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Evaluation of blood flow velocity envelope in common carotid artery for reference data

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ABSTRACT

The aim of the present study is to investigate the usefulness of envelope waveforms of blood velocity and its indices in the common carotid artery (CCA). The envelope waveforms are measured using a developed wireless measurement system. The CCA blood velocity waveforms of 202 healthy volunteers were analyzed. Multivariate analysis was used to determine the relationship between fixed factors and the selected hemodynamic data after adjusting for the fixed factors. The results revealed the effects of age, gender and exercise on the blood velocity waveforms in the CCA. The results suggest that evaluations of the envelope waveform indices are more reliable when these effects are accounted for. The normal blood velocity parameters in CCA are determined from 202 healthy subjects in the age range 20–69 years after adjusting for the effects of gender and exercise. The findings are expected to be a reference data for healthcare and clinical evaluations.

1. Introduction

Arterial hemodynamics is an important aspect of cardiovascular physiology. It is concerned with how the heart pumps blood through the cardiovascular system. Most cardiovascular diseases and disorders are related to systemic hemodynamic dysfunction [1]. Despite the universal acknowledgement that organ health depends on ensuring adequate oxygen delivery to all organs and that oxygen delivery depends on blood flow rather than blood pressure, blood flow is currently measured for only a very small percentage of the patient population. Most decisions in hemodynamic management (such as the management of hypertension) are based just on arterial blood pressure measurements. Consequently, there is no clear understanding of the effect of blood velocity.

A fundamental understanding of age-, gender-, and exercise-related changes in cardiovascular circulation and function is essential to effectively prevent and treat cardiovascular disease, particularly in older persons [2]. Flow velocities in the common carotid artery (CCA) are known to decline with age [3–8]. Most studies measure blood flow in terms of systolic and end-diastolic velocities and demonstrate that these velocities decrease with age [3–8]. Numerous studies have found that spectral analysis of the Doppler signal and blood flow waveforms in the CCA changes with aging and with vascular disease. Such analyses are extremely powerful, non-invasive tools for clinical diagnosis of conditions such as carotid artery disease [9–11]. An age-related reduction in physiological blood flow velocities in the CCA is known; however, exercise- and gender-related variations in blood flow velocity waveforms in healthy young or old individuals have not been well demonstrated.

Evidences for gender-related differences in arterial hemodynamic indices (such as the systolic blood pressure (SBP)) have been found in previous studies [13,14]. It is suggested that younger women have lower brachial and ankle SBPs and a lower ankle–arm pressure index than age-matched men [13]. It has been reported that the incidence of cardiovascular complications increases with SBP and increases in the pulsatile components of blood pressure are associated with higher cardiovascular risk in postmenopausal women [15,16]. Generally, gender-related differences in the higher SBPs of women are also associated with the smaller body sizes of women. However, the extent to which body size influences blood velocities in the CCA has not been well described.

Doppler ultrasound is a popular technique for investigating the hemodynamics of cardiovascular and cerebrovascular circulations. However, because commercial ultrasound systems are difficult to use and cannot be worn, only a few studies have measured the characteristics of blood flow velocity.

In the present study, we developed a wireless portable measurement system to measure arterial blood flow velocity synchronized with monitoring the electrocardiogram (ECG) and blood pressure

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(BP) [17]. These measurements can be used to evaluate arterial hemodynamic conditions both at rest and during physical exercise [18]. The aim of the present study is to examine the effectiveness of the envelope waveforms of the blood velocity and its indices in the CCA (which were measured using the developed measurement system) for monitoring the effects of gender, age and regular exercise.

2. Method and materials

2.1. Subjects

286 putatively healthy subjects participated in this study. From these subjects, we studied 202 subjects who were normotensive (SBP ≤ 140 mmHg), had a normal body mass index (≤30 kg/m^2), were not taking any medication, and had no medical history of overt chronic diseases (including hyperlipidemia, diabetes, arrhythmia). There were two groups: a young group (n = 138, age range: 20–44) and an old group (n = 64, age range: 45–69). In this study, there were 126 males and 76 females. Subjects who performed regular aerobic exercise more than three times per week were classified as doing regular exercise.

Subjects were recruited through various forms of advertisement. All subjects gave their written informed consent to participate. This study was reviewed and approved by the Ethics Committee of Tokushima University Hospital.

2.2. Data collection and measurement system

2.2.1. Anthropometric data

The following anthropometric parameters were measured for all subjects: weight, height, body mass index (BMI), body fat, visceral fat level and waist circumferences. Body weight (kg), body fat (%) and visceral fat level were measured using InnerScan body composition monitors (BC-610, Tanita, Japan). These monitors use bioelectric impedance analysis to monitor multiple indicators of overall health. The unit used for the visceral fat level is equivalent to a visceral fat area of 10 cm^2 as measured by an abdominal computed tomography scanner. Height was measured to the nearest 0.5 cm using a stadiometer (THP-DA, Ogawa Iriki, Japan). The BMI, an indicator of obesity, was obtained by dividing the body weight by the square of the height (kg/m^2). Waist circumference was measured to the nearest 0.5 cm using a 1-cm-wide measuring tape. The waist circumference was taken to be the minimal waist circumference between the umbilicus and the xiphoid process for a standing subject.

