Laser Speckle Contrast Imaging for Intraoperative Monitoring of Cerebral Blood Flow

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Abstract. Intraoperative monitoring of cerebral blood flow provides an important information required for clinicians to select optimal tactics during the neurosurgery procedures, including clipping cerebral vessel aneurysms, bypass, and arteriovenous malformation surgery. Presently, robust cost-effective noninvasive optical imaging techniques suitable to assess cerebral blood flow in the operating room do not exist. In current study we report a development of prototype of the Laser Speckle Contrast Imaging (LSCI) system as a complementary tool for non-invasive real-time visualization and quantitative assessment of cerebral blood flow during neurovascular surgery. The LSCI is based on the scattering of coherent laser light within dynamic tur- bid medium, such as biological tissues, including brain. The speckle patterns appeared due to interference of partial components of the dynamically scattered light are recorded by digital camera. To observe blood flow in large and small vessels as well as in the microcirculatory bed of the cerebral cortex the recorded images are quantitatively analyzed utilizing low-order statistical moment, known as imaging contrast or enhancement of visibility. The purpose of current pilot study is to assess general feasibility of the LSCI approach in terms technical abilities of image acquisition, its quality evaluation and further implication to day-to-day clinical practice.

Keywords: laser speckle contrast imaging, blood flow visualization, brain, carotid artery ligating

Introduction

The normal functioning of cerebral blood flow and in particular, microcirculation, is crucial for human mental functions and the maintenance of all the vital functions of the organism. Normal blood supply is threatened by various pathological statements, resulting in low life quality, loss of motor and sensory functions and even death. These include malignant tumors, aneurysms, hemorrhages, ischemic stroke, and other neurological disorders. Neurosurgeon requires continued control of cerebral blood flow in microsurgical manipulations. Assessment of blood flow and patency of the cerebral vessels seriously effects on the success of the surgical treatment. Currently, a series of methods mostly based on Doppler or contrast visualization are used for intraoperative cerebral blood flow monitoring, including indocyanine green angiography [1, 2], Doppler ultrasound [3], laser Doppler flowmetry [4] and intraoperative percutaneous transfemoral digital subtraction angiography [5]. All these methods have notable limitations. In this regard, developing a new diagnostic approach to per- form noninvasive control of cerebral blood flow in neurosurgical operation without the contrast medium injection and introduction of measuring probes into the operating field remains relevant.

Laser speckle contrast imaging is a promising method of blood flow imaging in neurosurgery [6, 7]. LSCI is an inexpensive relatively easy-to-implement method, which allows obtaining real-time maps of perfusion distribution in a wide field of view on the surface of biological tissue. This method is based on the analysis of speckle patterns utilizing low-order statistical moment, known as imaging contrast or enhancement of visibility. Speckle is a random interference pattern arising from backscattering of coherent laser radiation on surface roughness or scattering particles inside the object under its surface. The movements of the object itself or the scattering particles inside the object, which in biological tissues are red blood cells, cause fluctuations of the speckle pattern. Registration of these fluctuations with a finite exposure time greater or equal to the speckle decorrelation time τ_c leads to blurring of the speckle pattern, i.e., to reduction of its contrast [8]. The flow rate is assumed to be inversely proportional to the decorrelation time [9].

