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Artificial Circulation Effect on Oxygen Saturation in the Brain Phantom

Olga Nikona[1, *], Roberts Leibuss[2, 3, *], Rihards Starinskis[3], Davis Polins[2], Davis Mackevics[2, 4], Yuri Dekhtyar[1], Vlads Vulkanovs[5], Eva Strike[1, 3]

[1]Medical Engineering and Physics Faculty, Riga Technical University, Riga, Latvia

[2]Pauls Stradins Clinical University Hospital, Riga, Latvia

[3]Medical Faculty, Riga Stradins University, Riga, Latvia

[4]Medical Faculty, University of Latvia, Riga, Latvia

[5]Engineering Department, The University of Manchester, Manchester, United Kingdom

Email address:

nikonaolga@gmail.com (Olga Nikona)

[*]Corresponding author

Abstract: Cardiovascular surgery represents a field where the anesthetist frequently deals with quickly evolving conditions associated with anesthesia, perfusion, and the scope of surgery, that have a direct and indirect impact on the oxygen delivery to organs and tissues and its consumption ratio. The prospects of predicting the oxygen concentration influential factors on the brain create a possibility for effective decisions in the crucial moments of cardiac surgery during a cardiopulmonary bypass, to choose specific neuroprotection to decrease postoperative neurologic complication risk. Nowadays, near-infrared spectroscopy (NIRS) technology has been used to perform cerebral oximetry analysis. By reviewing available literature, the work on the possible dependence of artificial blood circulation on oxygen concentration in the brain is provided. This research aims to investigate how artificial circulation, specifically the flow and viscosity of the fluid equivalent to blood, affects oxygen concentration in the cerebral phantom. The thesis contains methodology for measuring the concentration of oxygen was considered, as well as the manufacture of a phantom of the brain and an equivalent blood fluid. The results illustrate that the artificial blood flow rate has a non-linear effect on the oxygen concentration in the brain phantom. This was confirmed through the value of the oxygen concentration in the brain phantom under conditions of artificial blood circulation $rSO_{2avg.}$= 85% with laminar flow and the value of $rSO_{2avg.}$= 78% with turbulent flow. Additionally, it was proven that as the viscosity of the blood-equivalent fluid increases, the oxygen concentration decreases almost linearly. The calculated average rSO_2 value at minimum viscosity η=2.0 mPa·s and flow rate Q=0.5 l/min has maximum $rSO_{2avg.}$=85%, while at maximum viscosity η=4.2 mPa·s, rSO_2 average value was the smallest $rSO_{2avg.}$=72%. The study demonstrates that the type and rate of flow, as well as viscosity of the cardiopulmonary bypass, affect the measurements of oxygen concentration in the brain phantom.

Keywords: Neuroprotection, Cardiopulmonary Bypass Machine, Cardiac Surgery, Brain Phantom, Near-Infrared Spectroscopy, Artificial Blood

1. Introduction

Nowadays, the primary goal in medicine is the safety of the patient during surgery. One of the several unsolved problems so far has been the timely transport of oxygen, and the assessment and analysis, prediction of its delivery efficiency during a cardiopulmonary bypass. This is significant in the brain, since it makes up 2% of the body weight but consumes 20% of the oxygen delivering the body. The brain possesses a vast capacity to accumulate nutrients, and this requires a constant high amount of oxygen. Moreover, the brain tissue can be without oxygen supply

only for a short period (up to 5 minutes). After this period, damage to the brain tissue begins to appear. The longer the time of anoxia, the higher the level of tissue damage [5]. Therefore, it is necessary for the medical staff to respond to changes in oxygen concentration parameters in the shortest possible time and to understand what could affect it to save the patient's life and avoid postoperative complications.

This field is particularly significant to cardiac surgery, where anesthesiologists are most often faced with rapidly changing factors that directly affect oxygen delivery to organs and tissues. Taking this into account, an opportune assessment of regional oxygenation adequacy can prevent potential neurological disorders. Foremost, it is related to the use of artificial circulation, as well as the effect of hypothermia not only on vascular tone but also on cellular oxygen transport mechanisms. There are several methods for assessing oxygen transport. It should be noted that most of them are distinguished by a higher degree of invasiveness and/or a soaring price.

Currently, one of the prospective indicators of oxygen transport is regional oximetry which reflects the oxygen content in the studied region rSO_2. Until now, oximetric analysis is performed using near-infrared spectroscopy technology (NIRS). This technique is distinguished by non-invasiveness, ease of use and the ability to analyze data in real-time. The use of cerebral oximetry has become widespread in clinical practice and especially in cardiac anesthesiology [2, 13].

