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Technical note

Development of a novel pulse wave velocity measurement system: Using dual piezoelectric elements

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ABSTRACT

The aim of this study is to develop a painless system of measuring the brachial-ankle arterial pulse wave velocity (baPWV) without compression cuffs. The PWV reflects the compliance of the artery and is measured for the early diagnosis of arteriosclerotic vascular diseases. However, the conventional baPWV system, which measures four cuff pressures simultaneously, easily causes circulation block and tightening pain at the extremities. In addition, approximately 15 min are required to stabilise the blood pressure for re-examination. Therefore, we developed a novel baPWV measurement system using dual piezoelectric sensor elements. The principle of this high-sensitivity pressure pulse detection system is based on adding the two in-phase outputs from the coaxially arranged dual piezoelectric sensor. As our system facilitates the measurement of the baPWV by detecting the pulsation of an artery using sensors fixed on the skin where the pulse is palpable, it does not cause pain and reduces examination time. The coefficients of correlation between the baPWV values obtained from the conventional and present methods were 0.93 (right side) and 0.90 (left side). The results suggest that our system can be used to measure the baPWV without pressure cuffs as accurately as the conventional method.

1. Introduction

In biomechanics, if the peripheral arterial segment is modelled as a thin-walled, isotropic, incompressible tube containing an incompressible fluid, the conduction velocity of the pressure wave travelling through the tube is related to the wall elastic parameter (stiffness) according to the Moens–Korteweg equation [1,2]:

$$\text{Conduction velocity of the pressure wave} = \sqrt{\frac{E \times h}{2r\rho}}$$

where h is the wall thickness, r is the lumen radius, E is the stiffness, and ρ is the blood density. The Moens–Korteweg equation implies that the conduction velocity of the pressure wave is proportional to the square root of the incremental stiffness E of the vessel wall. With an increase in the stiffness, the travelling speed of the pressure wave in the wall increases. Arterial pulse wave velocity (PWV) refers to the pressure wave velocity along the artery and is hence an index of arterial stiffness, which represents arteriosclerotic vascular change even at an early stage of the disease. Moreover, a systematic meta-analysis of prospective observational data from 17,635 subjects showed that PWV may enable better identification of high risk populations who may benefit from more aggressive cardiovascular risk factor management [3]. Therefore, we believe that measurement of PWV is very important in the evaluation of cardiovascular risk factor.

Brachial-ankle PWV (baPWV) is the one of the prevailing technique of PWV to assess arterial stiffness using pressure cuffs wrapped on the bilateral brachium and ankles [4–6]. However, this methodology requires applying simultaneous compression to the four extremities with blood pressure cuffs. Sometimes, such compression of all extremities can cause transient sympathetic hypertonia associated with tightening pain. In addition, when a re-examination is necessary, approximately 15 min are required to stabilise the condition of blood pressure.

We recently developed a highly sensitive biological vibration detection device using a coaxially designed dual piezoelectric sensor. This device enables aortic pulsation to be captured by placing

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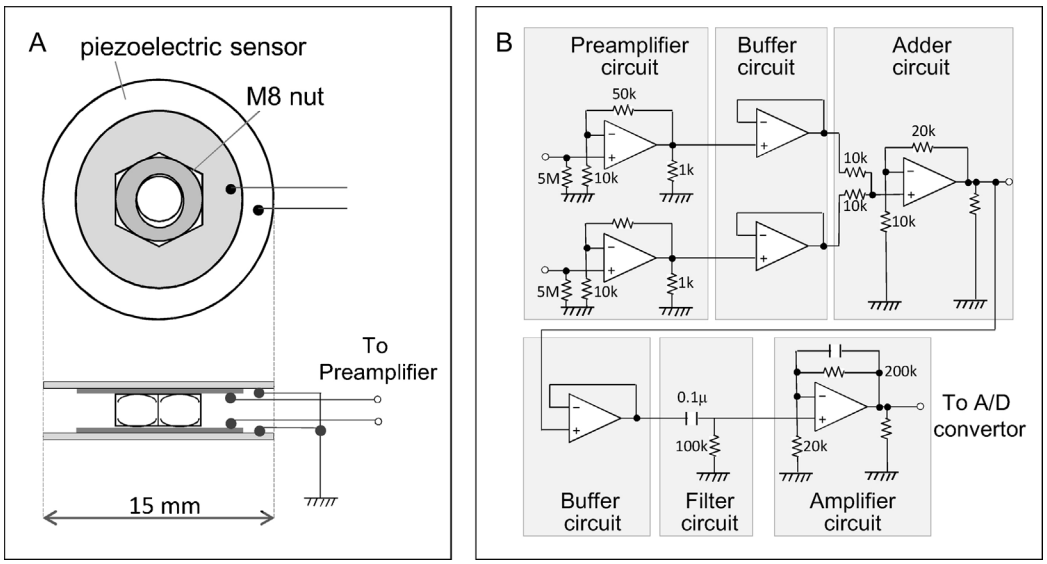

