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Skin temperature variations as a tracer of microvessel tone

Peter Frick*, Irina Mizeva, Sergey Podtaev

Institute of Continuous Media Mechanics, Korolyov 1, Perm 614013, Russia

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ABSTRACT

The problem of frequency-by-frequency cross-correlation detection is studied using two characteristics of blood microcirculation: blood flow and skin temperature. Skin blood flow variations are measured by Laser Doppler Flowmetry (LDF) and Skin Temperature (ST) – by a high-resolution (0.001 K) temperature recorder. The wavelet cross-correlation (WCC) is compared with Fourier coherence and demonstrates certain advantages for the frequency-by-frequency analysis of biomedical nonstationary signals. The WCC analysis of the LDF and ST signals performed for 17 healthy subjects reveales a high correlation in the low-frequency range $0.01 < \nu < 0.1$ Hz. The WCC function provides the phase difference between the oscillations of LDF and ST signals. This phase shift is used to estimate the effective depth of temperature wave generation. Taking into account the decay rate of temperature oscillations at each frequency and the LDF-ST phase shift, we perform an inverse wavelet transform for the frequency band that corresponds to active mechanisms of vascular tone regulation. This technique allows us to recover the filtered ST signal from the LDF signal and vice-versa. It is shown that the ST pulsations mirror the functional state of the microcirculation system and the ST monitoring can be used for microvessels tone control within the frequency ranges corresponding to endothelial, neurogenic and myogenic activities.

1. Introduction

Skin vasomotion is cross-sectional rhythmic oscillations of the microvessels responsible for skin microcirculatory blood flow. Experimental and clinical findings confirm that vasomotion is dependent on various physiological mechanisms, which cause pulsations in different frequency ranges [1]. Skin blood flow oscillations, with frequency intervals of 0.6–1.6 Hz and 0.2–0.6 Hz are respectively associated with heart and respiratory activities. It has been suggested that skin blood flow oscillations with the most interesting frequency interval of 0.009–0.1 Hz are connected with myogenic, neurogenic and endothelial activities [2]. A spectral decomposition is required to distinguish the contributions of different physiological mechanisms. However, the experimental data from biological organisms are "living in time". This creates barriers to keep the properties of the examined system constant and leads to the nonstationarity and poor repeatability of the experimental results. In addition, biomedical time series are mainly short and noisy.

The energy distribution over frequencies is given by the power spectral density (p.s.d.), which is correctly defined in classical Fourier analysis for periodic or decaying signals. The Wiener–Khinchin theorem establishes the p.s.d. for a chaotic but *stationary* signal [3]. The signals under discussion are neither periodic nor stationary. The wavelet transform introduced in the late 1980s [4] is a way to analyze the nonstationary signals. The wavelet transform uses some self-similar functions localized in both physical and Fourier spaces instead of harmonic functions (see i.e. [5]). Wavelets are known as an effective tool for p.s.d. estimation, especially for nonstationary, short and noisy data. Of special interest for the studies under discussion is wavelet cross-correlation (WCC) analysis, which is used to recognize the frequency-by-frequency (or scale-by-scale) mutual correlation of two signals. The WCC method has been developed for analyzing astrophysical data, which have common features with biological data, namely, they are rather limited and noisy and are derived from the complicated non-linear systems [6,7]. It should be noted that the results of the wavelet analysis need accurate interpretation, because the wavelet transform is based on the decomposition on functions with their own spectral portrait, and this influences the results obtained. The purpose of this study is to clarify the interrelation between the wavelet and Fourier cross-correlation analyzes and to reveal the advantages of the WCC and its applicability to the analysis of microcirculation variability.

Different non-invasive methods are applied to examine "in vivo" blood microcirculation [8]. The most common technique is Laser Doppler Flowmetry (LDF) [9,10], where laser light is utilized to measure the blood flux in the area covered by a laser probe. The

* Corresponding author. Tel.: +7 3422378322; fax: +7 3422378487.
E-mail address: frick@icmm.ru (P. Frick).

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spectral analysis of LDF signal has been performed using the fast Fourier transform [1], and wavelets were suggested to reproduce better the low-frequency range of LDF spectra [2,11]. Recently, high-resolution skin thermometry has been applied as an alternative indicator of the microcirculation functional state [12]. This technique is very attractive because it is cheap and easy to operate, although the use of temperature monitoring in vasomotion studies is not obvious.

Both LDF and Skin Temperature (ST) oscillations indirectly mirror somewhat blood flow oscillations. Wavelets were used in [13,14] to show the compatibility of both methods at low frequencies (below the respiratory frequency). The relationship between the blood flow and ST during vasoconstriction and vasodilation provoked by skin local cooling or heating has been studied in [15] and analyzed in terms of the wavelet-based time-localized phase coherence [16]. Measurements carried out on the volar side of the arm [13,15] or on the palm surface of the distal phalanx of the finger [14,17] and, irrespective of certain anatomical features (high arteriolovenular anastomosis content in the distal parts of limbs), gave similar results. Despite the terminological differences (wavelet cross-correlation [14] or wavelet phase coherence [13,16]), these studies employed the same mathematical technique, which is based on wavelet decomposition providing a complex characteristic for two signals relationship.

