Quantification of the arterial blood flow through the internal carotid arteries at patients with chronic cerebral ischemia by MRI

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Aims and objectives

In terms of morbidity, disability and mortality, cerebrovascular diseases represent the most common pathologies. More than half of ischemic strokes are associated with stenosing of the internal carotid arteries (ICA) [1, 2, 3]. The role of stenosing impairments of ICA has been well studied and diagnostic algorithms with evaluation criteria for the degree of stenosis and indications for carotid endarterectomy and stenting have been defined [4,5].

The CT-angiography and ultrasound techniques are the most important for the ICA assessment. They are used to define the localization of atherosclerotic plaques, the change of artery walls, the degree of stenosis and the hemodynamic cross-sectional area of the artery. However, CT-angiography requires the introduction of a contrast agent and it is radiation exposure, which sometimes limits its use. Ultrasound also has limitations. This technique is dependent on the operator; it visualizes the carotid arteries on a limited extent; the ultrasound visualization of the arteries is very difficult in the case of short and thick necks; ultrasound values of blood flow velocities normally have a wide range and sex-age features [6]. In addition, the clinic of the chronic cerebral ischemia is nonspecific and it could be occur at different pathological conditions. Therefore, in some cases it is necessary to perform the MRI.

Routine MRI protocol detects morphological changes in the brain at most cases; 3D-PCA visualizes the vascular structure. The quantitative phase-contrast magnetic resonance angiography (qPC-MRA) is used in determining the velocity parameters of blood flow successfully [7, 8, 9]. QPC-MRA being used together with other impulse MR-sequences provides extended results of morphological and functional survey of the cerebral arteries, as well as collects reliable quantitative characteristics of arterial blood flow. The aim of our investigation was to quantify the arterial blood flow through the ICA at patients with chronic cerebral ischemia by MRI.

Methods and materials

The 50 volunteers (control group) and 10 patients with chronic cerebral ischemia were examined on a 1.5T MR-scanner. The procedure to attract volunteers to the study was constructed strictly in accordance with the international requirements of the Declaration of Helsinki and with the endorsement of the local ethical committee of the institute.

Both groups of volunteers were examined using routine protocol and phase contrast MR-angiography. The routine brain MR-protocol was used for verification chronic cerebral ischemia and exclusion other pathologies. It was consisted of the T1-, T2-WI, FLAIR, MRA, DWI MR-sequences. The group of the chronic cerebral ischemia consisted of
patients with multiple dyscirculatory foci (spot) at subcortical localization and related clinic (Fig.1). Qualitative assessment of the internal carotid arteries was performed by 3D PCA-MRA at the frontal projection. The symmetry, deformation, stenosis of the arteries determined (Fig.2).

Quantitative hemodynamic characteristics were determined using a two-dimensional PC-MRA with ECG-based cardio synchronisation in the retrospective mode (continuous data collection in the R-R interval) with subsequent reconstruction and alignment in time of the cardiac cycle with the flow profiles obtained in the study (quantitative MR angiography procedure) [10, 11, 12, 13, 14, 15, 16, 17]. It was used for observe the values of peak velocity, mean velocity, mean flux of arterial blood flow and cross-sectional area through the 5 parts of the internal carotid arteries (Fig.3). Procedure parameters:

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\text{TR} = 14 \text{ ms}; \quad \text{TE} = 8.3 \text{ ms}; \quad \text{FA} = 15^\circ; \quad \text{slice thickness} = 5 \text{ mm}; \quad \text{blood flow rate factor} = 90 \text{ cm/s}; \quad \text{number of averages} = 2; \quad \text{duration} = 1 \text{ minute 30 seconds}; \quad \text{slice orientation} - \text{perpendicular} \quad \text{to} \quad \text{the} \quad \text{investigated} \quad \text{segment} \quad \text{of} \quad \text{the} \quad \text{artery}.
\]

The flow measurement was possible at the perpendicular to the direction of blood flow, so the scan plane for velocity images was chosen perpendicular to the straight portion of artery. The obtained images were evaluated qualitatively and quantitatively. Qualitative analysis consisted in visual assessment of the obtained tomograms to exclude artefacts related to the magnetic field inhomogeneity, the patient’s movements and swallowing motions, or caused by the pulsation of vessels or superposition of speeds. Meeting of the last criterion is mandatory, since the distortion of the image due to the mismatch between the true blood flow rate and the encoding speed factor \(V_{\text{enc}}\) specified in the procedure, further quantitative analysis would become technically impossible. Processing of the obtained information in order to derive the quantitative characteristics of blood flow included tracing the vessel outline along the border of the areas with hyperintense signal (pulsing blood) with the creation of an irregular geometric shape (ROI - region of interest); semiautomatic transfer of the geometry to each of the remaining 15 phases of the cardiac cycle; and manual correction of the hemodynamically significant outline of the arterial lumen for each phase of the cardiac cycle, if necessary. The flux, mean (average linear) and peak rates and cross-sectional area for each of the 15 phases of cardiac cycle were determined within the ROI by using the postprocessing program. The data was presented in tables with the parameters and graphs of these parameters as functions of the cardiac cycle phase (Fig.4). The post processing program visualizes arterial pulsation in cine-mode with colour flow mapping (FFE-M-Colour images) depending on its direction and rate (Fig.5).

Statistical analysis was performed by mean value and confidence interval (for \(p=0.05\)). Student’s paired t-test was performed to indicate significant differences between mean values the patients and control groups.

Images for this section:
**Fig. 1:** Example of the MR-signs of the chronic cerebral ischemia. The multiple spots hyperintense on T2-WI axi (a) and Flair cor (b) correspond to signs of chronic cerebral ischemia.

