau}_x)}{2\omega_0 \Delta t}. \qquad (6)$$

By multiplying the resultant velocity $\widehat{v}(x; t + \frac{\Delta t}{2})$ by the period $\Delta t$, the next object position $\widehat{x}(t + \Delta t)$ is given by

$$\widehat{x}(t + \Delta t) = \widehat{x}(t) + \widehat{v}(x; t + \frac{\Delta t}{2})\Delta t. \qquad (7)$$

From the resultant $\widehat{x}(t + \Delta t)$ and $\widehat{v}(x; t + \frac{\Delta t}{2})$, the object position and the vibration velocity on a large amplitude motion are simultaneously determined.

## III. PRINCIPLE OF SIMULTANEOUS MEASUREMENT OF VIBRATIONS ON PROXIMATE TWO POINTS

By the simultaneous measurements of small vibrations at adjacent two points on the arterial wall, the time delay and the pulse wave velocity is determined. From this velocity, the early stage of the arteriosclerosis is locally diagnosed [11].

Figure 1 shows the procedure for simultaneous measurement of small vibrations on proximate two points of arterial wall by controlling directions of ultrasonic beam. By the employed sector-type electronic scan probe, the ultrasonic beam is transmitted in one of the 128 directions. These directions are designated by the integer number in the ultrasonic diagnosis equipment. We added a circuit to the ultrasonic equipment, by which the numbers corresponding to the two directions of the points A and B are controlled synchronously with the transmitted trigger pulse. By controlling these two numbers for every transmitted interval, the beam is alternatively transmitted in two different directions. The two small vibrations on the points A and B are measured from the ultrasonic signals reflected at points A and B.

## IV. PRINCIPLE OF THE METHOD FOR OBTAINING LOCAL PWV AND ELASTICITY

From these two vibration signals, the delay time $\tau_{AB}$ between these points are determined. The distance $d_{AB}$ between these points is also determined by the B-mode image. Thus, the pulse wave velocity $c_0$ is determined by

$$c_0 = \frac{d_{AB}}{\tau_{AB}}. \qquad (8)$$

It is well known that there is the following relationship between the resultant pulse wave velocity $c_0$ and the Young modulus $E$ of the arterial wall:

$$c_0 = \sqrt{\frac{Eh}{2r\rho}}, \qquad (9)$$

where $r$ and $h$ are the radius and thickness of the arterial wall and $\rho$ is the blood density. By measuring the radius $r$ and the thickness $h$ of the wall, the young modulus $E$ of the arterial wall is obtained by the following equation:

$$E = \frac{2r\rho}{h} \times c_0^2. \qquad (10)$$

By this procedure, the hardness of the wall in the range of several millimeters is determined and it will be effective in the noninvasive local diagnosis of early stage arteriosclerosis.

## V. *In vivo* EXPERIMENTAL RESULTS

By using this equipment and the circuit we made, the following *in vivo* experiments of measurement of the local PWV are performed for the aorta in a normal male of age 23. Measurement points are on the aortic wall near the heart and the wall of the abdominal aorta.

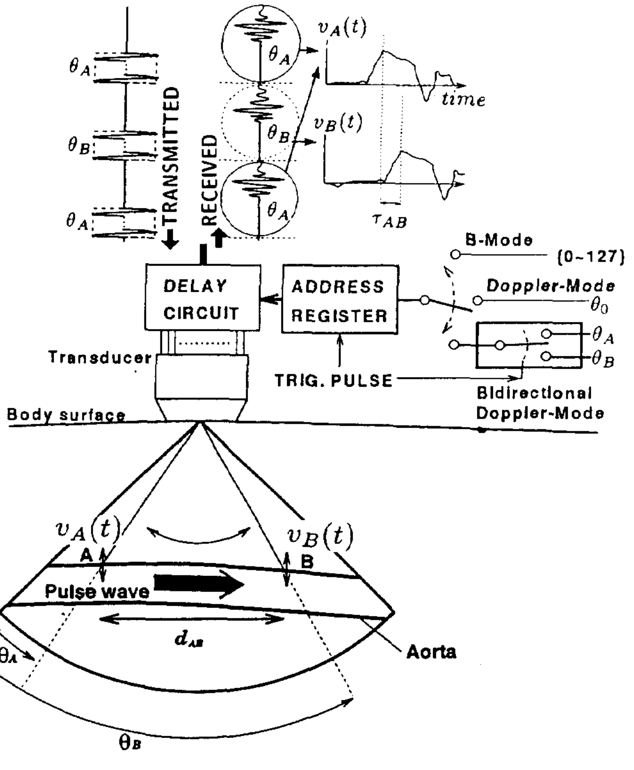

Fig. 1 Principle of the simultaneous measurement of small vibrations on proximate two points of arterial wall by controlling directions of ultrasonic beam.

