Experimental measurements and visualisation of a viscous fluid flow in Y-branching modelling the common carotid artery bifurcation with MR and Doppler ultrasound velocimetry

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Abstract. In our experiments, we investigate a flow of a viscous fluid in the model of the common carotid artery bifurcation. The studies are carried out using three hardware equipments: two magnetic resonance scanners by Philips and Bruker, and intravascular guidewire ComboWire. The flux is generated by a special pump CompuFlow that is designed to reproduce a flow similar to the one in the blood vessels. A verification of the obtained data is carried out. Conducted research shows the capabilities of the measurement instruments and reflects the character of fluid flow inside the model.

1. Introduction

One of the most important objects of research in haemodynamics is the brain circulatory system, since it manages all the functions of the body. From the point of view of mechanics of blood circulation, the brain is a separated haemodynamic system with four entrances and two outputs (blood enters the brain through the two internal carotid arteries and the two vertebral arteries, and its outflow occurs throughout the two jugular veins). The velocity of blood in brain arteries ranges from 20 cm/s to 150 cm/s. In the resting state, the brain consumes around 15% of the blood volume (750 ml/min) and about 20–25% of the oxygen obtained by breathing. In comparison with brain, in kidney at admission of 19% of the total blood flow, only about 7% of total oxygen volume is absorbed. Thus the brain is characterized by the elevated consumption of oxygen and consequently by the elevated consumption of energy [1].

Generally the pathological processes which cause cerebrovascular disturbance are characterised by the lesion of the cerebral and main arteries, the cerebral and jugular veins, and also the dural sinuses. There are various pathologies of vessels of the brain: thromboses, angulation and kinking, embolisms, luminal narrowing, arterial aneurysms, arteriovenous...
malformations. Therefore, a research of the cerebral haemodynamics in healthy state and in the presence of anomalies, is important challenge both from a theoretical point of view and from the point of view of medical applications.

Common carotid artery is a paired artery which originates in the chest region and rises almost vertically up along the neck and is divided into the external and internal carotid arteries at the top edge of the thyroid cartilage. The main function of the common carotid artery is the blood circulation of the brain, eyes and the larger part of the head. Carotid arteries provide about 70–85% of the blood flow to the brain. The length of the common carotid artery is 6–12 cm, the diameter is 7–11 mm, the internal carotid artery has the length of 10–11 cm and diameter of 5–8 mm, the external carotid artery is less in diameter in comparison with the internal one and almost immediately branches out. Because of the different kind of pathologies of the carotid arteries, the cerebral circulation is violated which leads to a decrease in the cerebral blood flow and disruption of metabolic processes (ischaemia).

An adequate modelling of the blood flow in the cerebral vessels is a fundamental problem, a solution of which allows us in particular to solve the problem of prediction and evaluation of quality of neurosurgical operations. For development and verification of mathematical models the experimental data are needed. The difficulty in obtaining these data in vivo leads to attempts to recreate and study in vitro. This work discusses an experimental research of the flow of a viscous fluid in the silicone model of the common carotid artery bifurcation.

One of the modern non-invasive methods of examining internal human organs is a magnetic resonance imaging (MRI). The scanner measures the electromagnetic response of atomic nuclei, most commonly the nuclei of hydrogen atoms, to their excitation by a particular combination of electromagnetic waves in a gradient magnetic field of a high strength. The results of the processing of these measurements can represent different values: the substance density, the velocity of molecule motion, the temperature, or the others. In particular, using the MRI one can investigate the flow of blood in vessels. The first description of the effects of flow on spin echoes was given by Hahn [2] many years before MRI became a widely accepted method to study the fluid flow in the vessels. A review of the flow effects in the MR imaging technique is given in a paper by Axel [3]. Determination of blood flow velocity by using the MRI as a non-invasive method has generated a great interest in medicine. To verify and determine the accuracy of the MRI methods a comparison with other reliable methods in model experiments is needed. A comparison of the MRI and the Doppler ultrasound techniques for measurement of the fluid flow velocity is conducted in [4]. The first experiments on estimation of the fluid velocity in the specially designed models with the help of the MR methods are described in [5]. The paper [6] presents the results of the MRI application for measurements of the flow rate in straight tubes. In addition the authors performed a comparison of MR and ultrasound methods on the abdominal aorta in volunteers which showed a good coincidence. In paper [7] an overview of MRI abilities for studying the flows of liquids is made. It is shown that MRI provides good possibilities for 3D visualisation of the flow and determination of the velocity field. MRI techniques are used to study the flow of gas and liquid in the channels of monolithic catalysts [8]. In the paper [9] it is shown that the nuclear magnetic resonance imaging can be used to study the flow of liquid and gas in the structured catalysts and reactors, allowing one to resolve the complexity of the flow.

