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Noninvasive blood pressure monitor using strain gauges, a fastening band, and a wrist elasticity model

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ABSTRACT

This paper proposes a novel continuous noninvasive blood pressure estimation method that is based on the variation of wrist skin strain occurring with changes in diastolic and systolic blood pressure. The wrist elasticity model used to estimate blood pressure was constructed according to an ultrasonic probe indentation method used for measuring and calculating the thicknesses and material properties of skin layers. The strain value of the wrist skin was measured using a dual strain sensor to avoid temperature drift. The dual strain sensor was fabricated using a screen-printing process on a polyimide film. To cause the dual strain sensor to indent the skin for ascertaining the depth to measure skin strain, the wristband is driven by a compact ultrasonic linear motor consisting of a piezoelectric slab and a flap clip. The compact ultrasonic linear motor provides an adequate driving distance, which was estimated using the energy method, and a constant holding force used for strain measurement without input power. In blood pressure measurement experiments performed with 30 subjects, the estimation mean error against a validated cuff-type blood pressure monitor was 1.6 mmHg at rest for diastolic pressure. The error increased when the subjects exercised, but returned to near the rest value when the subjects rested after exercise. These results showed that the noninvasive blood pressure monitor can estimate blood pressure with a small fastening force. This device can be used for bedridden patients who require continuous blood pressure monitoring.

1. Introduction

Blood pressure, which reflects cardiovascular system conditions, is one of the most critical physiological parameters. The well-known method for noninvasive blood pressure measurement is based on the auscultatory method, employing an inflatable pressure cuff that compresses a limb to intermittently measure blood pressure. Several continuous noninvasive methods for blood pressure monitoring have been developed. One approach is to detect the pulse wave velocity using a tonometer to evaluate central arterial pressure [1]. The correlations between pulse wave velocity and arterial pressure are modified by age and gender [2]. Another noninvasive device consisting of a cushioned sensor provides blood pressure measurements every 14 beats and demonstrates excellent correlation with measurements obtained through invasive methods [3]. In addition, impedance plethysmography for determining blood volumetric changes associated with the cardiovascular cycle is used to estimate blood pressure [4]. Kaniusas et al. proposed a method that involves using mechanical plethysmography in combination with standard electrocardiography (ECG) and subsequently discussed the measured blood pressure waves [5]. However, these methods [4,5] require the use of ECG electrodes. Another combination method based on a mechanical strain sensor and the pulse transit time minimizes the inconvenience imposed on patients during continuous blood pressure monitoring [6]. To estimate blood pressure using wrist skin strain without ECG electrodes, this study developed a novel continuous noninvasive blood pressure monitor that is based on a wrist elasticity model and involves a fastening band combined with strain gauges. This novel approach is suitable for bedridden patients who require noninvasive continuous blood pressure monitoring.

The auscultatory method, which involves using an inflated cuff to occlude the blood flow, is based on a pressure balance concept. Systolic pressure is the cuff pressure at which blood starts to flow when the cuff is deflated. The diastolic pressure is the maximum cuff pressure that has no effect on the blood flow. Blood pressure refers to the pressure exerted by the blood on the walls of the arteries. Thus, systolic and diastolic blood pressures have an obvious

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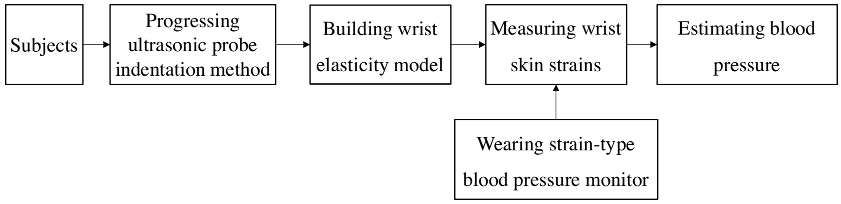

Fig. 1. Flowchart of the blood pressure estimation concept.

relation to skin strain. To estimate blood pressure from the strain on the wrist skin, knowledge of the mechanical properties of the skin is essential. Human skin is a complex living material composed of three main layers [7,8]: the epidermis, dermis, and hypodermis. The thickness of each skin layer varies according to race, location in the body, and age [9]. Several noninvasive methods for evaluating the mechanical properties of the skin are based on indentation [10], suction [11,12], and torsion [13] measurements. According to the relevant literature [9–15], the material properties and dimensions of human skin vary depending on individuals and skin zones. Consequently, in a mechanics model of wrist skin, the thickness and Young's modulus of skin layers should be measured individually to estimate blood pressure.

This paper proposes a new method involving an ultrasound device that is used for measuring the thicknesses and displacements of skin layers. Simultaneously, a load cell is used to measure the applied force on the skin, and the Young's moduli of the skin layers are then acquired. A flowchart of the blood pressure estimation concept is shown in Fig. 1. The thicknesses and Young's moduli of a subject's wrist skin were acquired using the ultrasonic probe indentation method. A wrist elasticity model that relates the wrist strain to the blood pressure was constructed using the wrist skin parameters. For measuring skin strain above the radial artery, a strain-type blood pressure monitor that consisted of a dual strain gauge with temperature drift suppression and was mounted on a lead zirconate titanate (PZT) actuator fastening band was worn by the subject. Finally, the estimated systolic and diastolic blood pressures were compared with those obtained from a validated cuff-type blood pressure monitor.

