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A new mathematical model of wrist pulse waveforms characterizes patients with cardiovascular disease – A pilot study

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ABSTRACT

The purpose of this study was to analyze and compare a series of measured radial pulse waves as a function of contact pressure for young and old healthy volunteers, and old patients with cardiovascular disease. The radial pulse waves were detected with a pressure sensor and the contact pressure of the sensor was incremented by 20 gf during the signal acquisition. A mathematical model of radial pulse waveform was developed by using two Gaussian functions modulated by radical functions and used to fit the pulse waveforms. Then, a ratio of area (r_A) and a ratio of peak height (r_{PH}) between percussion wave and dicrotic wave as a function of contact pressure were calculated based on fitted parameters. The results demonstrated that there was a maximum for waveform peak height, a minimum for r_A (r_A^{min}) and a minimum for r_{PH} (r_{PH}^{min}) appeared as contact pressure varied. On average, older patients had higher peak amplitude and a significantly smaller r_A^{min} ($p < 0.001$) and r_{PH}^{min} ($p < 0.02$) than the young and old volunteers. The r_A^{min} and r_{PH}^{min} calculated with the mathematical model had moderate to strong positive linear correlations ($r = 0.66$ to 0.84, $p < 0.006$) with those directly calculated without the model. The receiver operating characteristic (ROC) analysis showed that the r_A^{min} calculated with the model and the contact pressure measured at the r_A^{min} had good diagnostic accuracy to distinguish healthy volunteers vs. diseased patients. Therefore, using the mathematical model to quantitatively analyze the radial pulse waveforms as a function of contact pressure could be useful in the diagnosis of cardiovascular diseases.

1. Introduction

Radial pulse waves can be measured by a pressure sensor mounted on the wrist over the radial artery and provide important physiological information of a patient [1]. It is an innovative method to perform safe and fast physical testing without burden [2]. The characteristics of pulse waves could directly reflect the cardiovascular condition of patients [3] and are crucial for the development of novel tools for cardiovascular assessment. By using advanced electronic detectors, a series of pulse waves may be acquired and analyzed to obtain quantitative results regarding a patient's physiological and pathological information [4–6].

In 2000, Yoon et al. [7] characterized the relationship between the pulse peak amplitude and the contact pressure measured from the left radial artery demonstrating that there was a maximum pulse peak amplitude as contact pressure varied that could be used for diagnostic purposes. Similarly, Kim et al. [8] proposed an algorithm to classify the measurements of the floating pulse (a pulse potent when felt with no pressure applied but impotent when felt with pressure applied) and sunken pulse (a pulse impotent when felt with no pressure applied but potent when felt with pressure applied) versus contact pressure, and found that subjects in the sunken pulse group had a significantly higher body mass index than those in the floating pulse group. In contrast to varying the contact pressure, other techniques have been developed to assess the pulse depth (the depth of maximum pulse feeling with figures), based on, for example, the displacement of the skin's surface [9,10], the width of the artery [11], and the effect of contact force in the context of pulse transit time measurements [12]. Moreover, the concept of contact pressure measurements is not limited to radial pulse measurements. In the work of Forouzanfar et al. [13], for example, the effect of external pressure applied with a cuff on

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Table 1
Characteristics of young and old healthy volunteers without known heart problems, and old patients with known heart problems participated in this study. The reported values are in average ± standard deviation.

	Young volunteers ($n = 16$)	Old volunteers ($n = 15$)	Old patients ($n = 14$)
Male (n)/Female (n)	10/6	7/8	9/5
Age (years)	23.4 ± 2.2	67.7 ± 10.4	69.8 ± 11.0
Height (cm)	172.3 ± 10.6	163.4 ± 5.5	161.4 ± 4.9
Weight (kg)	69.4 ± 19.9	61.5 ± 14.4	59.5 ± 11.3
Heart rate	74.9 ± 10.3	69.6 ± 12.7	68.1 ± 7.1
pSBP (mmHg)	115.4 ± 13.9	124.9 ± 20.8	158.0 ± 36.8
pDBP (mmHg)	73.4 ± 7.9	86.5 ± 11.1	90.8 ± 18.1

non-invasive arterial pressure measurements was investigated. The influence of contact pressure on the variation of pulse morphology may provide new features that reflect the characteristics of cardiovascular system.

The radial pulse waves have been analyzed in many different ways to study heart disease and/or related problems [14–17]. Some ideas for analyzing the radial pulse waves were adopted from the analysis of pressure waves [18,19]. The sub-endocardial viability ratio and augmentation index calculated by the area ratio and peak height ratio of reflected wave and forward wave, respectively, were often used in radial pulse waves analysis to evaluate the cardiovascular conditions [20,21].