Another method for measuring the fluid flow characteristics inside of the object is the use of a special intravascular guide wire ComboWire. This guide wire is used in neurosurgical endovascular operations for monitoring the velocity and pressure of blood flow inside the vessels. A feature of this sensor is the ability to measure the pressure inside the vessel, whereas the MR methods cannot measure this parameter. Velocity measurement is based on the ultrasound Doppler effect when ultrasonic waves reflect from the blood cells [10, 11]. Information about the dynamics of the flow inside the artery plays an important role. It is used by neurosurgeons for
performing operations on treatment of various types of the vascular anomalies. The paper [12] presents the results of study on haemodynamics in 4 patients in the presence of an aneurysm. The measurements were performed with the guide wire ComboWire. The character of the flow inside the aneurysm and connecting arteries is shown. In the articles [13, 14, 15, 16] the results of measurements of the velocity and pressure with the guide wire ComboWire are used in computer modelling for obtaining additional information about the characteristics of the flow.

For creation of a flow similar to the flow in the artery, a special pump controlled by the computer is used. The pump is connected to the silicone model of carotid artery by the series of tubes. The measurements are performed using three hardware facilities: the intravascular guide wire and two different MR scanners.

Two series of experiments are performed. In the first series MR scanners are used to investigate the velocity profile of flow. In the second series the measurements are conducted with the intravascular guide wire and MR scanner, the local parameters—velocity and pressure in the flow—are examined.

2. Materials and methods

2.1. Model of the common carotid artery

The silicone model of the common carotid artery is designed by the Shelley Medical Imaging Technologies company [17] in accordance with the physiological parameters: the length of the common carotid artery is 90 mm, the diameter is 8 mm, the lengths of the internal and external carotid arteries are 60 mm, the diameters are 5.56 mm and 4.62 mm respectively. The channel which models carotid artery is made of elastic silicone block for modelling elastic vessels and external environment. The material used allows one to perform the measurements by using X-ray, magnetic resonance imaging (MRI), optical measurements of velocity fields of liquid or gas (PIV).

2.2. Experimental setup

The motions of blood is modelled by the motion of a viscous fluid in a closed system consisting of the model of carotid artery (Fig. 1, a), CompuFlow 1000 MR pump (Fig. 1, b) and the system of connecting tubes (Fig. 1, c), providing communication between the pump and the model.

![Figure 1. Experimental setup.](image1)

![Figure 2. The model of carotid artery with marked places of measurements.](image2)

2.3. CompuFlow 1000 MR pump

Fluid motion is generated by the special pump CompuFlow 1000 MR developed by Shelley Medical Imaging Technologies. This pump is able to generate flow similar to the flow in blood vessels. CompuFlow 1000 MR has a number of default settings for dependencies between flow and time and also allows one to programme arbitrary dependence between flow and time in the range from 0.01 to 35 ml/s with an accuracy of ±3%. The liquid used in the experiment has the same mechanical properties as blood: viscosity $\mu = 0.004$ Pa·s, density $\rho = 1000$ kg/m$^3$. 
2.4. Magnetic resonance imaging

The method used to determine the flow rate is based on measuring the phase shift of the MR signal caused by liquid motion. As a result of the scanner’s post-processing we get the distribution of the normal component of the velocity vector of liquid in a given cross section. The spatial resolution with which the velocity field can be obtained directly depends on magnetic field of the scanner: the stronger is the field the higher is the spatial resolution. The measurements of the liquid velocity field in the carotid artery model are performed with two devices:

- Philips Achieva with the field strength 1.5 T (designed for diagnostic studies of human).
- Bruker BioSpec 117/16 USR with the field strength 11.7 T (designed for studies of small animals in biomedical science, for biomedical and preclinical researches).

The main difference of Bruker scanner from Philips, except it’s higher resolution, is that it is able to monitor the flow dynamics directly during the study with the help of method Flash-ToF-2D-Saturation, which allows one to track the movement of the magnetized transverse and longitudinal liquid layers (Fig. 3).