By reviewing available literature, the work on the possible dependence of oxygen concentration in the brain phantom on artificial blood circulation is highlighted. Konishi et al. present research which demonstrates how brain oxygen concentration and cerebral blood flow rate change in mild +Gz hypergravity conditions [4]. In this study, cerebral flow velocity in the middle cerebral artery (MCBFVMCA) was measured using transcranial Doppler sonography. Simultaneously, data for regional brain oxygenation during C-rSO_2 mild +Gz hypergravity with participants in a seated position was collected. C-rSO_2 generators did not change significantly throughout the centrifugation, but MCBFVMCA gradually decreased from the beginning from 0 to 5 minutes (-1.2%) and significantly decreased at 5-10 minutes (-4.8%), 10-15 minutes (-6.7%) and 15-20 min (-7.4%). According to the results, it was noted that as the brain flow rate decreases, the regional brain oxygen saturation also decreases. Additionally, the spreading of the results decreases and becomes more stable. The study reported a near-fainting case, suggesting the possibility that C-rSO_2 may significantly decrease in CBF during the development of the pre-fainting state during +Gz hypergravity [4]. Analyzing the research data, it can be hypothesized that as the artificial blood flow rate decreases, the average value of oxygen concentration and the correlation of the obtained measurements will decrease.

Two main types of blood flow were distinguished in human blood vessels: laminar and turbulent flow. Above all, the blood flow in blood vessels possesses a laminar characteristic movement in a layer: blood cells move in the center, plasma moves closer to the wall. At the wall itself, it remains almost static. The narrower the blood vessel, the closer the central layers are to the wall, consequently, the greater the inhibition of blood flow speed [7]. As a result, analyzing the literature sources on the possible influence of the type of flow on the oxygen concentration, it is a possibility that with a turbulent flow type, the oxygen saturation in the brain phantom will be lower.

Until now, there have been few experiments and clinical studies related to the results of cerebral oximetry on an artificial blood circulation machine. Guskov studied regional oximetry under conditions of artificial blood circulation, specifically at different temperature regimes [3]. These were:

1) normothermic (group 1A) - perfusion temperature 36.0°C
2) moderately hypothermic (group 1B) - perfusion temperature 32.0°C
3) hypothermic (group 1C) - perfusion temperature 28.0-29.0°C.

In this experiment, measurements were conducted at the beginning of the operation before artificial blood circulation, after 15 minutes with artificial circulation (AC), after 45 minutes with artificial circulation and at the end of the operation. In the normothermic group, the brain and tissue oxygenation demonstrated a reduction before AC on the background of a slight decrease in temperature (no more than 0.7°C). Moreover, this was significantly lower than the initial level at all subsequent stages of the operation. The maximum decrease in $SctO_2$ was observed in the 15-minute AC phase when $SctO_2$ was significantly lower than the result of the previous phase. Tissue oxygenation, like that of the brain, decreased during the second phase of the study and was also lower at all stages of the operation except at the end of the operation. Core temperature was considerably lower than output in the pre-AC and AC 15-minute stages. In the AC group, the brain and tissue oxygenation were reduced before AC and remained reduced during the subsequent phases of the study in moderate hypothermia. At the end of the operation, $SctO_2$ and StO_2 increased significantly after AC and returned to baseline. In the hypothermic AC group, cerebral oxygenation decreased concerning the outcome from the second follow-up period and remained notably low throughout the operation.

According to J. Frenkel's theory, the viscosity of the liquid depends on the temperature (by increasing the temperature, the viscosity decreases, or vice versa). Based on the results of this study, it is possible to predict what the oxygen concentration measurements will be at different viscosities of the blood-equivalent liquid. It can be assumed that it will be the effect of viscosity on the results of oxygen concentration measurements [3]. This is consequential to the fact that the viscosity of a liquid is inversely proportional to the temperature. Therefore, at the perfusion temperature the oxygen content in the brain also decreases and as the viscosity of the blood-equivalent fluid increases, it is highly possible that the oxygen content in the brain may decrease.