In addition to direct calculations, mathematical models are often used to fit the waveforms prior to any calculations. The sum of two Gaussian functions is a popular model used to fit the waveforms because of its bell shape that is similar to an individual pulse wave [22,23]. Unfortunately, the sum of two Gaussian functions could not fit the waveform precisely. Goswami et al. [24] improved the fitting at the rising edge of waveform by using two Rayleigh functions. Furthermore, mathematical models using three or multi-Gaussian functions [15,25], sums of sinusoids (with slowly varying amplitudes, phases, and frequencies) [26,27], and piecewise Gaussian-cosine functions [28] were all proposed to fit the waveforms. Although the waveforms were fitted more accurately by using more functions with more parameters, it is hard to compare the parameters between experiments due to potential overfitting issues.

In this study, the radial pulse waveforms as a function of contact pressure were acquired from young and old healthy volunteers and old patients diagnosed with cardiovascular disease. A new mathematical model of radial pulse waveform was developed by using two Gaussian functions modulated by rational functions and then fitted to the pulse waveforms. The areas and peak heights of the percussion and dicrotic waves were calculated by using fitted parameters. The ratios of area and ratios of peak height between the percussion wave and dicrotic wave as a function of contact pressure were used to characterize the healthy volunteers and patients with cardiovascular disease.

2. Materials and methods

2.1. Subjects

A total of 16 young healthy volunteers (mean age = 23.4 years, range 21-26 years), 15 old volunteers (mean age = 67.8 years, range 56–85 years) without known cardiovascular disease, and 14 old patients (mean age = 69.8 years, range 55–86 years) diagnosed with cardiovascular disease, participated in this study. All of the patients had cardiac insufficiency and five of these patients also had a myocardial infarction. All participants gave their informed consent, and were recruited from Northeastern University and Shengjing Hospital of China Medical University in Shenyang, China. The study was approved by the Institutional Review Board of Northeastern University in Shenyang, China. The average (± standard deviation (SD)) characteristics of participants are given in Table 1.

2.2. Pulse waves collection

Radial pulse waves were measured using an in-house developed pulse wave acquisition device [29] with a pressure sensor placed directly on top of the radial artery in the left arm. The contact pressure was adjusted during the measurements. The subject was in the sitting position after he or she had rested for at least 10 min, and the contact pressure of the sensor was incremented by approximately 20 gram-force (gf) during the acquisition of pulse wave signals. Under each contact pressure, a series of stable pulse signals were measured and the measurements were stopped when the patient complained about too much pressure or that the pulse waves were worsening. The signal from the pressure sensor was digitized using a 12-bit analogue-to-digital (ATD) converter with a sampling frequency of 1 kHz.

2.3. Mathematical model of pulse waveforms

Since the sum of two Gaussian functions and the sum of two Rayleigh functions (with a sharp turn) could not fit the radial pulse waveform precisely, a new mathematical model was developed by using two Gaussian functions modulated by rational functions to model the percussion wave ($W_f(t)$) and dicrotic wave ($W_r(t)$) as follows:

$$W(t) = W_f(t) + W_r(t) = \frac{t^2}{1+B_1 t^2} \cdot \frac{A_1}{\sigma_1\sqrt{2\pi}} \exp\left(-\frac{(t-T_1)^2}{2\sigma_1^2}\right) + \frac{1}{1+B_2(t-T_2)^2} \cdot \frac{A_2}{\sigma_2\sqrt{2\pi}} \exp\left(-\frac{(t-T_2)^2}{2\sigma_2^2}\right), \quad (1)$$

where t is time in milliseconds, A_n, T_n, and σ_n ($n = 1, 2$) are the scaling constants, centers, and widths of the nth Gaussian, and B_n ($n = 1, 2$) is the constant which influences the slopes of the waves. Please note that the idea of using rational functions to modulate the Gaussian function is to improve the fitting at the rising edge of a pulse waveform, but at the same time to minimize the effects on Gaussian functions.

2.4. Data analysis

Data analysis was performed in Matlab (MathWorks, Natick, MA, USA) with in-house written software. First, the noise of pulse wave signal was minimized by a five-point moving average technique. The drifting baseline was determined by the curve obtained from piecewise cubic spline interpolation where each period began, and then the drifting baseline was removed from the pulse signal. Second, each individual waveform was identified and an average waveform was calculated from all individual waveforms. Third, the correlation between each waveform and the average waveform was calculated. Finally, the mean waveform was calculated from the top 10 waveforms having the best correlation with the average waveform for further analysis. The technique used to