Using of two devices of different classes allows one to perform mutual verification of the measured values.

2.5. ComboWire guide wire

The intravascular ComboWire guide wire is designed for simultaneous measurement of the blood velocity and the pressure in blood vessels. The guide wire was developed by Volcano Corporation. The velocity is measured with the help of Doppler method with the frequency of 12 MHz, the pressure is measured with piezoelectric method. The measured data are recorded with the frequency of 200 Hz. Velocity and pressure sensors are mounted on the end of the guide wire which is 0.36 mm in diameter and 185 cm in length. The ComboWire guide wire is used together with the ComboMap computer system which directly processes the measured data.

2.6. Investigated flow regimes

The purpose of the measurements is to study liquid flow in the carotid bifurcation model under conditions that are close to ones in a living organism. For studying the flow we use the sequence of the flow regimes “from simple to complicated”. This sequence allows at first to reveal effects that appear in transition from some simple flow regime to a more complicated one and secondly to verify the measurement method. Such a choice is caused also by the complexity of the measurement devices: the transition from one flow regime to the more complicated one often requires the correction of measurement parameters of the devices.

From the flow regimes chosen for study let us point out the next ones:

- Fluid flows with a constant rate: 5, 10, 15 ml/s.
- Fluid flows in which the next periodic dependencies between flow rate and time are realized: \( A + B \sin(\pi t), A + B \sin(2\pi t), A + B \sin(4\pi t), A + B \sin(2\pi t) + C \sin(4\pi t) \text{ ml/s} \). Here \( A, B, C \) are some constants varied in experiments. Constant \( A \) takes values from 0 to 10 ml/s, amplitudes \( B, C \) are chosen from the range of 1.25 to 15.
- Dependence between flow rate in carotid and time measured experimentally during neurosurgical operation [10].
- Dependence between flow rate and time corresponding to blood flow rate in carotid averaged over the big and representative group of patients.

Measurements are made on the straight section before bifurcation, in bifurcation area and daughter branches of carotid. In Fig. 2 measurement places are marked with dotted lines.
3. Results of the measurements

3.1. MRI

In the measurement of the velocity field there are high-frequency perturbations with amplitude \( \sim 15\text{–}20\% \) superimposed on the main flow. Additional assumptions allow one to filter out the noise. Thus, in the measurement of the velocity profile along the straight section of the common carotid artery we can assume that the flow is axisymmetrical. This assumption allows us to perform the averaging of the velocity profile by angle:

\[
F_{2n}(r) = \frac{1}{2n} \sum_{k=0}^{2n-1} F(r \cos(\frac{k}{n}), r \sin(\frac{k}{n}))
\]

where \( F \) is measured velocity values, \( 2n \) is the number of the sectors by which averaging is performed, \( R \) is the vessel radius, \( r \in (0, R) \).

In Fig. 3 the dynamics of the movement of the magnetized liquid layers in the area of the carotid artery bifurcation for the constant flow rate 5 ml/s is shown. In Fig. 4 averaged by angle velocity profiles along the straight section of the common carotid artery for the constant flow rate 5 ml/s measured by the Bruker and the Philips scanners are shown.

![Figure 3.](image1.png)

**Figure 3.** The movement of the magnetized liquid layers in the area of the carotid artery bifurcation for the constant flow rate 5 ml/s.

Another stage of the measurement verification is a comparison of the measured and generated by the pump flow rates. For each moment of time at which the measurement is performed, the flow rate through a given cross section is calculated by formula

\[
\int_{\Sigma} (\vec{v} \cdot \vec{n}) \, d\sigma,
\]

where \( \Sigma \) is the cross section of the vessel in which the measurement is performed, \( \vec{v} \) is the liquid velocity, \( \vec{n} \) is the vector normal to the cross section, \( d\sigma \) is an element of the cross section. Note that the scanner measures the normal component of liquid velocity for a given cross section, equal to \( \vec{v} \cdot \vec{n} \).

In Fig. 5 the results of measurements of flow with the flow rate \( 0.1 + 10 \sin(2\pi t) \) ml/s in the straight section of the carotid artery are presented. In Fig. 6 the diametrical velocity profiles at the time moments \( t_1, t_2, t_3 \) are shown.
The calculated fluid flow rate and the given constant flow rate (generated by the pump) differ by 1–3% for both devices.

During the experimental sessions about 100 measurements on the Philips scanner and 90 measurements on the Bruker scanner were performed.

