

Endovascular blood flow measurement system

A K Khe^{1,2}, A A Cherevko^{1,2}, A P Chupakhin^{1,2},
A L Krivoschapkin³ and K Yu Orlov³

¹ Lavrentyev Institute of Hydrodynamics, Novosibirsk, Russia

² Novosibirsk State University, Novosibirsk, Russia

³ Meshalkin Novosibirsk Research Institute of Circulation Pathology, Novosibirsk, Russia

E-mail: alekhe@hydro.nsc.ru

Abstract. In this paper an endovascular measurement system used for intraoperative cerebral blood flow monitoring is described. The system is based on a Volcano ComboMap Pressure and Flow System extended with analogue-to-digital converter and PC laptop. A series of measurements performed in patients with cerebrovascular pathologies allows us to introduce “velocity–pressure” and “flow rate–energy flow rate” diagrams as important characteristics of the blood flow. The measurement system presented here can be used as an additional instrument in neurosurgery for assessment and monitoring of the operation procedure. Clinical data obtained with the system are used for construction of mathematical models and patient-specific simulations. The monitoring of the blood flow parameters during endovascular interventions was approved by the Ethics Committee at the Meshalkin Novosibirsk Research Institute of Circulation Pathology and included in certain surgical protocols for pre-, intra- and post-operative examinations.

1. Introduction

Real-world data play a crucial role in mathematical modelling since it is the main ingredient for verification and justification of the theory being developed. Designing a proper experimental set-up and a measurement system is a challenging task in engineering sciences. And it is even more difficult in natural and medical sciences. In this work we describe the measurement system we use in the context of mathematical modelling of cerebral haemodynamics. Clinical data are collected during endovascular neurosurgical treatments of cerebral blood vessel diseases (arteriovenous malformations and aneurysms).

A number of lesions of the brain lead to a change in the blood flow régime. Cerebrovascular diseases include atherosclerosis, embolism, aneurysms, vascular malformations, and others [1]. All these pathologies can be a cause of a stroke with high disability and mortality rates. According to the World Health Organization, cardiovascular diseases are “the top major killers” during the past decade [2]. The second leading cause of death in the world is the stroke following the ischaemic heart disease. Despite the great technological advances in diagnostic and operating medical equipment, treatment planning and a choice of a particular surgery heavily depend on the surgeon’s experience and common medical practice.

For these reasons, mathematical modelling of the circulatory system is one of the urgent and topical questions in biomechanics. Patient-specific simulations will allow the clinicians to perform pre-operative modelling and to assess the risks of post-operative complications. At the



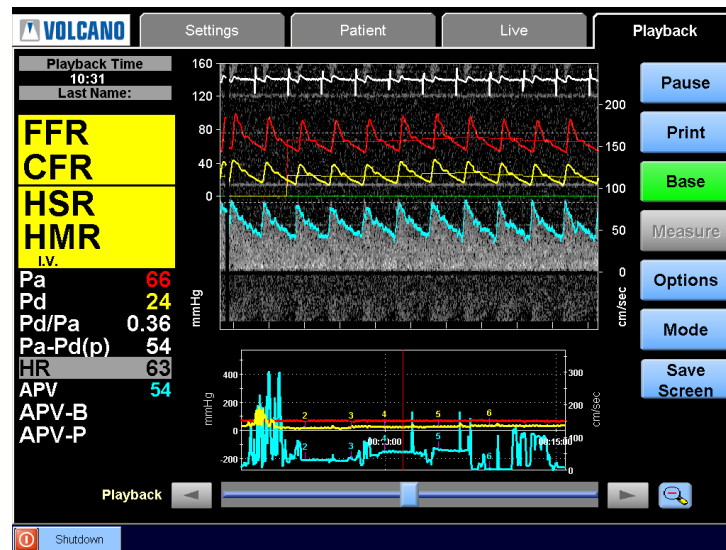


Figure 1. ComboMap screen showing pressure (yellow) and velocity (cyan); external data: systemic pressure (red), ECG (white). Top: current readings; bottom: current measurement session

same time, in order to construct a proper mathematical model one has to base on a reliable set of clinical or laboratory data.

A widely used method to measure the cerebral blood flow is the transcranial Doppler ultrasonography [3]. The method is applicable for relatively large vessels—carotid and vertebral arteries and their first level branches: anterior, middle, and posterior cerebral arteries. Another non-invasive technology is the magnetic resonance (MR) velocimetry [4]. The latter provides also with 3D geometry of the vasculature which can be reconstructed from the MR angiography. The MR imaging depends on the magnetic field strength and the finer resolution is needed the longer scanning time it takes.