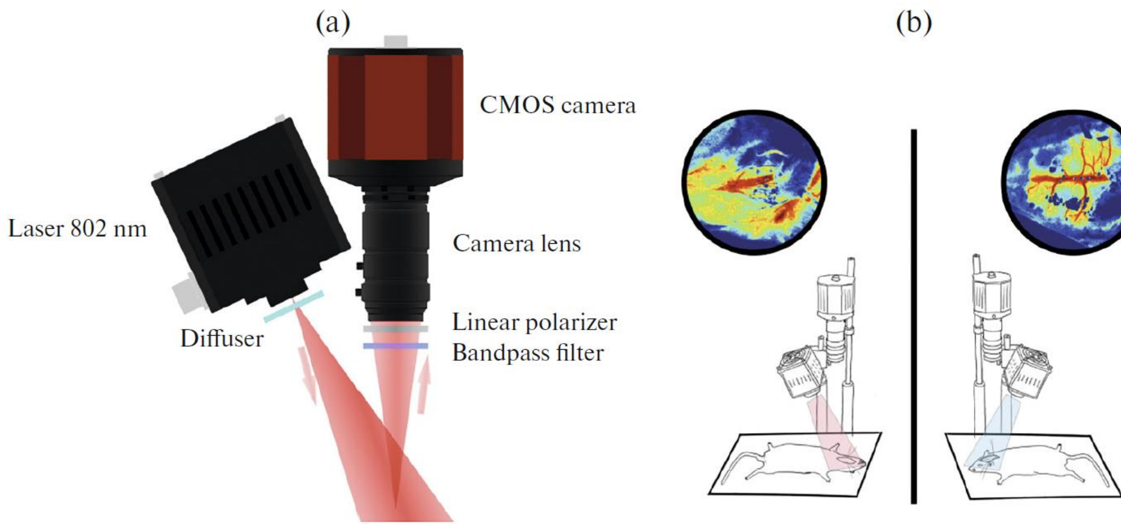

Fig. 1. Schematic presentation of the developed prototype of LSCI experimental system (a), and two types of the performed experiments (b): neck region operational access and determination of carotid artery perfusion (left), and observation of craniotomy and cerebral surface perfusion (right).

In this work, a prototype of the LSCI system is developed to provide the real-time monitoring of blood flow in a rat experimental model. The cortical perfusion and common carotid artery (CCA) patency is observed during the vascular occlusion experiment.

Experimental

To test the sensitivity of LSCI to flow velocity changes, two experimental in vivo approaches were introduced external and intraluminal bilateral vascular occlusion followed by an intracranial blood flow visualization. The animal study protocol was reviewed and approved by Local Ethic Committee of Sechenov University on June 25, 2022 (protocol no. 26). The surgical protocol included two experiments: carotid artery patency via neck region operational access and cerebral cortex surface perfusion measurement (Fig. 1). The carotid artery blood supply changes were simulated in 2 months old laboratory Wistar male rats ($n = 3$) weighed 220-250 g. The animals are anesthetized with an isoflurane-based inhalation system (AWD Technology, USA) to provide surgical access to the common carotid artery and record the vessel's per- fusion patterns using LSCI system prototype. The experiment of blood flow measurements included the simulation of local occlusion of the external carotid artery by ligation, and then the common carotid artery is clamped by the vessel's clip. To visualize blood flow through intracranial vessels, the anesthetized animal is fixed in a stereotaxic system. Operational access to the brain arteries was carried out by drilling a window in the roof of the skull and subsequent removing of osteal debris with a bone cutter. All the aforementioned vascular manipulations are accompanied by the registration of the LSCI images 5-7 min before and immediately after the common carotid artery occlusion.

For performing the experiments, a developed LSCI setup prototype is used (see Fig. 1). This system included a CS505MU monochrome camera (Thorlabs, USA) with an MVL50M23 camera lens (Thorlabs, USA) and an 802 nm laser diode. The camera exposure time in all experiments is 5 ms. The laser radiation is scattered using an ED1-C20 engineered diffuser (Thorlabs, USA). A film polarizer is installed in front of the camera to cut off the radiation mirrored from the object's surface because it does not carry information about the motion of red blood cells [10]. Also, FB800-10 bandpass filter (Thorlabs, USA) is installed in front of the camera to reduce the influence of background lighting.

Speckle contrast is defined as the ratio of the standard deviation of the intensity of neighboring pixels to the average intensity: $K = \sigma/\langle I \rangle$, where σ is the standard deviation of the intensity, $\langle I \rangle$ is the average intensity. In this work, the speckle contrast is calculated with a 7 × 7 pixel moving window using the algorithm developed in Matlab (MathWorks, USA).