The research aims to investigate how the results of measurements of oxygen saturation in the brain phantom depend on the viscosity, flow rate and type (turbulent/laminar) of the flow in the blood fluid equivalent to artificial blood circulation. The obtained results can be implemented by personnel in hospitals that perform heart and aortic arch surgeries with artificial blood circulation to prevent neurological complications during surgery. The processed results can be used for the identification of an abnormal blood circulation condition in the brain in clinical situations. Defined metrics can help determine the accuracy of readings.

2. Materials and Methods

Oxygen is vital for maintaining the rational physiological functions of the human body, especially for the unobstructed functioning of the brain. For patients undergoing heart or aortic arch operations, an artificial blood circulation device is used. Through implementing a pump, it ensures optimal blood flow in two directions (venous and arterial blood flow) and metabolic processes in the body. Additionally, it is intended for the short-term performance of heart and lung functions. Therefore, it is significant to control oxygen saturation parameters during surgery and maintain optimal blood flow conditions under artificial blood circulation. To simulate the experiment, it is necessary to perform measurements in an anatomically and physiologically similar brain phantom with blood-equivalent fluid.

2.1. Brain Phantom Construction

After analyzing the market for available NIRS brain phantoms, it was concluded that commercial phantoms were overly expensive for this experiment. Therefore, it was decided to replace it with a substantially cheaper alternative, creating a brain phantom in laboratory conditions that would comply with all the requirements. Since the phantom simulates complex human structures, it must satisfy several criteria to be able to perform the measurements correctly. One of the key features is sufficient permeability to red and infrared radiation. This is to be able to obtain a stable signal and make measurements with a cerebral oximeter. Secondly, the dimensions of the phantom must demonstrate the ease of alteration, as the radii of the tube will be changed during the experiment to simulate turbulent flow. Moreover, the phantom must be movable and resistant to the pressure of artificial blood flow. The phantom must be practically equivalent to the human brain. Anatomically, the human head consists of five layers: skin, skull, cerebral cortex, and cerebral blood vessels [6]. Since the meninges present a complex structure, it was decided to simplify the structure of the phantom and divide it into two types of tissue: soft and hard. The soft tissue or area inside of the head is simulated by a blood-equivalent fluid. The blood vessels are simulated by silicone tubes designed to resemble the main cerebral arteries that transport oxygen from the heart (Figure 1). Hard tissue or the human skull is simulated by a plastic container

(200x200mm) with a thickness of 2mm.

To design a phantom that is physiologically equivalent to a human, it is necessary to model the main arterial and venous system of the brain. This will be created according to anatomical parameters and total vascular resistance. For the total resistance of the blood vessels of the cerebral phantom to be identical to the blood vessel resistance of the human brain, the required length of the middle cerebral artery will be calculated. The rest of the cerebrovascular parameters are presented in Table 1. The diameters of arteries and veins were shown in millimeters, which are in the following intervals:

Table 1. Dimensions of the blood vessels. Source: [1, 10, 12].

Type of the blood vessel	Diameter [mm]	Length [mm]
Aorta	30	50
Common carotid artery	6-8	130
Internal carotid artery	4-6	80
External carotid artery	4-6	100
Middle cerebral artery	3-4	—
Jugular vein	10-17	120
Right brachiocephalic vein	10-14	20
Superior vena cava	20-25	60

According to the theoretical limits of blood vessel parameters, silicone tubes with appropriate lengths and diameters were selected to create a simplified cerebral blood vessel system that will form an artificial circulatory circle. The system includes a path of about 300 mm from the artificial blood circulation apparatus to the cerebral phantom. With tubes exiting the artificial blood circulation apparatus, the cannulation site in the aorta, the common carotid artery. After which a bifurcation is created into the external and internal carotid arteries, the middle and other cerebral arteries. These are allocated directly in the phantom of the brain, and the path to the artificial blood circulation apparatus which was assumed to be about 300 mm begins with the jugular vein and flows to the right brachiocephalic vein, the superior vena cava and enters the artificial blood circulation apparatus. Soft silicone tubes with an internal radius of $\emptyset 6$ mm, $\emptyset 4$ mm, $\emptyset 4$ mm and $\emptyset 1.5$ mm have been used to simulate the blood vessels of the brain: the common carotid artery, the internal and external carotid arteries, and the middle cerebral artery.

Based on the anatomical parameters of the blood vessels of the brain, the total resistance in the blood vessels of the human brain was calculated using the equivalent circuit of the vascular system of the brain phantom, respectively the electrical circuit (Figure 1). It was calculated according to Ohm's law, the formula of series and parallel connection in circuits, and according to Pauzeil's formula. Knowing the total hydraulic resistance, the required length of the tube that models the middle cerebral artery can be calculated [9]. In the calculations, it was acceptable to use the minimum values of the numbers from Table 1.