The main shortcoming of any non-invasive technique is its inability to measure the blood pressure (at least in the vessels not near the body surface), which is one of the essential characteristics of the fluid flow. In our work we use endovascular flow and pressure measurement system Volcano ComboMap (Volcano Corp., USA). The measurements are carried out during minimally invasive endovascular neurosurgical operations in patients with cerebral arteriovenous malformations and arterial aneurysms.

2. Endovascular measurement system

The flow monitoring system is based on a ComboMap Pressure and Flow System, which is a PC-based portable machine with 15 inch LCD touch screen and remote control. The information about current readings along with the averaged values are shown on the screen (figure 1). The measurements are performed using a ComboWire guide wire (Volcano Corp., USA). The guide wire is 0.36 mm in diameter and 185 cm in length (figure 2). Doppler sensor at the tip of the wire measures flow velocity approximately 5 mm from the tip. The pulsed Doppler beam angle is 45 degrees and insonifies the maximum diameter of approximately 4 mm [5].

The ComboMap system has additional input and output plugs allowing for connection of other medical equipment and measuring instruments. In our flow monitoring procedures we use two additional input signals—systemic arterial pressure and electrocardiogram. The output plugs of the ComboMap allow one to read the measured pressure and flow velocity, and the systemic arterial pressure (which duplicates the external input signal). We use E14-140M portable USB

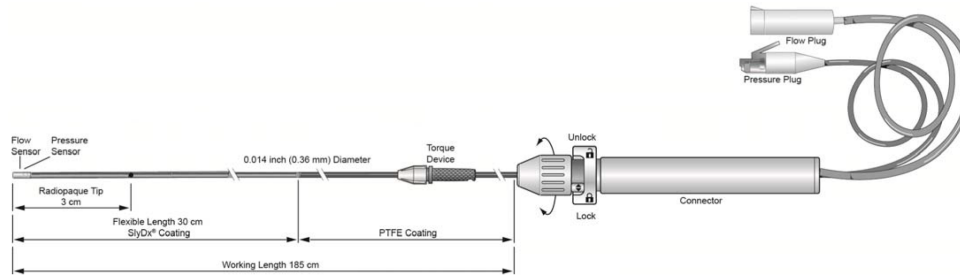


Figure 2. Volcano ComboWire guide wire

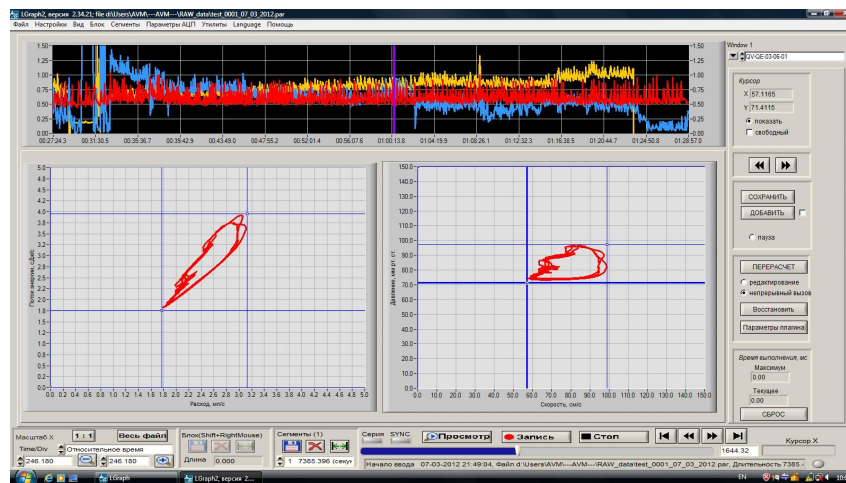


Figure 3. LGraph2 with plug-ins showing real-time data during the measurement session. *Top:* the entire session, *bottom left:* “flow rate–energy flow rate” diagram, *bottom right:* “velocity–pressure” diagram

analogue-to-digital converter (L-Card, Russia) connected to a PC laptop. The E14-140M is a 14-bit ADC with maximum sampling rate of 200 kHz, 16/32 commutation lines, input voltage ranges of ± 10 , ± 2.5 , ± 0.6 , ± 0.15 V; the data acquisition can be carried out in synchronous or asynchronous modes [6]. During endovascular blood flow monitoring we use 198.216 Hz sampling rate.