2.2.2. Hemodynamic data

In this study, blood velocity data from the CCA were collected using the developed wireless measurement system shown in Fig. 1. This system was developed for measuring blood velocity spectra with synchronized measurement of ECG and BP [17,18]. Measurements of blood velocity signals from CCA were performed non-invasively using the Doppler ultrasound technique, as described below.

2.2.3. Measurement system

The measurement system consisted of a probe, a Doppler signal discriminator (DSD), a transmitter, a receiver, an analog–digital converter and a laptop personal computer. The DSD was miniaturized using a surface mounting technique, giving a substrate size of 67 mm × 48 mm [17]. The probe was designed with a small size (W 34 mm × H 20 mm × D 42 mm, approximately weighing 20 g) using two piezoelectric zirconate titanate transducers (PZT) with a diameter of 15 mm, where one was for transmitting ultrasound and

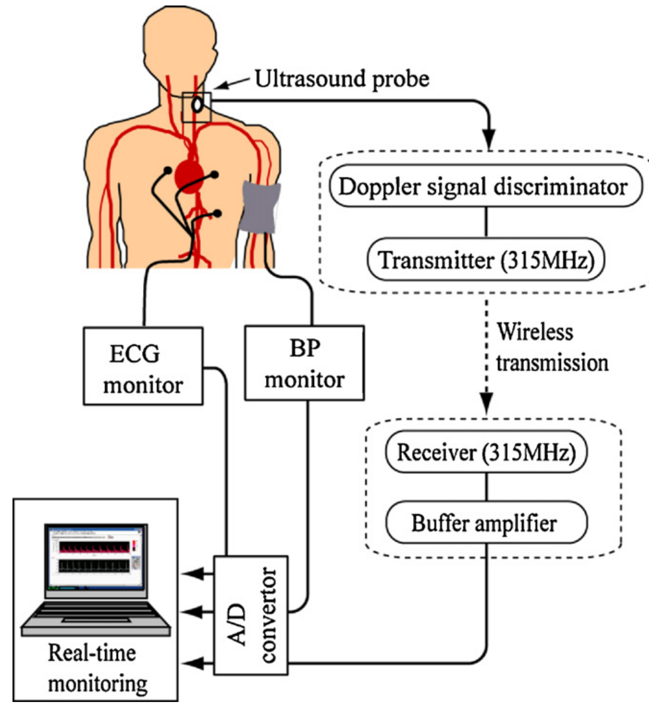

Fig. 1. Portable system for measuring blood flow velocity with synchronized ECG and BP measurements.

the other was for receiving the Doppler echoes using continuous-wave ultrasound. The ultrasonic probe was lightly attached to the left side of neck with 50° of the Doppler angle of insonation. The miniaturization of the DSD enabled the blood flow velocity to be monitored during physical exercise and postural changes [18]. The power consumption of the DSD was reduced to 2.1 W, allowing it to be powered by a battery installed in the portable system.

Blood flow velocities were determined from the Doppler-shift frequency of signals from the CCA. The signals, which included low-frequency and harmonic noise, were filtered by a band-pass filter (0.1–4.2 kHz) installed in the DSD. Blood flow velocities could be measured for frequencies in the same range as the band-pass filter. The velocity (V_d) could be estimated from its Doppler shift frequency (f_d) using $V_d = c\,f_d/(2\,f_0\cos\theta)$, where c is the speed of acoustic waves in human tissue (=1540 m/s), f_0 is the irradiated ultrasound frequency (=2.0 MHz) and θ is the Doppler insonation angle (=50°).

Data are transmitted using a 315-MHz FM/FSK transmitter that has a transmission rate of 28.8 kbps and an output of ~0.5 mV/m (Japanese standard for weak radio waves). The data were converted into a digital signal with a sampling frequency of 10 kHz using an analog-to-digital converter (Interface, CBI-360116TR) and then transferred to the computer for display and data analysis.

Real-time spectrogram monitoring was implemented through a program written in Visual C++® as a stand-alone Windows® application. It was implemented using a programmed loop, the interval of which was set to 50 ms (corresponding to 500 data points). However, data were analyzed by taking fast Fourier transforms (FFT) of intervals of 256 points in a Hanning window. The spectrogram was processed by performing decimation using the frequency radix-2 FFT algorithm with a small discrete Fourier transform (DFT) to reduce the computation time. To increase the efficiency, the decomposition of the DFT was optimized for real-valued signals, which is known as real DFT computation. As reported in a previous study [17], the average of CPU load was 25%, memory used was 5304 kB, and the computation time was 16.2 ms using obsolete laptop PCs (Pentium® 3, 1.0 GHz, 256 MB RAM). The output latency time was