As a result, the length of the tube that models the middle cerebral artery of the brain phantom is about 93.5 mm. Through the obtained value, the hydraulic resistance of the

vascular system in the phantom with the tubes used to simulate blood vessels is equivalent to the hydraulic resistance of the vascular system in the human brain. By knowing the necessary parameters for modelling, a brain phantom was developed.
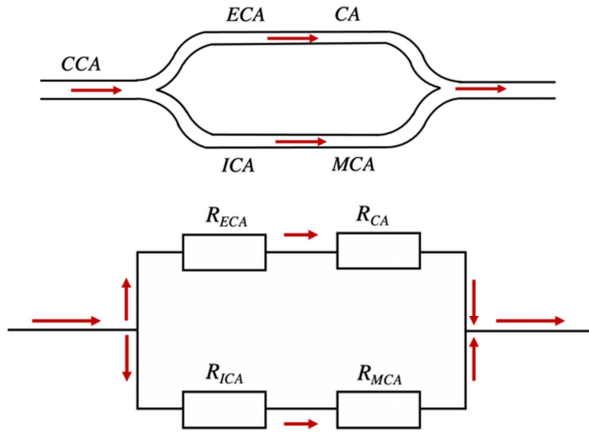

Figure 1. *Schematic representation of brain phantom tube system.*

(CCA – common carotid artery, ECA – external carotid artery, ICA – internal carotid artery, CA – other cerebral arteries, MCA – middle cerebral artery).

2.2. Blood Equivalent Fluid Formation

The blood prototype received special attention during manufacturing, as all the results of the analysis will be based on data read directly from the blood-equivalent fluid and was designed to match the parameters of human blood at 37°C, namely fluid density is 1053 kg/m^3 and fluid viscosity is 3-4 mPa/s [8].

Since a blood-equivalent fluid that does not contain hemoglobin (to which oxygen molecules physiologically bind) is used instead of human blood, the fluid must be created with particles that absorb and scatter infrared radiation. In addition, the particles must obtain a stable oxygen saturation rSO$_2$ value within 50 - 80%, in near-infrared spectroscopy at 730 and 810 nm wavelengths. Furthermore, already existing studies were analyzed where ink is most often used to ensure the absorption coefficient, due to its' reduced scattering coefficient μs ~ 0. To ensure scattering, an intralipid solution is typically used that forms microspheres in an aqueous solution which represents nanoparticles with an average size of 100 nm.
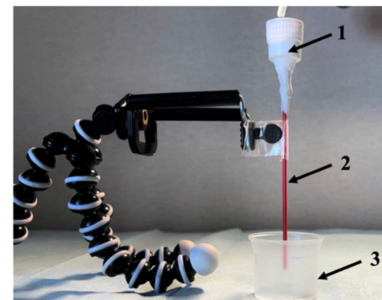
The first homemade blood phantoms were made from NaCl solution, dark blue "MALEVICH" pen ink and different proportions of soybean oil to achieve desired rheological parameters and a stable signal on the cerebral oximeter. However, to obtain a stable rSO$_2$ signal in the range of 50-80%, it was necessary to apply a large amount of soybean oil which makes the viscosity higher than that of blood. Therefore, it was experimentally decided to use an emulsion for intravenous administration of "Propofol" that contains soybean oil. This, in turn, provides scattering microspheres that reflect infrared waves in NaCl solution which are nanoparticles in nature and give the required measurement

result. Additionally, it was decided to replace the ink with potassium permanganate (KMnO$_4$), as it is much more beneficial and cheaper. Moreover, it requires a much smaller quantity with the same absorption effect.

The first measurements of oxygen concentration with potassium permanganate are made by mixing 3g of potassium permanganate (KMnO$_4$) with 250 ml of NaCl solution and connecting the electrodes. This resulted in the INVOS 5100 cerebral oximeter generating a Poor Signal Quality (PSQ) error. Next 40 ml of "Propofol" emulsion were mixed, after which an rSO$_2$ indicator of 54% was observed. This corresponds to the patient's norm indicators during surgery with an artificial blood circulation apparatus. Afterwards, another 40 ml of "Propofol" was added and a value of rSO$_2$ = 71% was obtained. It was decided to maintain the blood-equivalent fluid composition and change the viscosity by adding glycerol.