Data acquisition is performed on a PC laptop with LGraph2 software (L-Card, Russia). The software is designed to collect, store and export the data acquired via LCard ADC. The primary functionality of the LGraph2 can be extended with additional plug-ins. To visualise qualitative properties of hydrodynamic parameters of the flow and the relation between the velocity and pressure, we developed and implemented a plug-in showing “velocity–pressure” and “flow rate–energy flow rate” diagrams for current measurement data (figure 3). The information is shown on the laptop screen in real time in addition to the data on the ComboMap display.

The data acquired during the pre-, intra- and post-operative blood flow monitoring is a single tabulated function representing the time series of the flow parameters. In order to mark the site of a measurement, we minute down the time of the measurement, its location, average pressure and velocity along with the series number of the digital subtraction angiography with the position of the ComboWire (figure 4).

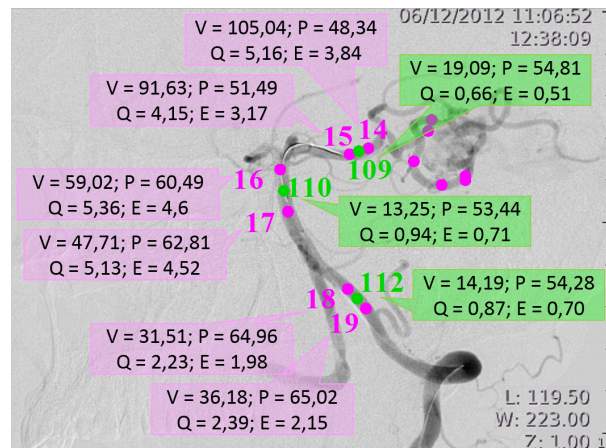


Figure 4. Digital subtraction angiography with measurement locations and average values of the velocity, pressure, flow rate and energy flow rate. *Magenta*: before the operation, *green*: after the operation

3. Post-processing

The post-processing of the blood flow monitoring data includes several steps. The resulting patient record contains all the information on the cerebral flow which is used in the future analysis and mathematical modelling.

The output of the data acquisition procedure is a one block of data containing the measurements and irrelevant noise due to wire repositioning or neurosurgical activities. The initial step of the post-processing consists in the extraction of the time intervals and data ranges corresponding to the actual measurements. Using the minutes of the intraoperative blood flow monitoring and digital subtraction angiography, we identify and map the data ranges to the measurement sites in the cerebral vessels. A typical duration of a measurement at one site in pre- and post-operative examinations is 30 to 60 seconds. During the surgery the ComboWire is usually placed at some location proximal to lesion, so we can monitor the flow changes during the intervention.

Once the data are divided into appropriate intervals, each of these individual data ranges is processed in a home-made software written in Wolfram Mathematica.

We use methods of wavelet analysis for noise filtering and frequency analysis. In particular, we compute the continuous wavelet transform of the measured data and zero out the coefficients corresponding to high frequency waves. The transform is computed using the complex non-orthogonal Gabor wavelet of frequency 6: $\psi(x) = \pi^{-1/4} \exp(iwx) \exp(-x^2/2)$ with $w = 6$. The wavelet scalograms along with the denoised time series are placed into the patient's measurement record.

The qualitative characteristics of the cerebral haemodynamics can be described with the help of “velocity–pressure” and “flow rate–energy flow rate” diagrams. The former is constructed as a trajectory of a point with coordinates $(v(t), p(t))$ on the (v, p) plane, where $v(t)$ and $p(t)$ are time series of the measured velocity and pressure in the blood flow.

The flow rate $Q(t)$ and energy flow rate $E(t)$ are computed by formulae: $Q(t) = \pi d^2 v(t)/4$ and $E(t) = Q(t)(p(t) + \alpha \rho v^2/2)$. The diameter of the vessel d is measured using the angiography. Coefficient α is the Coriolis coefficient describing the non-uniformity of the velocity cross-sectional profile: $\alpha = 1$ for a flat profile, $\alpha = 2$ for a parabolic velocity profile. In our computations we take $\alpha = 1.5$. The exact value of the Coriolis coefficient does not significantly change the total pressure and is often considered to be equal to 1.

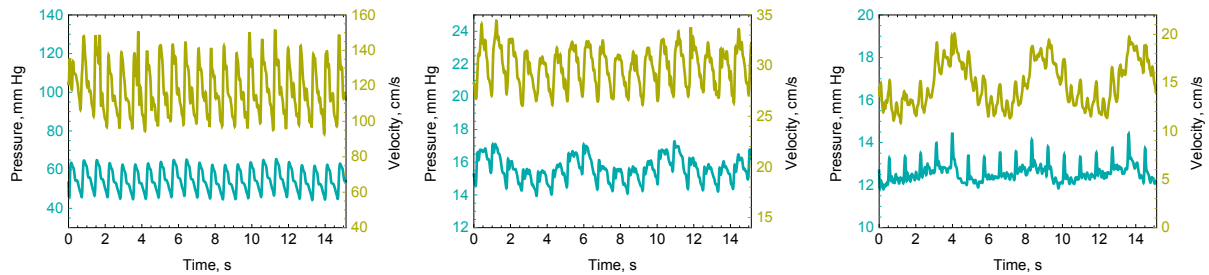


Figure 5. Velocity and pressure in blood flow in different cerebral vessels. *Left: artery, middle: vein, right: sinus*