The small vibrations $v_A(t)$ and $v_B(t)$ at two points A and B on the aortic wall near the heart are accurately measured as shown in Fig. 2 for the twelve beat periods. The distance $d_{AB}$ between these points is 9.1 mm. The transit time $\tau_{AB}$ from point A to point B is determined from $v_A(t)$ and $v_B(t)$ in the period $T_0$ of 100 ms in length, which correspond to the ejection period of these twelve heart beats, and $\tau_{AB}$ is 2.44 ms. Thus, the local PWV is 3.7 m/s from Eq. (8).

The small vibrations $v_A(t)$ and $v_B(t)$ are also measured at two points A and B on the wall on the abdominal aorta for nine beat periods from the same person. The distance $d_{AB}$ between these points is 7.7 mm. The transit time $\tau_{AB}$ from point A to point B is determined from $v_A(t)$ and $v_B(t)$ in the period $T_0$ of 200 ms in length by the similar procedure as described above, and $\tau_{AB}$ is 1.85 ms. Thus, the local PWV is 4.2 m/s.

## VI. CONCLUSIONS

This paper proposes a new method for accurate measurement of small vibrations at two adjacent points on the aorta by *alternating-beam method*. Using this method, the small local vibrations on various parts of the artery with the large motion by heartbeats are simultaneously measured at two adjacent points in a frequency range up to a few hundred hertz and local PWV is obtained. This measurement of the local PWV is considered to be effective especially in noninvasive diagnoses of the early stage arteriosclerosis.

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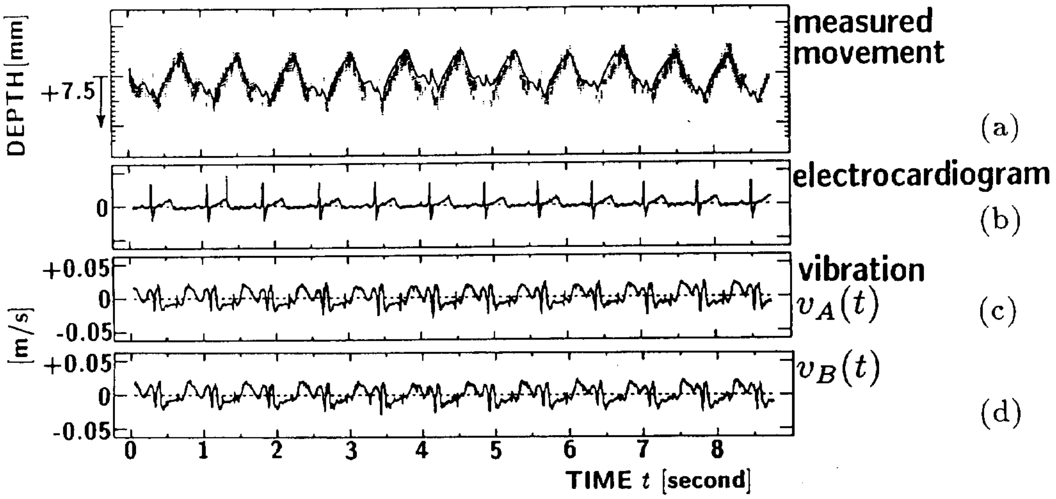

Fig. 2 The experimental results of the small vibrations on the two points (A, B) of the aortic wall near the aortic valve in a young normal man. (a) Estimates of the movement of the point A superimposed on the M-mode image. (b) The electrocardiogram (ECG). (c) and (d) The estimates of the vibration velocity signals $\widehat{v}_A(t)$ and $\widehat{v}_B(t)$ on the points A and B, respectively.