2.3. Capillary Viscometer

Traditionally, the viscosity of liquids is measured with instruments called viscometers. To determine the viscosity of the liquid and control it during the work, it was decided to measure it experimentally by creating a capillary viscometer which was made at home from a photo stand. A tube of WD-40 oil with a funnel was attached to the stand, and a medicine cup of 15ml with a volume was placed under it which simulates a reservoir (Figure 2).

1— Funnel, 2—pipe, 3—reservoir

Figure 2. *Capillary viscometer.*

To determine the viscosity of the blood-equivalent fluid, a comparison method was implemented. The time of filling a certain volume of water through a capillary tube in the reservoir (up to a marked level) is measured and, equivalently, the artificial blood filling time. The time ratio should be equal to the ratio of the viscosity coefficients of water and blood, according to Hagen-Poiseuille's law (fluid flow, Q is inversely proportional to blood viscosity, η and inversely proportional to flow time, t). From this, the viscosity is directly proportional to the flow time. The ratio of the viscosity coefficients of water and blood is directly proportional to the ratio of the filling time of water and blood flow. Therefore, knowing the viscosity coefficients and the experimental water filling time of the reservoir, it is possible to calculate what the reservoir filling time should be so that the blood-equivalent fluid viscosity (at room temperature)

coincides with the blood viscosity. By inserting known parameters, the required filling time of blood-equivalent fluid can be expressed from the expression.

2.4. Brain Phantom Vascular Flow Delivery Tube System

The cerebral oximetry device "SOMANETICS INVOS 5100C" is used to perform measurements and observe the relationships between artificial blood circulation conditions and the results of oxygen concentration measurements in the brain phantom. To ensure the supply of fluid flow in the phantom of the brain, the "STOCKERT S5" artificial blood circulation device was selected (see Figure 3).
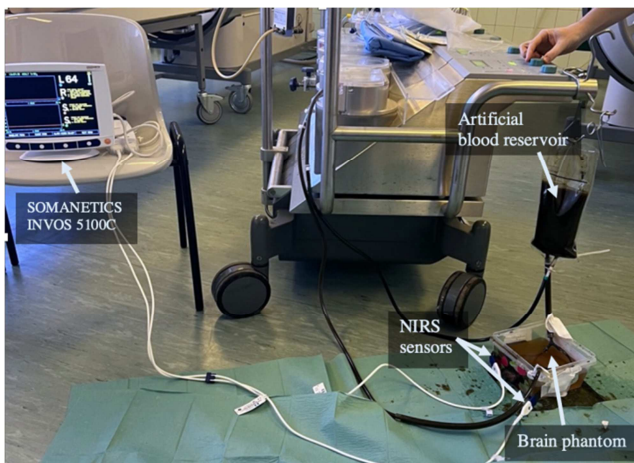

Figure 3. Brain phantom vascular flow delivery tube system.

A simplified closed-loop artificial blood circulation system was used for the study. The system represented a connection of the brain phantom with the artificial blood circulation machine. From the arterial side of the phantom, tubes were connected to the main pump which supplies blood-equivalent fluids to the phantom. From the venous side of the phantom, tubes are connected to a fluid reservoir. This is where the blood-equivalent fluid was aspirated and delivered to the phantom continuously.

The artificial blood circulation machine can provide blood flow at different rates, from 0.5 to 7 l/min. These values could be calculated individually for each patient to ensure the support of the essential physiological function. For adults, the optimal blood flow rate is about 70 ml/kg/min which means that for a patient with a mass of 70 kg the blood flow rate Q is about Q= 4.9 l/min [11]. Because this experiment simulates the path to the brain and back, the velocities between 0.5 and 1.2 l/min were used. This is about 10-15% of the blood supply from a whole body which represents the consumed volume of blood in the brain at rest [10]. Since the pump for the artificial blood circulation machine works regardless of whether the total resistance in the system has changed, the pump delivers the same amount of fluid. Due to this, the measurement results showed oxygen concentration data as dependent on the flow rate Q. To conduct an experiment and check the effect of artificial blood circulation on the oxygen concentration in the brain phantom, a blood-equivalent fluid

(with equivalent rheological parameters – viscosity and density) was created. This is regarded as a blood phantom with a stable oxygen concentration generator rSO_2 on a cerebral oximeter.

3. Results

Measurements were made 17 times and the sensor that reads the data was not moved during all the experiments to avoid influence on the result values.

