Real-Time Mapping of Blood Perfusion during Neurosurgical Interventions

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Abstract:
Laser speckle contrast imaging (LSCI) in neurosurgery is a promising method for vascular blood flow mapping during surgery for aneurysms and other interventions. In order to introduce this method into routine practice, it is necessary to solve the urgent issue of its conjugation with the normal surgical algorithm and the extent to which the method allows detecting changes in perfusion in the vessels during various interventions. In this work, blood flow through the carotid arteries of laboratory rats was analyzed supported by two types of light collection: camera lens and neurosurgical microscope. Carotid arteries were chosen for the study because of ease of access and close dimensional characteristics to typical human cerebral arteries. Carotid artery clipping was chosen as the procedure that changes the level of blood flow. The registered map sequences were evaluated in terms of differences in blood flow during the clipping period and during control measurements. The results showed that when working with the LSCI-neurosurgical microscope setup, the calculated ratio was significantly lower than when working through the camera lens.

Keywords: laser speckle contrast imaging, cerebral neurosurgery, intraoperative blood perfusion monitoring, blood vessel clipping, signal processing

I. Introduction

The study of blood perfusion using noninvasive diagnostic methods is an actively developing field research. Today they are widely used for tasks in the assessment of microcirculation of cutaneous blood flow [1], 1 aparoscopic interventions [2], open surgery [3].
Neurosurgical, and even more vascular neurosurgical operations, are associated with the continuous need to control blood flow [4]. This is necessary both to exclude stenosis and occlusion of vessels, and to assess the completeness of aneurysm exclusion during clamping. It is relevant to both vascular neurosurgery and central nervous system tumour surgery. During such surgeries, information about the functional significance of a vessel can influence intraoperative tactics. It is worth noting that there is a high demand for these technologies. According to the report the Russian Ministry of Health, 188.251 neurosurgical operations were

performed in the Russian Federation in 2020: 7031 were performed for brain aneurysms, 1506 for arteriovenous malformations, 583 for cavernous angiomas, 4548 for hypertensive hematomas, 31232 operations were performed on central nervous system tumors. At the same time there is an annual trend of increase in the number of such surgical interventions. The availability of continuous information on blood flow and tissue perfusion is an important factor that can improve surgical outcomes.

Currently, various methods such as contact Doppler ultrasonography (DU), indocyanine green angiography (IGA), digital subtraction angiography (DSA) are used for intraoperative blood flow control. However, these methods have a number of limitations. DSA and IGA are comparatively expensive and invasive. For DU, it is impossible to assess blood flow in the smallest vessels. In addition, there is a need to place a thin probe close to the vessel. A similar problem occurs using laser Doppler flowmetry for intraoperative assessment of blood perfusion in vessels [5]. In addition, all these methods do not allow evaluating blood flow parameters continuously and at any moment of surgical intervention. The promising option would be a technique that can easily connect to a neurosurgical microscope and show the proper demonstration of blood flow presence/absence in the area of interest during surgical procedure by necessity of surgical team. Such a method is laser speckle contrast imaging (LSCI) which has improved technical and methodological support in past decades [6]–[8] in case of tumors [9], lymph vessels visualization [10] and transcranial blood perfusion mapping [11]. This method is capable of providing real-time blood flow mapping for a wide field of view for cerebrovascular neurosurgical cases [12].

The theoretical concept of the method is based on registering changes in random fluctuations of scattered light for media characterized by static and dynamic scattering [13]. Registered images blur more significantly at the area with intensive flow than with static scatters or with less intensive flow and depend on speckle size, camera pixel size, inhomogeneities geometry, light source characteristics and so on. Besides, relationship between real blood perfusion and the recorded signal is nonlinear [14], making quantitative interpretation of the recorded signal difficult. Registered blurring pattern is described by speckle contrast parameter, K. To date, methods of calculating the single-exposure K parameter have been divided into temporal, spatial and spatio-temporal approaches, characterised by different applications and resolution. For blood flow imaging tasks in real time, high temporal resolution and low signal processing complexity are required.

II. Problem Statement

According to the abovementioned findings, the main task of translating the LSCI technique into the practice of neurosurgery is to clearly distinguish a perfused vessel from a nonperfused one, with the capability to assess gradations of blood perfusion. It is particularly crucial to solve the issue of real-time signal processing and demonstrate the result during the operation.

This work shows the results of recording blood flow changes during arterial clamping for camera lens and microscope setups, with an assessment of the differences recorded.

