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SPIE.

Event: European Conferences on Biomedical Optics, 2023, Munich, Germany

Wavelet analysis of laser speckle contrast reveals new feature space for transcranial assessment of cerebral blood flow

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ABSTRACT

This work shows the application of LSCI for mapping the cerebral vessels of a laboratory animal, and also presents the time-frequency processing of the registered signal. Thus, we expand the capabilities of the existing LSCI approach and demonstrate spatial mapping of blood flow fluctuations.

Keywords: laser speckle contrast imaging, cerebral blood flow fluctuations, wavelet transform.

1. INTRODUCTION

Recently, laser speckle contrast imaging (LSCI) has been widely used to image blood flow in biological tissues. The ability to map blood flow makes the technique applicable in the studies of blood microcirculation in various medical and scientific cases.[1,2] LSCI technology has been extensively applied to visualize regional cerebral blood flow.[3–5] This method provides a stack of images (perfusion maps) representing the temporal evolution of blood flow. This provides the possibility of performing a time-frequency analysis of the acquired signal in areas of interest.[6–8] In this work, we present the results of time-frequency analysis of laser speckle contrast recording on the laboratory rat brain, produced using a new method of LSCI data processing and representation.

2. MATERIAL AND METHODS

In the experiment, a one-month-old Wistar rat (male) with an initial body weight of 200 g was used. The experimental studies were carried out in accordance with the principles of GLP. The work was approved by the Ethics Committee of Orel State University (protocol No.12 dated 6 September 2018). The study protocol included animal anesthesia by intramuscular injection of Zoletil/Xyla drug composition in standard proportions and dosages. The animals were placed on a heated table (37 °C) to maintain stable body temperature. After that, the animal was fixed in a 3D printed stereotaxis to avoid movement artifacts. To access the study area (cerebral), the skin was cut and removed from the head of the animal. The animal's skull was not removed and therefore a noninvasive transcranial cerebral imaging was performed. The physiological parameters of the animal were controlled by the special monitoring system (Rodent Surgical Monitor+, Indus Instruments, USA). Images were captured transcranially for 5 minutes.

Experimental studies were carried out using a specially developed LSCI experimental setup. The rat brain was illuminated with the LDM785 laser source (Thorlabs, USA) with a light power of 20 mW and a wavelength of 785 nm through the set of diffusers. The backscattered light was collected via a high-resolution UI-3360CP-NIR-GL CMOS camera (IDS, USA). NIR linear polarizer was placed in front of the MVL25TM23 camera objective (Thorlabs, USA). The images were obtained for 90 FPS and 11 ms exposure time for all experiments.

Raw speckle images were processed using an original algorithm. The average speckle contrast was calculated as follows:

$$K = \frac{\sigma}{\langle I \rangle}, \tag{1}$$

where $\langle I \rangle$ is the mean intensity value and σ is the intensity standard deviation.

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Translational Biophotonics: Diagnostics and Therapeutics III, edited by Zhiwei Huang, Lothar D. Lilge, Proc. of SPIE Vol. 12627, 1262711
© 2023 SPIE · 0277-786X · doi: 10.1117/12.2667818

To visualize the vessels in a better quality, raw speckle images were processed with a number of frames for a temporal averaging equal to 90. Thus, the data was averaged over one second of recording. After temporal averaging, we additionally applied a spatial algorithm with a window equal to 7. For frequency analysis, we used time averaging over 4 frames and spatial averaging with a window of 7.

The time-frequency analysis of the obtained perfusion value was performed by the continuous wavelet transform (CWT).[9] To study the dynamics of cerebral blood flow in various parts of the brain, three regions of interest (ROIs, 12×12 pixels) were selected: the superior sagittal sinus, its tributaries, and brain areas that have no clearly visualized vessels. The data inside these ROIs were used for wavelet decomposition. In addition, pixel-by-pixel wavelet analysis was used for a detailed study of the spatial frequency distribution.

3. RESULTS AND DISCUSSION

Fig. 1 shows images of the rat brain obtained on the camera in initial monochrome mode, as well as the speckle contrast image.

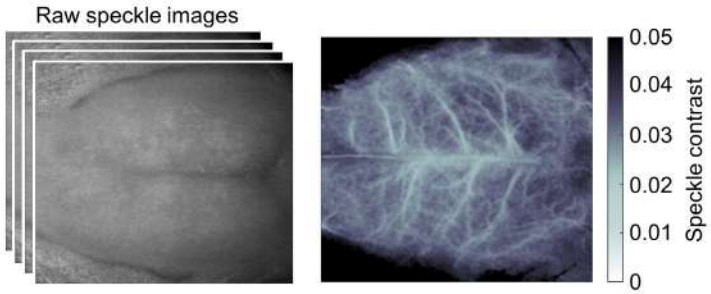

Figure 1. Raw speckle and processed images of the rat brain obtained transcranially.