3.2. The ComboWire guide wire

During the measurement the ComboMap system obtains data from ComboWire guide wire about velocity spectrum and builds an envelope around it. The value of the spectrum envelope is accepted as the value of the fluid velocity.

In Fig. 7 the velocity values measured by ComboWire guide wire and Philips scanner in the straight section before the bifurcation for the given flow rate typical for the carotid artery are presented. In Fig. 8 VP–diagrams (“velocity–pressure”), which visualize the relationship between pressure and velocity in the flow, are presented. In Fig. 9 measurements of the fluid flow typical for the carotid artery in cross section C₁, I₁, I₃, E₁ and E₃ (Fig. 2) are shown.

12 periodic flow regimes were investigated and 96 measurements were performed with ComboWire guide wire in total. The average duration of one measurement is 2–3 minutes.
For four flow regimes corresponding measurements by Philips scanner were performed.

4. Discussion

The velocity profiles measured by the Philips and the Bruker scanners coincide quite well, except for the area where the liquid moves with the highest velocity (Fig. 4).

The calculated fluid flow rate and the given constant flow rate (generated by the pump) differ by 1–3% for both devices. Thus, under these conditions the Philips scanner gives results comparable to the results of the Bruker one.

The areas near the bifurcation, in which liquid magnetized layers do not propagate are stagnation areas (Fig. 3). From a medical point of view, such areas are potentially dangerous because blood properties significantly depend on its movement velocity and in a stagnant area a thrombus may occur.

Averaged over cross section velocity values measured by the Philips scanner differ in 1.5–2 times from the values measured by the ComboWire guide wire (Fig. 7). This difference is caused by the fact that the ComboWire guide wire is situated in the centre of the blood vessel and measures the local velocity, whereas the comparison is performed to the averaged over the cross section velocity measured by the MR scanner. The dependence between the measured average and maximum velocities is similar to the dependence between average and maximum velocities for steady Poiseuille flow.

The pressure measurement is important for further studies of liquid dynamics and external environment. Dependence between pressure and velocity defined in such way (Fig. 8) can be used for constructing the state equation which characterises the rheology of the composite system “fluid flow – elastic environment”. The measured pressures are used in computer modelling as boundary conditions.

The ComboWire guide wire flow investigations show that the maximum values of the velocity in cross section $I_1$ are $\sim 30\%$ less than the maximum values of the velocity in $C_1$, maximum velocity values in sections $C_1$ and $E_2$ are greater than the maximum value of the velocity in common carotid artery by $\sim 20\%$ and $\sim 25\%$ respectively (Fig. 9). The maximum and minimum pressure values for each flow generated by the pump almost do not change throughout the model of the carotid artery bifurcation, in contrast to the velocity values.

When the pump is set up for the periodic flow rate $A + B \sin(N\pi t)$ ml/s with almost zero flow rate at the period ($0 \leq A \leq 1$) the experimental setup reproduces the defined flow not accurately enough: the difference between the maximum values of the measured and defined ones can reach $25\%$ (Fig. 5).

During the experiment it has been found that the pressure sensor reacts to light and
environment temperature — the zero level of the measured pressure shifts. Therefore, it is necessary to maintain a constant level of lighting and constant liquid temperature.

Performed investigations demonstrate the capabilities of the measuring devices and show the character of fluid flow inside the model.

5. Conclusion
The result of the experimental studies is qualitative and quantitative information about the dynamics of fluid flow inside the model of the carotid artery for different flow regimes.

Averaged over cross section velocity values measured by the Philips scanner differ in 1.5–2 times from the values measured by the ComboWire guide wire. This difference is caused by the fact that the ComboWire guide wire is situated in the centre of the blood vessel and measures the local velocity, whereas the comparison is performed to the averaged over the cross section velocity measured by the MR scanner.

The velocity profiles measured by the Philips and the Bruker devices coincide quite well, except for the area where the liquid moves with the highest velocity. The calculated fluid flow rate and the given constant flow rate (generated by the pump) differ by 1–3% for both MR scanner. So, under these conditions the Philips scanner gives the results comparable to the results of the Bruker one.

Thus, the measurement equipment consisting of the intravascular ComboWire guide wire, CompuFlow 1000 MR pump and two Philips and Bruker MR scanners can be used to obtain reliable and consistent data in the investigation of fluid flow in the vessel model.

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