2. Wrist elasticity model

The wrist dermis, which is a soft layer covered by the epidermis and located above the radial artery, consists of a grid of collagen and lymphatic elements [8]. The subcutaneous tissue between the radial artery and the radius is composed of the hypodermis and muscle. A double-layer elastic model is suitable for describing the different Young's moduli E and Poisson's ratios ν of the two layers. The principle of skin indentation used in this research is based on a uniform load being applied to the wrist; the load causes vertical (z-axis) and tangential (x-axis) displacements of the skin, as shown in Fig. 2. The proposed skin model neglects the viscous part of the skin and assumes isotropic elastic material, consistent with prior studies [13–15].

The global stiffness of skin tissues is the equivalent stiffness k_e of a double-layer material. For an elastic material in contact with a uniform load, the global stiffness is given by

$$\frac{1}{k_e}=\frac{l_e}{AE_e^*}=\frac{1}{k_d}+\frac{1}{k_s}=\frac{l_d}{AE_d^*}+\frac{l_S}{AE_S^*} \tag{1}$$

where k is the stiffness, A is the contact area between the ultrasonic transducer probe and the skin, l is the displacement caused by the resultant force, and E^* is the reduced Young's modulus defined by $E/(1-\nu^2)$. The suffixes d, s, and e indicate the wrist dermis, subcutaneous tissue, and equivalence, respectively. The stiffnesses of the

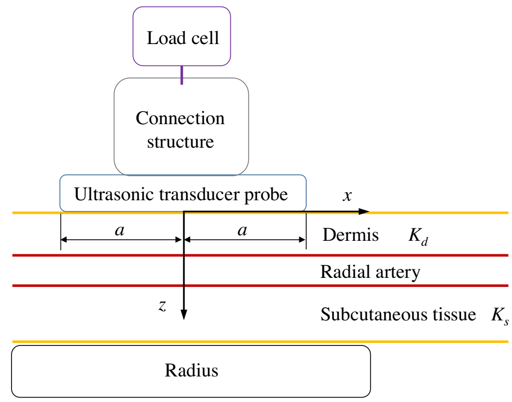

Fig. 2. Schematic representation of the measurement apparatus, and the two-layer model composed of the wrist dermis and subcutaneous tissue.

dermis and subcutaneous tissue are determined from the applied forces and the resultant vertical displacements of the skin layers. The global stiffness k_e and reduced Young's modulus are calculated from Eq. (1) by using the values of k_d and k_s.

To obtain the equivalent Poisson's ratio, the tangential and vertical displacements associated with the uniform load were analyzed. Because the equivalent Poisson's ratio was calculated using the tangential displacement on the skin surface, the value of the equivalent Poisson's ratio approached that for the wrist dermis. The assumption of the Poisson's ratio of the subcutaneous tissue being equal to that of the wrist dermis is acceptable because the skin strain caused by blood pressure is insensitive to the Poisson's ratio of the subcutaneous tissue. Wrist skin indentation can be considered a uniform normal pressure load p over the contact area where normal tractions exist. The pressure load is obtained by dividing the resultant force by the contact area between the ultrasound probe and the skin. The displacements resulting from contact stress in the linear elastic half-space model were derived in [16] on the assumption that the interface is frictionless. The vertical displacement of a point in the loaded region ($-a \le x_1 \le a$) is given by

$$\overline{u_z}=-\frac{\left(1-{\nu_e}^2\right)p_1}{\pi E_e}\left[(a+x_1)\ln\left(\frac{a+x_1}{a}\right)^2+(a-x_1)\ln\left(\frac{a-x_1}{a}\right)^2\right]+C \tag{2}$$

An ultrasound transducer probe of width $2a$ is centered on the y-axis, and C is the constant of integration determined by the vertical displacement at the probe center $x_1 = 0$. By determining $\overline{u_z}$ at $x_1 \neq 0$, the relationship between ν_e and E_e in Eq. (2) is acquired. On the assumption that the origin is not displaced, the tangential displacement in the loaded region ($-a \le x_2 \le a$) is provided by

$$\overline{u_x}=-\frac{(1-2\nu_e)(1+\nu_e)}{E_e}p_2x_2 \tag{3}$$

The suffixes 1 and 2 of x and p are used to indicate that $\overline{u_z}$ and $\overline{u_x}$ correspond to different locations and loads. Substituting Eq. (2) into Eq. (3) yields the equivalent Poisson's ratio, which is formulated as

$$\nu_e=\frac{p_2\pi(C-\overline{u_z})x_2+p_1\overline{u_x}(a-x_1)\ln\left(\frac{a-x_1}{a}\right)^2+p_1\overline{u_x}(a+x_1)\ln\left(\frac{a+x_1}{a}\right)^2}{2p_2\pi(C-\overline{u_z})x_2+p_1\overline{u_x}(a-x_1)\ln\left(\frac{a-x_1}{a}\right)^2+p_1\overline{u_x}(a+x_1)\ln\left(\frac{a+x_1}{a}\right)^2} \tag{4}$$

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