3.1. Results of Oxygen Saturation Measurements Dependence on Flow Rate

The experimental data show that the artificial blood flow rate has a non-linear effect on the oxygen saturation in the brain phantom. From the minimum flow rate Q=0.5 l/min to Q=0.75 l/min the average value of the oxygen concentration significantly decreases, at a minimum viscosity of 2mPa*s the maximum $rSO_{2avg.}$ = 85% was observed, at Q= 0.75 l/min concentration decreased to $rSO_{2avg.}$= 69%. Furthermore, by increasing the flow rate to Q=1.0 l/min, the rSO_2 average value increases to 71%, at rates Q=1.1 l/min and Q=1.2 l/min oxygen concentration increases to 77% and plateaus afterwards.

Additionally, the data confirm that oxygen saturation depends on the type of flow. At the laminar flow in the brain phantom, the average value of oxygen concentration $rSO_{2avg.}$ = 85% is greater than the average value of oxygen concentration $rSO_{2avg.}$ = 78% at turbulent flow.

Another crucial result represented that at the same flow rate Q=0.5 l/min, as the viscosity increases, the oxygen saturation decreases. At a minimum viscosity of η=2.0 mPa·s, a maximum $rSO_{2avg.}$=85% was observed. By increasing the viscosity to η=2.7 mPa·s, the oxygen concentration value decreases to $rSO_{2avg.}$=78%. Subsequently, by increasing the viscosity to η=3.4 mPa ·s, the mean value of oxygen concentration continues to decrease, and at the maximum viscosity of η=4.2 mPa·s the average value of rSO_2 was the smallest $rSO_{2avg.}$=72%. The effect of artificial blood flow rate on the oxygen saturation in the brain phantom at different viscosities of the blood phantom was considered to increase the accuracy of the study. Measurements of rSO_2 have been performed at artificial blood circulation flow delivery rates of 0.5; 0.75; 1.0; 1.1 and 1.2 l/min. The obtained data were organized and represented graphically in one image (Figure 4).

Analyzing the relationship graphically represented in Figure 4, it can be observed that at different viscosities of the blood equivalent in liquid, the nature of the change in oxygen concentration is similar, but not linear: by increasing the minimum flow rate from 0.5 l/min to 0.75 l/min the average value of oxygen saturation decreases. However, when increasing the flow rate from 0.75 l/min to 1.0 l/min oxygen concentration increases. The case with the minimum viscosity stands out as the average value remains the same. Increasing the flow rate to 1.10 l/min the oxygen concentration continues to increase at all used viscosities. Significantly, when increasing the flow rate to 1.2 l/min, the

oxygen concentration remained the same.

It is possible that the obtained result could be affected by the formation of pipe vibrations in the brain phantom due to gradual increase of the flow rate in the static state. Moreover, this could cause the formation of oxygen bubbles in the pipe system. This can be proven by calculating the standard deviation of the oxygen concentration. The observation is that at minimum viscosity the standard deviation was the highest σ = 4.26 at Q = 0.75 l/min flow rate, while the lowest σ = 1.06 is at maximum viscosity and at the same values of Q =0.75 l/min.
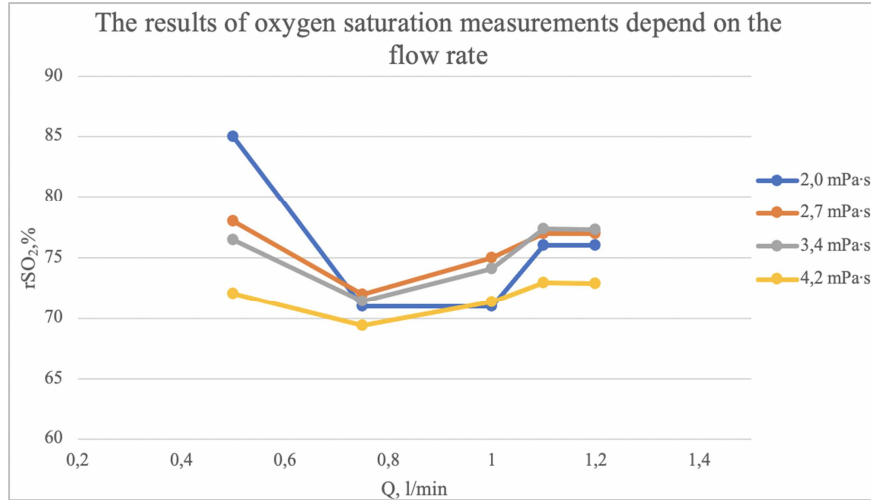

Figure 4. Oxygen concentration dependence on liquid viscosity.