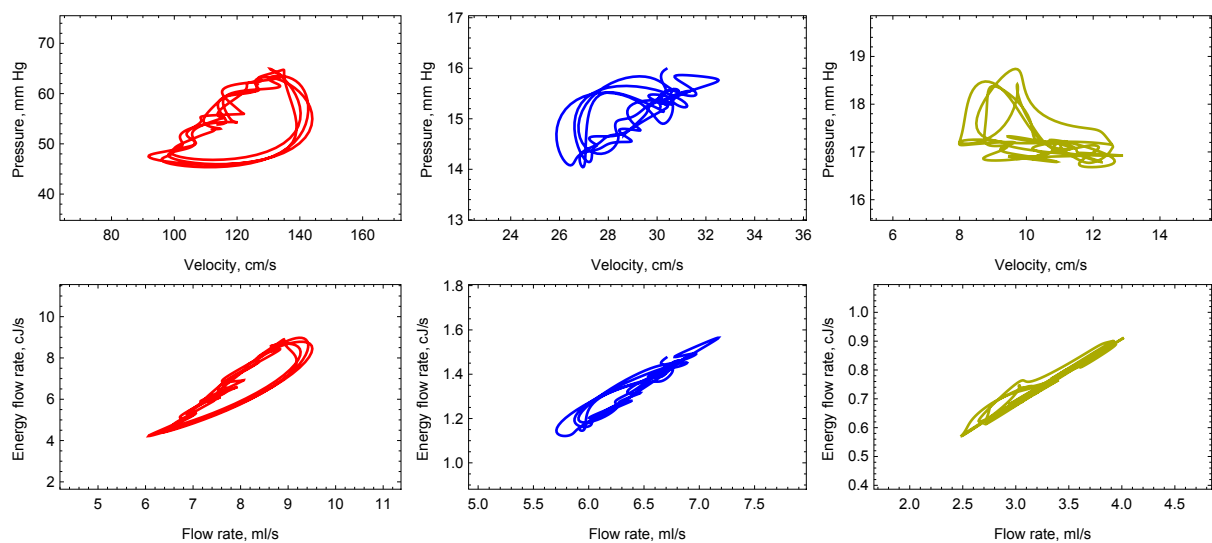


Figure 6. Velocity–pressure and flow rate–energy flow rate diagrams in different blood vessels. *Top: vp-diagrams, bottom: QE-diagrams; left: artery, middle: vein, right: sinus*

4. Results

In this section we present several characteristic examples of the endovascular blood flow monitoring in patients with arteriovenous malformations and arterial aneurysms.

Figure 5 shows time series of the measured hydrodynamic parameters—velocity and pressure—in different blood vessels: arteries, veins and sinuses. In distal cerebral arteries, the pressure wave, in general, still carries the information about the systemic pressure and their wave forms are more or less qualitatively similar. However, in veins and sinuses they are significantly different. The amplitude of the pulse wave decreases and the respiratory wave becomes more apparent.

The velocity–pressure and flow rate–energy flow rate diagrams for the flows in different blood vessels are shown in figure 6. There are several distinct features characteristic to different types of the vessels. The *form* of the *vp*-diagrams varies depending on the compliance of the vessel: it has a half-circle shape for the arteries and veins and a triangle shape for the sinuses. The *movement direction* of a point along the diagram is counterclockwise for the arteries and clockwise for the veins and sinuses.