III. Materials and Methods

Two types of setup were used in this work: a scientific camera with a camera lens (Fig. 1A) and a system combined with a surgical microscope (Fig. 1B). In both cases a CS505MU monochrome camera (Thorlabs Inc., USA) with a 2448×2048 sensor size and a laser diode with a central wavelength of 802 nm and 150 m W output power. The camera exposure time was 10 milliseconds for all experiments. In both cases an ED1C20 engineering diffuser (Thorlabs Inc., USA) was installed in front of the laser diode to provide suitable light scattering. A band-pass optical filter FB800-1 0 (Thorlabs Inc., USA) with a central wavelength of 800 nm and a bandwidth of 10 nm was used to eliminate external illumination. This band is not emitted by the built-in light source of the surgical microscope.

The MVL50M23 camera lens (Thorlabs Inc., USA) was used in common LSCI system developed. To get rid of glare, a linear polarization filter was mounted in front of the lens in addition to a band-pass filter. The laser and diffuser were placed on the side of the camera (Fig. 2A).

In order to combine the LSCI system with the surgical microscope, the camera was mounted in the side port via dedicated adapter (Fig. 2B). A band-pass optical filter was also placed inside the adapter. In the system combined with the microscope, no polarisation filter was used due to too strong attenuation of light in the microscope channel. The laser diode was placed in the lower part of the microscope, near the entrance pupil, by means of a 3D printed holder, which also included a diffuser. The holder provided the ability to adjust the angle of illumination of the laser to the position of the microscope focus to ensure an evenly spaced field of view.

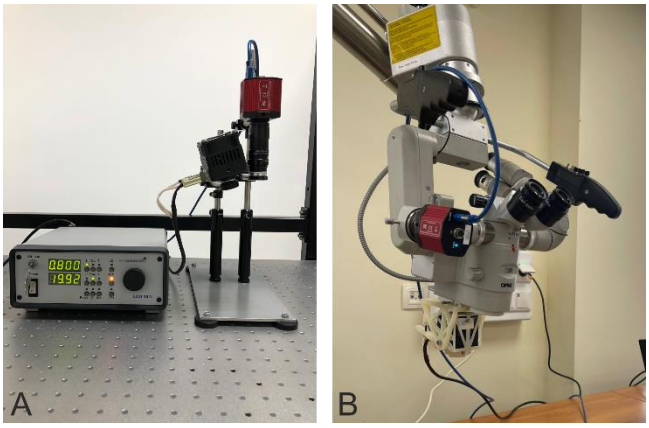

Fig. 1. Exterior view of the used setups for laser speckle contrast imaging. A - setup with camera lens; b - setup with microscope.

The animal study protocol was reviewed and approved by the Local Ethics Committee of Sechenov University on June 25, 2022 (protocol no. 26). The 2-month-old Wistar rats underwent general anesthesia with a combination of the drugs tiletamine/zolazepam (Zoletil 100, Vibrac, France) 20 mg/kg+ xylazine (Xyla, Interchemie, The Netherlands) 5 mg/kg intraperitoneally. In both cases, wide surgical access on the neck to the common carotid arteries (CCCs) was performed. To enhance contrast, a layer of static scatters was placed under CCC for better visualization of the area of interest. The clipping process was performed with vascular clips. Schemes of the setup for the described experiment are shown in Fig. 2.

As described early the blood perfusion-dependent parameter is calculated according to basic statistical characteristics [15]:

$$K = \sigma/\langle I \rangle, \quad (1)$$

where σ is the standard deviation of pixel intensity and $\langle I \rangle$ is the mean pixel intensity for a certain square block of pixels. In other words, this parameter shows how strong the intensity fluctuations are in comparison to the average intensity [16]. The whole perfusion map of the K-value was calculated by convolution of all image pixels intensities with a sliding 7×7 window. In further processing, areas of interest in 40×40 pixels were chosen on the surface of both CCCs for clamping/nonclamping effect visualization. In the next step, the mean perfusion index was calculated for all image sequences in a certain time intervals.

All manipulations of the surgeon were recorded in real-time with custom-designed software. This software provides the ability to control camera properties through the data interface, record images, and recalculate pixel intensity into blood perfusion maps. The processing speed for obtaining K values was increased by optimized algorithm for the graphical processing unit. During the intervention, the surgeon could look at the monitor with the provided visualization of blood perfusion at any time.

IV. Results

During neurosurgical interventions for vascular pathologies, the problem arises of recording the necessary information against the background of the noise signal using LSCI technique [17], [18]. The area of interest should be visually distinguishable from the surrounding cortical areas perfused with blood. It is well known that any LSCI technique is sensitive to motion artifacts that have to be eliminated by stereotaxic device and/or algorithmically. In addition, the outer regions may have a closer amplitude in LSCI units than in the area of interest.