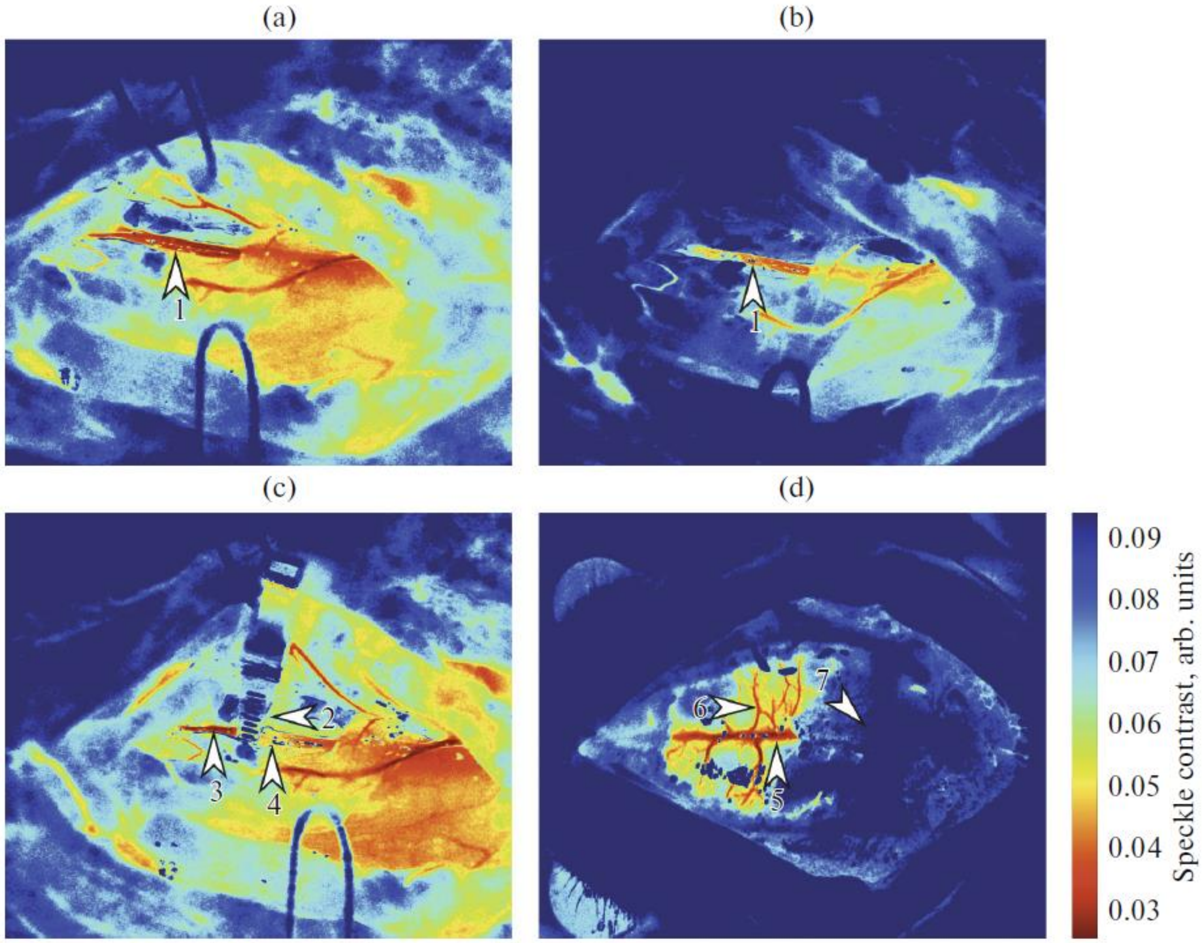

Fig. 2. Examples of speckle images in first (a, b, c) and second experiments (d). The common carotid artery (1) is clearly visualized prior all further manipulations (a). A significant decrease in blood flow in the vessels branch observed (4) after a ligation of the external carotid artery (c). The common carotid artery blood flow (c) is observed after the clamping (4) and its stop after the clamp (2), with preservation of blood flow before the clamp (3). In conducting experiments on the brain (d), the superior sagittal sinus (5) and its tributaries (6) is clearly discernible, but there is no blood flow images through the cranial bone (7).

Results

For the first experiment, the common carotid artery is dissected via the anterior midline neck approach. The sternocleidomastoid muscle was lateralized with hooks. A wide dissection of the common carotid was performed. The patency of the carotid artery is confirmed by LSCI (Fig. 2a) and by visual pulsation, before occlusion. The occlusion of CCA was performed with the vessel's clip on the trunk of CCA. Experiments on carotid artery occlusion in rats demonstrated the sensitivity of LSCI and its applicability for blood vessel visualization during the surgical procedure. Thus, after ligation of the external carotid artery (see Fig. 2b), the average perfusion in the common carotid artery decreased by 50% compared with the baseline stage. After clamping the common carotid artery by vessel's clip (see Fig. 2c), blood flow in the section after clamping is completely stopped. At the same time, the blood flow in the place before the clamp returned to its baseline level. The fact that blood flow persists in the carotid artery after ligation may be related to retrograde blood flow from the vessels of the circle of Willis. The LSCI images is improved by threshold setup the of pseudocolor scale (see Fig. 2). It is chosen the same threshold for all carotid artery images so that it could be visualized as clear as possible against the surrounding tissues. To reduce noise, all LSCI images are averaged over 20 consecutive frames.