In this paper we compare the low-frequency pulsations of LDF and ST data series, collected simultaneously from distal phalanges of second and third fingers of 17 healthy volunteers. The significance of the correlation is estimated using surrogate data that has the same p.s.d. and the randomized phase [18]. Skin surface temperature oscillations are caused by blood flow pulsations in microvessels. Knowing the decay rate of temperature oscillations and the LDF-ST phase shift for each frequency, we can recover the blood flow pulsations using the ST series. A similar problem was considered in [19], where the photoplethysmography-measured blood flow was compared with the temperature field obtained with the infrared camera. However, application of photoplethyzmography to determine the functional state of the microcirculation is under discussion [20], while LDF is the most common technique. It is important to study whether blood flow variations measured by LDF can be recovered from temperature signals, especially in the frequency band of interest. The previous studies of the relations between the ST and LDF oscillations ignored the skin temperature and optical signal phase shift for various vascular tone regulatory components. We will show below that the ST variations can be recovered from the LDF signal and vice-versa.

The paper is organized as follows. In Section 2 we describe the subjects and the measurement procedure, in Section 3 we give the mathematical background, showing the relation of the corresponding formulae in terms of Fourier and wavelet decompositions, and introduce the algorithms. Section 4 includes the experimental results and statistics obtained for all subjects. In Section 5 we estimate the effective depth of temperature wave production and recover the ST variations from the LDF signal. Section 6 summarizes our study.

2. Subjects and measurement procedure

The simultaneous LDF and ST measurements were carried out for 17 healthy volunteers (7 male and 10 female) under controlled environmental (temperature 24 °C and humidity 50%) conditions. The mean age of the subjects was 35 ± 5. The subjects were sitting in a relaxed position. They were not permitted to drink coffee, and there were no smokers or ex-smokers in the group. All subjects gave their informed consent.

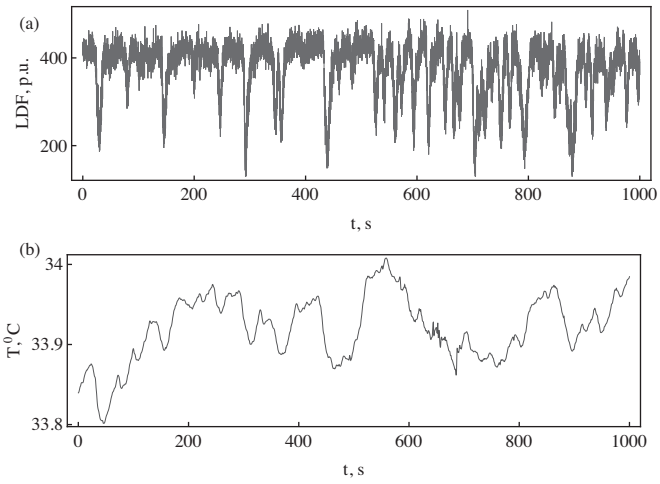

Fig. 1. Example of LDF (upper panel) and ST (lower panel) data series.

LDF was measured using a laser Doppler monitor (Moor Instruments FloLAB Server, UK, VP-1 probe) with a near-infrared laser (wavelength 780 nm) and probe optical surface, attached to the tissue pulp of the index finger. The probe design minimized interference from external light sources. A bandwidth of 22 kHz was used, providing wide band measurement of red blood cell velocities, with easily discernible vasoconstrictor responses, and minimal damping of the pulsatile component of the LDF trace. LDF was measured in arbitrary perfusion units ($p.u.$). The sampling frequency was 40 Hz.

The temperature measurements were performed with a Microtest (FM Diagnostics, Russia) designed for recording temperature with a resolution 0.001 K and sampling frequency 20 Hz. An independent probe was used to control the environmental temperature.

Both probes (LDF and ST) were attached to the skin surface of the distal phalanx of the second (LDF) and third (ST) fingers with double-sided adhesive discs, which avoided the disturbance of the blood supply of the skin that would arise with a clamp.

All the subjects had 10 min acclimatization period in the lab, and the duration of signal collecting was 20 min. For the data analysis we preprocessed the data: resampled both data streams for the sampling frequency of 10 Hz (taking points in corresponding time without averaging) and removed the linear trend from the ST data (calculating linear fit for the original data), which occurred for some measurements in spite of the rather long adaptation period before the temperature series were taken.

3. Fourier and wavelet cross-correlation

To illustrate the methodology of the frequency-by-frequency cross-correlation analysis, we use the typical data series of LDF and ST shown in Fig. 1. A cross-spectral analysis is required to estimate a correlation measure of the variations in different frequency bands.

For a signal $x(t)$ the energy distribution of oscillations over the frequency range is given by the p.s.d. $F_{xx}(\nu)$, which for a chaotic (but statistically stationary) signal is defined through the Fourier transform of the autocorrelation function $R_{xx}(\tau)$ [21]

$$R_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T (x(t) - \overline{x})(x(t+\tau) - \overline{x}) dt, \quad (1)$$

$$F_{xx} = \int_0^T R_{xx}(\tau) e^{-2\pi i \nu \tau} d\tau, \quad (2)$$