**Fig. 2:** 3D-PCA of the ICA in coronal projection. Arrows indicate the pathology. a) stenosis at cervical segment of the ICA, b) kinking and stenosis at cervical segment of the ICA, c) S-shape tuortuosity (without stenosis) at cervical segment of the ICA.
Fig. 3: The investigated segments of the ICA and the orientation of the qPC-MRA scans. 1 - proximal part of the cervical ICA segment; 2 - middle part of the cervical ICA segment; 3 - vertical part of the petrous segment; 4 - horizontal part of the petrous segment; 5 - cavernous segment.
**Fig. 4:** Post processing program. Types of images obtained by the PC-MRA technique:

a) - FFE/M - images obtained in the FFE (fast field echo) mode; 
b) - PCA/M - images obtained by phase contrast method; 
c) - PCA/P - images with phase differences - directly reflect the phase difference (rate) values by brightness; 
d) - FFE-M-Colour images reflect arterial pulsation in film mode with colour flow mapping depending on its direction and rate. The red and green circles at C) are regions of interest. 
f) - table with the velocities and graph of flux velocity as functions of the cardiac cycle phase.
**Fig. 5:** Arterial pulsation in cine-mode with colour flow mapping (FFE-M-Colour images) depending on its direction and rate.
Results

The qPC-MRA procedure parameters have been optimized so that the resulting images exhibited a high signal-to-noise ratio at the shortest possible duration of patient examination, encoding direction and approximate blood flow rate has been selected, as well as the optimal location of sections. The transverse profile of blood flow has been visualized at different parts of the ICA. Arterial pulsation has been visualized with increases lumen area and acceleration of blood flow in central segments under the influence of cardiac contractions during systole. Analysis of the obtained images of axial section of the vessel revealed a decrease of the intensity of MR signals due to the flow at the periphery and an increase at the centre, which indicates slower parietal stream of blood and a faster central stream. At the same time, systole phase is characterized by an increase in the cross sectional area of the central rapid stream with a corresponding increase in the blood flow rate characteristics with pulsing and an increase in the cross sectional area of the vessel. However, it should be noted that at the periphery of the vessel, in the parietal region, slow blood flow rate is recorded throughout the cardiac cycle (Fig.4).

The absolute values of the flux, mean (linear), peak velocities and cross-sectional area through the investigated parts of the ICA were obtained for control group and patients with chronic cerebral ischemia (Fig.6). At the control group, the flux rate is constant at the first three levels and is reduced at the intracranial levels, which can be explained by the presence of branches and the outflow of some blood volume in the petrous and cavernous segments of the internal carotid arteries. The mean velocity is at its maximum in the middle of the cervical segment, where the artery has the longest straight-line path, and decreases in the petrous and cavernous segments distal to the physiological curvatures of the artery. The peak rate also increases in the middle portion of the cervical segment, then decreases slightly at the petrous segment and is at its maximum at the cavernous segment level, which may be associated with restriction of flow pulsation caused by the surrounding cavernous sinus.

The 4 patients with coiling and kinking of the ICA and 4 patients with atherosclerotic lesion of the ICA (it was confirmed by ultrasound) were identified by use of the 3D-PCA among 10 patients with chronic cerebral ischemia. The combination of atherosclerotic lesions and pathological tortuosity of the ICS was defined at the 3 patients. The blood flow decrease was identified at the 3D-PCA as reducing signal intensity and narrowing the width of the registered flow 15-30% at the 4 patients.

The curve of the velocity characteristics depending on the ICA parts at the case of the chronic cerebral ischemia repeat the dynamics of changes found in the control group, except cavernous segment of the internal carotid artery. The values of the flux, mean (linear), peak flow velocities was significantly lower than the values found in the control group (Fig.6). The most significant decrease in flow rates occurred in the...
middle of the cervical segment of the ICA. The linear velocity of blood flow was changed most significant compared to other indicators. It was decreased at 37% at middle ICA cervical segment. The blood flow velocity decrease was less significant at the cavernous segment of the artery. The flux velocity was higher at patients with chronic cerebral ischemia compared control group. It exceeds the normal value by 18%. The linear velocity reduction at this part of the artery was minimal compared to other portions (about 17%). At the same time the cross-sectional area of the artery is significantly higher in case of chronic cerebral ischemia through the all ICA parts. It is increased the most significant (about 30%) at the cavernous segment of the artery. It may to explain the change of the blood flow rate at some extent.

Images for this section:

**Fig. 6:** The absolute values of the flux velocity (a), peak velocity (b), mean (linear) velocity (c) and cross-sectional area (d) through the investigated parts of the ICA for control group (blue line) and patients with chronic cerebral ischemia (red line). * - indicate significant differences.
Conclusion

QPC-MRA could be successfully applied to quantification of arterial blood flow at the different levels of the ICA. Arterial blood flow through the internal carotid arteries primarily follows the blood flow laws that apply to musculo-elastic type arteries. Furthermore, it is a function of the cardiac cycle phase. Type of the artery pulsation in the case of the chronic cerebral ischemia is the same as the control group. The normal values of the blood flow velocities through different parts of ICA were determined for comparison with chronic cerebral ischemia. The hemodynamic changes of the blood flow velocities occur through the all parts of the ICA in patients with chronic cerebral ischemia. The arterial blood flow velocities are significantly lower at patients with chronic cerebral ischemia. The values of the linear velocity decreases more significantly. This is parameter could be used as diagnostic indicator for chronic cerebral ischemia. However, hemodynamic changes of the blood flow velocities are less significant at the cavernous segment of the ICA. May be it is due to other regulatory mechanisms of intracranial blood flow. The cerebral blood flow through the ICA has a complex symmetrical character needed to ensure the compensation mechanisms in case of cerebral circulation disorders.

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