3.2. Results of Oxygen Saturation Measurements Dependence on the Type of Flow

The effect of artificial blood circulation on the oxygen saturation in the brain phantom was considered, at the constant flow rate Q=0.5 l/min. By reducing the radius of the tube to 0.5 mm which simulates the carotid artery in the cerebral phantom, a turbulent flow of artificial blood circulation (Re>4000) is created. This provided a significantly lower oxygen concentration observed than with a tube radius of 3 mm and laminar flow (Figure 5).

At laminar flow, a decrease in oxygen saturation from rSO_2 = 90% to rSO_2 = 82% is observed, starting from the appearance of the signals until 18 seconds of the experiment. This could be because the experiment is started from a static state and when the blood phantom flow supply is turned on, tube vibrations could appear. This affects the increased result at the beginning of the experiment. A stable oxygen concentration of 82% was then observed with a slight fluctuation within error limits of ±1. On the other hand, with the turbulent flow there is an increase and decrease in oxygen concentration in the range of 76% to 79%. This symbolizes that with the turbulent flow there is a greater dispersion of data, excluding the initial period of laminar flow data recording.
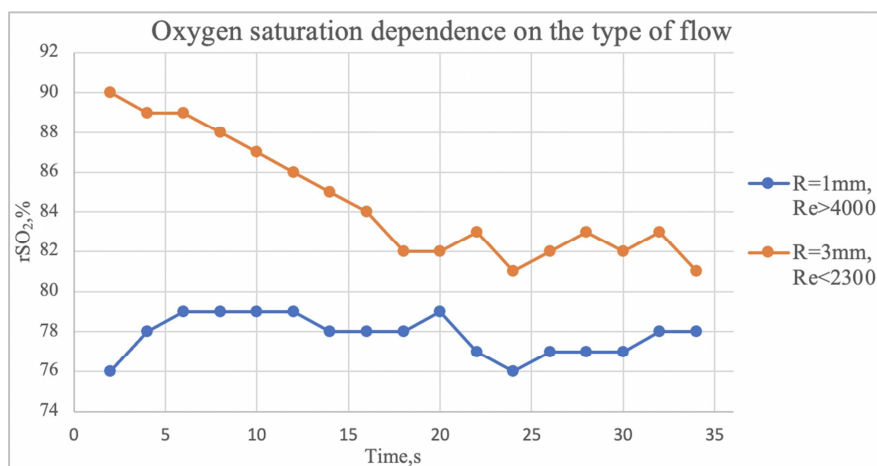

Figure 5. Oxygen saturation depends on the type of flow.

The obtained data confirmed that with the type of turbulent flow the oxygen concentration in the brain phantom will be lower. This can be presented through the value of the oxygen concentration in the brain phantom under conditions of artificial blood circulation $rSO_{2avg.}$ = 85% with the laminar flow which is higher by 7% than the turbulent flow value of $rSO_{2avg.}$ =78%. This could be influenced by the nature of the movement of the molecules of the blood-equivalent fluid -

the creation of eddies which could interfere with the normal reflection or absorption of the signal.

3.3. Results of Oxygen Saturation Measurements Dependence on Viscosity

Measurements of oxygen saturation dependence on blood-equivalent fluid viscosity were made. The viscosity was increased experimentally using glycerol. Data were recorded at a minimum flow rate Q=0.5 l/min, as this is the rate at which the highest rSO_2 values were obtained. Additionally, the concentration of oxygen in the brain phantom and dependence on the viscosity of the blood-equivalent fluid is graphically reflected in Figure 6.