Fig. 1. (A) Schematic of dual piezoelectric sensor. (B) Block diagram of the circuit for vibration detection device. The present baPWV measurement set is a system comprising three channels of these circuits.

a sensor on the skin at a site where the pulse is palpable. In the present study, we developed a new baPWV measurement system using a recently developed high-sensitivity dual piezoelectric sensor and evaluated its measurement performance by comparing its results with those from the conventional baPWV instrument (Form PWV/ABI, Colin Medical Technology, Komaki, Japan) using pressure cuffs.

2. Materials and methods

2.1. Dual piezoelectric sensor

Fig. 1A shows the dual piezoelectric sensor, which has a sandwich construction comprising a nut and two coaxially arranged piezoelectric sensor elements (7BB-15-6, Murata Manufacturing Co., Ltd., Japan). The sandwich construction ensures that a sensor has a structure that is sensitively deformable by external force when it is clamped with a holder. The diameter, height, and weight of the dual piezoelectric sensor are 15 mm, 5 mm, and 15 g, respectively.

2.2. Biological vibration detection system circuit

Fig. 1B shows the block diagram of the circuit of a biological vibration detection system for measuring the PWV using a dual piezoelectric sensor. A signal from the dual piezoelectric sensor is amplified five-fold at the preamplifier circuit, and the amplified signal is transferred once to the buffer circuit (to isolate the adder circuit from the preamplifier load) and then transferred to the adder circuit. In the adder circuit, two in-phase outputs from the sensor are added and the output is further augmented twice by the amplifier. Then, the output signal from the adder circuit is transferred to the buffer circuit and the low cut filter to remove noise interference. Finally, the filtered signal is additionally augmented 10 times by the amplifier. The amplified analogue signals are then converted into digital data by a 16-bit A/D converter (Contec ADA 16-32/2(CB)F, Japan) at a 3 kHz sampling rate and stored in a personal computer.

2.3. Method of determination of arrival time of pulse wave

The pulse wave arrival time (obtained by plethysmography) is the time of appearance of the initial upstroke of the pressure pulse wave at the point of observation. However, reproducible identification of the upstroke point of the pulse wave is not simple. When a piezoelectric sensor is deformed by arterial vessel volume change, it generates a voltage. However, the output signal wave of the piezoelectric sensor is not the same as the blood flow plethysmogram of the optical sensor. The piezoelectric sensor signal is the velocity of the volume change of the vessel caused by the pressure pulse wave (i.e. the value obtained by the differentiation of the vessel volume change (plethysmogram)). Consequently, one more differentiation of the output of the piezoelectric sensor yields the value of the acceleration of the plethysmogram. Generally, the upstroke point of the original data corresponds to the initial peak point of the latter's second derivative. Therefore, the initial upstroke point of the plethysmogram corresponds to the initial peak point of the data obtained by differentiating the output of the piezoelectric sensor (Fig. 2). Using this property of the differential value of the piezoelectric sensor signal, we can measure the arrival time of the pulse wave automatically by reproducible identification of the initial peak point of the data obtained by computing the location of the maximum (peak point) of the first derivative of the piezoelectric sensor signal using commercial data processing software (Origin 8 SR4, OriginLab Corporation, USA). In the present system, the digitised data of the dual piezoelectric sensor was preprocessed using fast Fourier transformation filtering to remove high frequency noise, and then, differential transformation was performed.

2.4. Method of determination of baPWV

baPWV is derived as follows:

$$\text{baPWV} = \frac{\Delta Sba}{\Delta Tba}$$

where ΔSba is the difference between the distances from the sternoclavicular joint to the brachium (Db) and to the ankle (Da), and ΔTba is the difference in the arrival times from the heart to the brachium and to the ankle.

ΔSba is derived as follows:

$$\Delta Sba = Da - Db$$