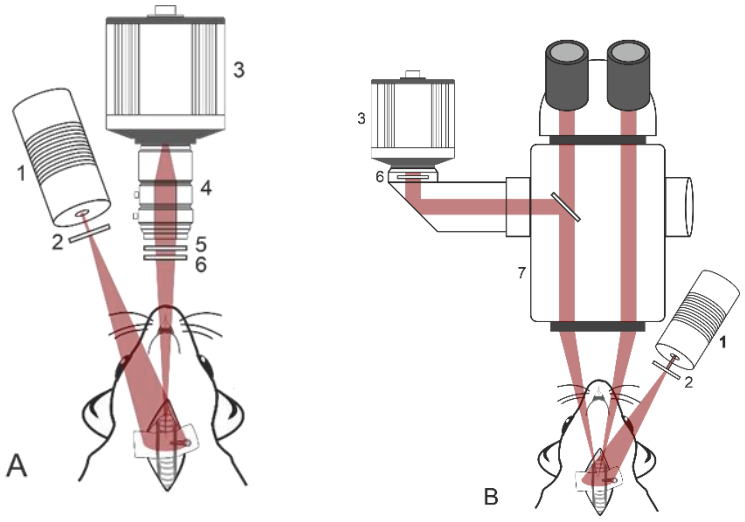

Fig. 2. Simplified graphical schemes of experimental setups: a) - with camera lens; b) with microscope. 1 -laser diode, 2 - diffuser, 3 - camera, 4 - camera lens, 5 - polarizer, 6 - optical bandpass filter, 7 - neurosurgical microscope.

Thus, the main challenge is to clearly visualize blood flow in the area of interest on the surgical monitor screen in pseudocolors, contrasting gradations of blood flow and its absence.

In this report we analyzed the ability of developed setups to recognize the presence/absence of blood flow in vessels. An example of pseudocolored mapping of clamped and nonclamped CCC is shown in Fig. 3.

The results showed (Table I) that the ability of the LSCI method to contrast the absence of blood flow when working with a microscope is significantly reduced compared to working through a camera lens.

This effect may be due to the attenuation of light in the optical channel under conditions in which it is impossible to increase the intensity of radiation due to the danger of damage to biological tissue during surgical interventions. There are also differences in the aperture and optical magnification between the two setups. In connection with the results obtained, the potential to switch to a real-time speckle contrast imaging method as an exoscope is being considered.

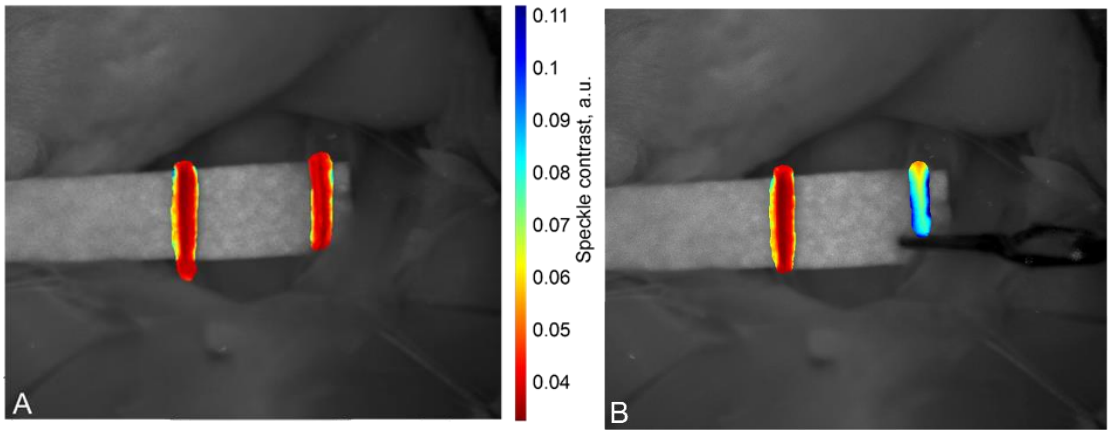

Fig. 3. Example of received images with clamped common carotid arteries (b) and nonclamped (a). The colorbar denotes pseudocolored perfusion map in speckle contrast units.

Table I. Result of experiment

Experiments	Mean perfusion in clamped area, a.u.	Mean perfusion in clamped area, a.u	Ratio
Arterial clipping with camera lens	0.038±0.0003	0.077±0.013	2.08
Arterial clipping with microscope	0.051±0.001	0.071±0.008	1.39

V. Conclusion

Further work will be related to improving the signal-to-noise ratio, processing algorithms and optical scheme. The main aim of the study is to provide the surgeon with a convenient way to distinguish vessels by the presence/absence of blood perfusion with real-time LSCI. In addition to animal studies, further research of this project will lie in the development of microfluidic phantoms that mimic the mechanical and optical properties of the small arteries of the brain.

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