From Figure 6. it can be observed that as the viscosity of the blood-equivalent fluid increases, the oxygen concentration decreases almost linearly. The calculated average rSO_2 value at minimum viscosity η=2.0 mPa·s and flow rate Q=0.5 l/min has maximum $rSO_{2avg.}$=85%, while at maximum viscosity η=4.2 mPa·s rSO_2 average value was the smallest $rSO_{2avg.}$ = 72%.
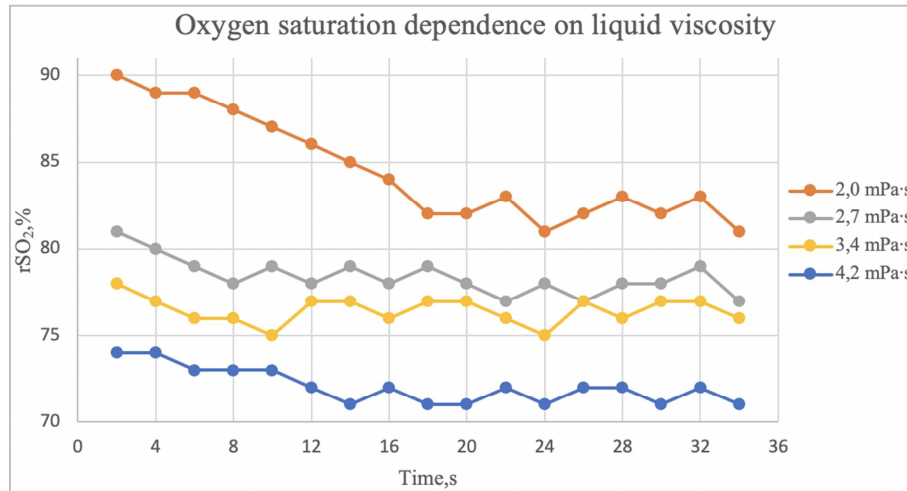

Figure 6. Oxygen concentration dependence on liquid viscosity.

4. Discussion

As a result of the research, the influence of the flow and viscosity of the equivalent blood fluid on the oxygen concentration in the brain phantom was investigated. The analysis was performed under conditions of artificial blood circulation, similar to cases in patients undergoing heart and aortic arch operations with artificial blood circulation. The methods implemented aid that it is possible to create a phantom of the brain with a vascular network and blood-equivalent fluid using data and experimental theory available in the literature. Furthermore, the possibility to use potassium permanganate ($KMnO_4$) in a dissolved NaCl solution for the preparation of a blood-equivalent fluid was proven to be acceptable for the experiment. This was achieved through using an emulsion for intravenous administration of "Propofol" as scattering nanoparticles that reflect infrared waves.

It is possible to continue the started research and analyze other possible influencing parameters on the oxygen concentration in the brain phantom. The following recommendations can be made for further research:

1) Repeat oxygen concentration measurements in the brain phantom at higher flow rates, in the range from 1.2 l/min to 5 l/min with a step of 0.25 l/min to check the effect on the measurement results;
2) Repeat oxygen concentration measurements in the brain phantom at viscosities less than 2.0 mPa*s and viscosities greater than 4.2 mPa*s to check the effect on the measurement results;
3) Perform measurements of the concentration of oxygen in the phantom of the brain, using maximum theoretical values for the construction of vascular networks, in order to check the effect on the measurement results;
4) Measure the oxygen concentration in the brain phantom by changing the depth of blood vessels continuously to check the effect on the measurement results;
5) Place the sensors from different sides of the phantom to collect the oxygen concentration data in the phantom of the brain;
6) Use brain and blood phantoms of different materials to measure the oxygen concentration in the brain phantom;
7) Collect oxygen concentration measurements in a more detailed brain phantom, creating the most complex vascular system with capillaries;
8) Utilize other available NIRS sensors to measure the oxygen concentration in the brain phantom;
9) Record the data of the oxygen concentration in the phantom of the brain which is designed according to the anatomical parameters of the blood vessels in the head of children, to observe the potential new relationship.

5. Conclusion

The work investigated how the results of oxygen

concentration measurements in the brain phantom depended on artificial blood circulation, i.e. on the rate of supply of artificial blood flow, the type of flow and the viscosity of the created blood-equivalent fluid. To conclude, the oxygen concentration in the cerebral phantom depends on artificial blood circulation.

The findings of the study could be used to further investigate the dependencies. It is possible to consider each of the influential factors separately to observe which of them possesses the most explicit features of critical impacts on the oxygen concentration. For instance, the implementation of liquids with viscosity exactly equal to that of the real blood could improve acknowledgement of the research. Additionally, experiments with the range of temperatures of the liquid while utilizing the same methodology may provide new insights and dependencies. Moreover, other anesthetic drugs can be used in the study to simulate cardiac surgery and reveal drug properties crucial to the artificial blood circulation.

This is significant, as the further research in this area may be useful for improved detection of neurological complications during cardiac surgery. Furthermore, new dependencies can be identified that can be used to detect circulatory disorders in the brain in clinical situations.

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