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Determination of carotid disease with the application of STFT and CWT methods

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Abstract

In this study, Doppler signals were recorded from the output of carotid arteries of 40 subjects and transferred to a personal computer (PC) by using a 16-bit sound card. Doppler difference frequencies were recorded from each of the subjects, and then analyzed by using short-time Fourier transform (STFT) and the continuous wavelet transform (CWT) methods to obtain their sonograms. These sonograms were then used to determine the relationships of applied methods with medical conditions. The sonograms that were obtained by CWT method gave better results for spectral resolution than the STFT method. The sonograms of CWT method offer net envelope and better imaging, so that the measurement of blood flow and brain pressure can be made more accurately. Simultaneously, receiver operating characteristic (ROC) analysis has been conducted for this study and the estimation performance of the spectral resolution for the STFT and CTW has been obtained. The STFT has shown a 80.45% success for the spectral resolution while CTW has shown a 89.90% success.

Keywords: Doppler signal; Signal analysis; Carotid artery; Carotid disease; Sonogram; Short-time Fourier transform (STFT); The continuous wavelet transform (CWT); Receiver operating characteristic (ROC) curve

1. Introduction

In the last three decades, Doppler blood flow methods have been widely used in medical practice. As a result, both pulse wave and continuous wave Doppler devices have been commonly used. Both of these devices transmit ultrasonic waves into blood and receive some part of them which are reflected in red blood cells. There is a direct relationship between the flow velocity of the blood and Doppler difference frequency which is obtained after the demodulation of transmitted signal with reflected signal. Some spectral analysis methods were applied to the Doppler signal in order to obtain medical information by taking into consideration the relationship between the Doppler signal and the flow velocity of the blood. For this reason, the sonograms that show the change of Doppler spectrum with time were obtained [1,2].

Doppler ultrasonography is a reliable technique which demonstrates the flow characteristics of carotid arteries. Stenosis occurs in carotid arteries due to lipid molecules and therefore blood volume decreases. Owing to stenosis, systole and diastole peaks do not occur in perfect form. In this study, Doppler signals were obtained from carotid arteries of 40 subjects (23 of them were patients with carotid disease and 17 healthy individuals), and examined by taking into consideration formation of their sonograms. Short-time Fourier transform (STFT) and continuous wavelet transform (CWT) methods were used for spectral analysis of Doppler signals. The frequency resolutions of these methods and their relationship with clinical diagnosis were assessed.

2. Materials and method

2.1. Hardware

The block diagram of the measurement system is shown in Fig. 1. The system consists of five blocks. These are a linear

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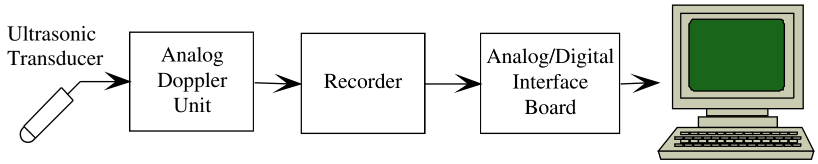

Fig. 1. Block diagram of measurement system.

multifrequency 5–11 MHz ultrasonic transducer, analog Doppler unit (Thosiba SSA-770A Aplio 80, Tokyo, Japan), recorder, analog/digital interface board (Sound Blaster Po-16 bit), and a personal computer with a printer [3]. The ultrasonic transducer was most often placed at a 30° angle toward the carotid arteries.

2.2. Spectral analysis of Doppler signal

Spectral analysis methods are widely used to investigate the information from Doppler blood flow signals. Spectral analysis methods examine Doppler signal against time. Transcranial Doppler signals obtained from the carotid artery are sampled and grouped in suitable frames. The most commonly used frame lengths are 64, 128, and 256. After the framing process, a power spectral density $P(f)$ of each frame can be calculated using STFT and CWT methods. These are combined to construct three-dimensional sonograms. The horizontal axis represents time (t) and the vertical axis represents frequency (f). The gray scale of the diagrams shows the power of the frequency component of the graph $P(f)$. As the gray scale turns into black, it means that the power of related frequency component is increasing, otherwise it is decreasing [4].

The frequency content of the signal will be determined from the sampling rate to be used, since the maximum frequency analyzed is half of the sampling frequency. Since the maximum frequency is not known in advance and depends upon the vessel on which the measurements are performed, it is useful to implement the system such that it is capable of operating at various sampling frequencies. The available sampling frequencies in the system are 2.56, 5.12, and 10.24 kHz while the expected transcranial Doppler frequencies change between 0.5 and 5 kHz even in stenoses.

In general, the Doppler signal is nonstationary. The signal may be assumed to be stationary for 10 ms or greater time periods if the flow is laminar and the velocity is not very high. However, this assumption is not valid for high-velocity turbulent flows such as vessel narrowing where the Doppler spectrum changes very rapidly. In this case, the frame length should be shortened to validate the above assumption. On the other hand, very short frame lengths may yield statistically poor spectral resolution. Therefore, selection of frame length is an important factor in Doppler spectral analysis. The frame length used in this work is 128.

The time-frequency representation of the signal associates with the time-varying velocity of blood flow and its variations. The STFT has been the commonly used method for generating time-frequency representations of Doppler blood flow signals [5,6]. This method requires that the signal being analyzed is stationary during a short time interval. By compromising between frequency resolution of the spectrum and the blood ejection rise time during systole, a 10 ms window is often used in practice. To increase the frequency resolution, a longer time interval is required. Consequently, the stationarity assumption may not be valid. Additionally, the spectral components occurring in a large interval will be smeared in the time domain, resulting in a decreased resolution in time. The Choi–Williams distribution, the reduced interface distribution, and the Bessel distribution were tested for analysis of the Doppler blood flow signal of the femoral artery. It had been proved that the Bessel distribution is the best among these techniques for Doppler signal analysis [7].

2.3. The short-time Fourier transform

After the signal is passed through a frame described in the time domain, the Fourier transform is performed. The frame function is transmitted in time axis to include all signals, and frequency responses (frequency spectrum) in time intervals of frame function width of the signal are obtained. This way, the frequency response change of the signal with time is obtained [8].

Consider a signal $x(t)$, and assume it is stationary when seen through a window $w(t)$, whose duration is T, centered at time location τ; the Fourier transform of the windowed signal $x(t)w(t-\tau)$ is the STFT

$$X_\tau(f) = \int_{-T/2}^{T/2} x(t)w(t-\tau)\mathrm{e}^{-\mathrm{j}2\pi f t}\,\mathrm{d}t. \tag{1}$$

STFT maps the signal from time domain into a joint time-frequency plane (t, f) (Fig. 2).

STFT gains significance if the signal is not stationary. In this case, the signal is divided into stationary segments and FT of each segment is alike (or similar) and STFT and FT become alike (or similar). The stable width of the frame function used in short term Fourier transfer during scanning causes the signal to be localized precisely in time domain of fast changing high frequency changes. This case happens particularly in severe insufficiency and stenosis of the veins. The solution to this problem is the usage of wide frame functions to capture the slow changes in Doppler signals, whereas, where fast changes are seen, narrow frame functions are considered and consequently wave transfer analysis has come up instead of constant width frames [9].