A series of measurements in patients with different cerebral vascular pathologies reveals that the shape of the diagram can characterise the type of the lesion [7]. In patients with arteriovenous malformations the diagrams are more semi-circular, while in the presence of the

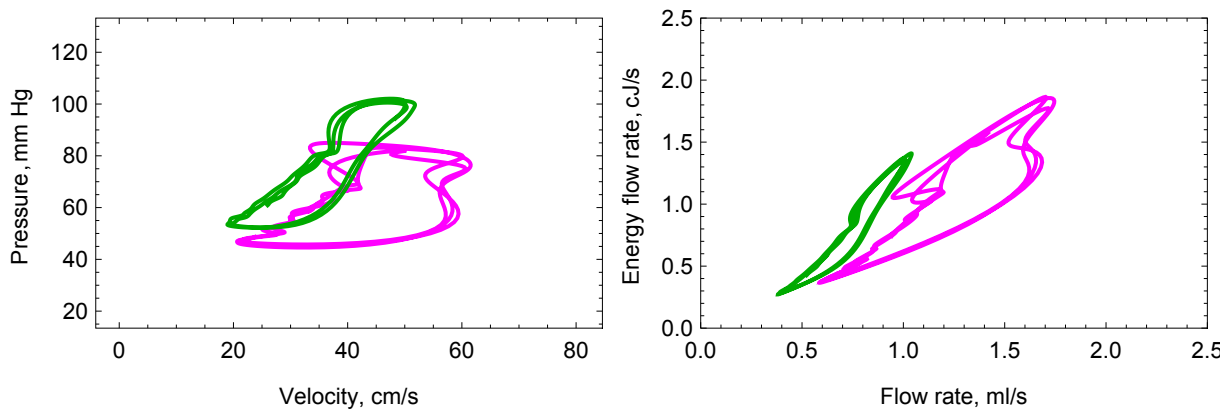


Figure 7. Velocity–pressure (*left*) and flow rate–energy flow rate (*right*) diagrams in the cerebral arteries with aneurysm. *Magenta*: before the operation, *green*: after the operation

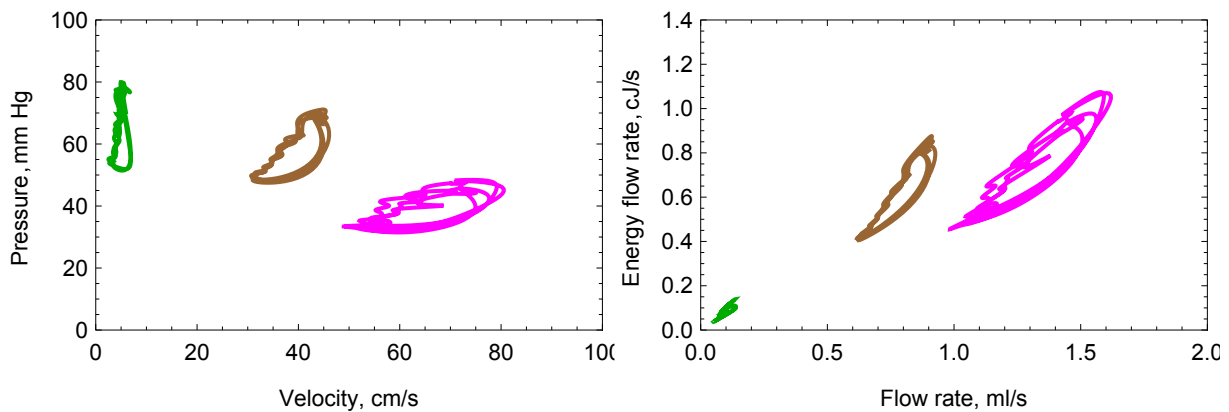


Figure 8. Velocity–pressure (*left*) and flow rate–energy flow rate (*right*) diagrams during the embolisation. *Magenta*: before operation, *brown*: 90% partial embolisation, *green*: total embolisation

arterial aneurysms they have more rectangular shape with *S*-like sides (figure 7).

In case of arteriovenous malformations, the *vp*-diagrams constructed for the flow in the afferent vessel (incoming vessel supplying the AVM nidus with the blood) can be used to describe the degree of the embolisation during the treatment procedure. The goal of an embolisation is to fill the AVM nidus with the embolisation agent (adhesive or non-adhesive material) in order to block the blood flow through it. During this procedure the velocity and flow rate decrease and the pressure increases leading to a shift of the *vp*-diagram in the upper-left direction (figure 8).

5. Conclusion

The data retrieved during the operation can be used for patient-specific numerical modelling and evaluation of the operation. In particular, the common medical recommendation for the AVM treatment is to embolise the fistula compartment, if present, at first, and to limit the volume of the embolisation to 60%. Using the clinical data, these recommendations are confirmed in [8, 9]. Applications to patient-specific numerical simulations of the blood flow in cerebral arterial aneurysms are presented in [10, 11].

The measurement system presented in this work can be used as an additional instrument in neurosurgery for assessment and monitoring of the operation procedure. The monitoring of the

blood flow parameters during endovascular interventions was approved by the Ethics Committee at the Meshalkin Novosibirsk Research Institute of Circulation Pathology and included in certain surgical protocols for pre-, intra- and post-operative examinations [12].

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