The second experiment on cerebral cortex perfusion was performed via craniotomy. The cerebral sur- face of both hemispheres is visualized. Blood flow through the cerebral vessels is clearly discernible through a window in the roof of the skull. We obtained LSCI perfusion of the superior sagittal sinus and cortical vessels. The unilateral common carotid artery is ligated. The small spherical occlusive catheter was inserted in the internal carotid artery (ICA) for its occlusion. The LSCI perfusion data of the cortex did not change by unilateral ICA occlusion (see Fig. 2d). Which could be related to well compensated collateral blood flow from the vessels of the circle of Willis. The LSCI visualization of blood flow also could be improved by the threshold setup the of pseudocolor scale.

LSCI system showed blood flow of the carotid artery in 3 rats and cerebral cortex vessels in one rat. We found that our settings of LCSI could show blood flow through soft tissue fascia covered carotid artery and its branches. We could not get any blood flow images through firm tissue, such as muscle and cranial bone.

Discussion

Laser speckle contrast imaging is of great potential for non-invasive blood flow control throughout the neurosurgical operation without the introduction of a contrast medium [7]. This technology is actively used in conducting cerebral blood flow in rat experimental models [11]. A number of studies have demonstrated the use of LSCI for monitoring of cerebral blood flow during neurosurgical manipulations [7, 12, 13]. Due to its simplicity, it is excellent for continuous monitoring of blood flow in real-time. Experiments on animals show (Fig. 2) that LSCI is well suited for visualization of large vessels during surgical operations. This method is demonstrated good sensitivity to assess the changes in vascular blood flow [14–17]. The currently available methods for intraoperative blood flow monitoring have a number of significant disadvantages. Angiography requires injection of a contrast medium through the venous bloodstream. Therefore, the use of this method is limited in time and does not allow for continuous blood flow monitoring throughout the operation. It also requires the operation to be sus- pended. The disadvantage of Doppler is that measurements are only taken at one point where the probe touches, which does not allow the surgeon to see the entire blood flow pattern within the operating field. In addition, the use of Doppler also requires the surgeon to stop all manipulation and introduce an additional measuring probe into the operating field.

An undeniable advantage of laser speckle contrast imaging is the ability to monitor cerebral blood flow within the entire surgical field without the need for intravenous administration of contrast medium or the use of additional probes. The LSCI system combined with the operating microscope does not interfere with its operation, it allows visualization of blood flow continuously throughout the operation, without requiring stopping surgical manipulations or withdrawal of the microscope [7].

On the other hand speckle contrast is a relative parameter that depends on a large number of parameters, which significantly complicates direct flux measurements with this method. For this reason, LSCI can only be considered as a semi-quantitative method [18]. The limitation on the use of LSCI in diagnostics is also imposed by the non-ergodicity of speckle patterns [19]. An important issue in speckle contrast imaging is the reduction of sensitivity to the “mechanical” motion of the object under study. These movements can be induced by vibration, patient movements, respiration or tremor and cause speckle contrast changes indistinguishable from blood flow [20]. In fact, these experimental artefacts can be suppressed with easier by the time-space Fourier kω’ filtering approach [21], specially developed for advanced brain imaging.

In addition, despite a large number of studies, LSCI has not yet become widespread in clinical practice. In general, it can be hindered by high variability of obtained data due to great heterogeneity of biological tissues. In contrast to the skin, the mucosa is characterized by significantly lower scattering properties, less variability of scattering properties and less deep location of vessels.

Conclusion

In this work, we introduce a prototype of LSCI system that allows direct monitoring of crossability of small vessels during routine neurovascular surgery procedures. The cortical surface perfusion and major arterial vessels crossability are monitored during vascular occlusion. The obtained results illustrate the ability and performance of LSCI system towards noninvasive real-time monitoring of blood flow during neurosurgery. The results also show a great potential of LSCI and its implementation in day-to-day clinical neurosurgery practice.

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Conflict of interest
The authors declare that they have no conflicts of interest.

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