Fig. 2 shows the results of the wavelet analysis of obtained perfusion in each ROIs. In the data for all regions, there were more or less pronounced (depending on the region) amplitudes of oscillations (fluctuations) caused by vasomotions (0.11–0.13 Hz), respiratory activity (1.3 Hz), and heart beats (6.3–6.7 Hz). The frequency localization of the cardiac and respiratory peaks was confirmed using data recorded by a rodent surgical monitor. The animal had 386 heart beats per minute (approximately 6.44 Hz) and 73 breaths per minute (approximately 1.22 Hz) on average. Fig. 2 also illustrates the fact that LSCI is sensitive to blood flow not only in visible superficial vessels, but also in tissue regions that lack the spatial resolution of the method. The presence of oscillations in such regions suggests that the dynamic characteristics of the speckle contrast contain information on the blood flow of the underlying microvessels.

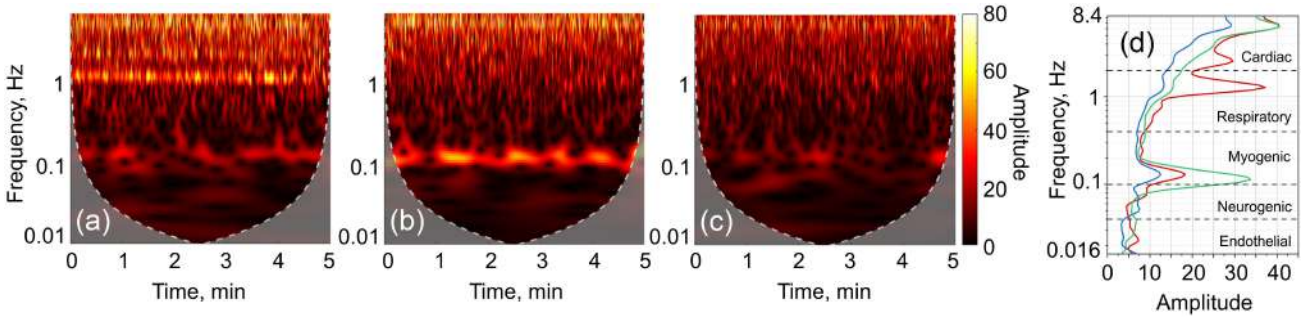

Figure 2. Wavelet analysis of obtained perfusion values: (a) CWT amplitude scalogram for the superior sagittal sinus (red line in d), (b) tributary (green line in d), and (c) brain tissue that does not have clearly visualized vessels (blue line in d); (d) time-averaged spectra for data obtained in the aforementioned ROIs.

Next, we performed a pixel-by-pixel wavelet analysis of perfusion and obtained oscillation distribution maps for the three dominant components (Fig. 3). A high amplitude of cardiac oscillations is observed fairly evenly in

large vessels over the entire surface of the rat brain. As expected, according to the mean time-averaged spectra calculated above, respiratory oscillations have a pronounced amplitude only in the central vessel, and myogenic oscillations are most pronounced in peripheral vessels of small diameter.

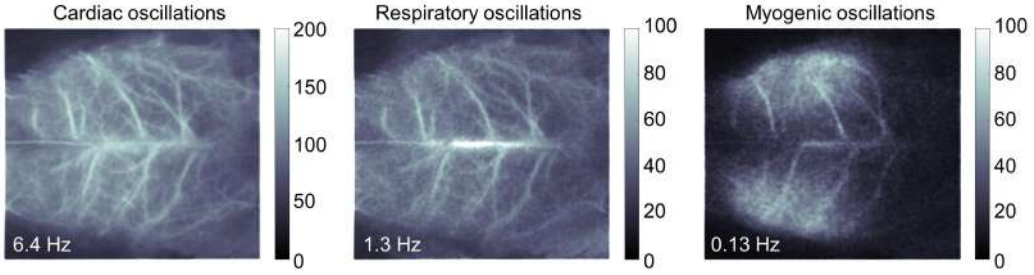

Figure 3. Spatial variations in cardiac (6.4 Hz), respiratory (1.3 Hz), and myogenic (0.13 Hz) activity.

4. CONCLUSION

In this paper we presented the results of time-frequency analysis of laser speckle contrast recording on the laboratory rat brain. The proposed technology makes it possible not only to measure the relative cerebral blood flow of the cerebral cortex, but also to expand diagnostic capabilities for detailed analysis of the physiological mechanisms of changes in cerebral blood flow. To the best of our knowledge, this is a new approach in the processing of speckle patterns.

ACKNOWLEDGMENTS

The study was supported by the Russian Science Foundation under the project No. 22-75-10088.

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