The cerebral network’s reconstruction by MRI methods and the hemodynamics study of small laboratory animal in type 1 diabetes

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Abstract. The blood realizes the transport of substances, which are necessary for livelihoods, throughout the body. The assumption about the relationship some disease and structure of vasculature (in particular of brain) is natural. In the paper we consider models of Willis’ circle for two groups of laboratory mice – one control group and another with diabetes. Vascular net obtained as a result of preprocessing MRI data. The purpose of the work is to determine the effect of type 1 diabetes on the properties of the laboratory mice vasculature.

1. Introduction

Magnetic resonance imaging (MRI) is a non-destructive technique used to examine the inner structure of objects. The MRI is based on the Nuclear Magnetic Resonance (NMR) phenomenon, which is the rearrangement of magnetic moments of nonzero-spin nuclei in the external magnetic field. Employment of MRI in the investigation of bio-tissues and bio-fluids is based on NMR of hydrogen atoms. A specialized MRI technique called Magnetic Resonance Angiography (MRA) was developed to examine the circulatory system in living organisms [1]. Reconstructing the vasculature (and, in particular, that of the brain) of small laboratory animals in type 1 diabetes is of interest by virtue of applications of these results to deeper and more precise study of this severe disease. Animals genetic line and causing diabetes manipulation is briefly described in Section 2. MRA methods and reconstructed cerebral vasculature [2-4] is described in Section 3. Results of numerical analysis of the blood flow in the constructed models are obtained using software ANSYS/CFX and presented in Section 4. Results of statistical analysis of geometric configuration of blood net for the vessels of the Willis’ circle and results of numerical analysis are carried out in Section 5.
2. Description of used animals
In this work used MRA angiograms obtained from male and female mice line NOD.CB17-Prkdcscid/J (NOD SCID). These mice were investigated in 14 weeks old. The diabetes group was injected intraperitoneally with streptozotocin (STZ; Sigma, USA) dissolved in 0.01 M citrate buffer at pH 4.2. A total of 150 mg STZ/kg body weight mass. The control group was injected with the same volume of the citrate buffer.

3. MRA methods and reconstructed cerebral vasculature
Non-fragmented three-dimensional models of vessel nets of all animals under investigation have been constructed using cylindrical RF coil MRI data. We use the software ITK-Snap [5] for segmentation. In Figure 1 you can see images of three-dimensional models of cerebral vessel nets for female animals of NOSCID genetic line, in Figures 2 — for male animals. Hereafter we denote Mxx male animals and Fxx female ones. The suffix "d" is used to indicate a sick animals.

![Figure 1. Models of vessel nets for female animals of genetic line NOSCID.](image-url)
Figure 2. Models of vessel nets for male animals of genetic line NOSCID.
The next stage is the trimming and smoothing of the vasculature. Examples of the resulting vascular network in the vicinity of the circle of Willis are shown in Figure 3.

![Figure 3](image)

**Figure 3.** Examples of trimmed and smoothed vasculature.

At the received configurations of all mice vascular networks were measured geometrical parameters. Namely, the angles between the vessels of Willis’ circle and sections of vessels in selected positions. Measured angles of the circle of Willis are shown in Figure 4.

![Figure 4](image)

**Figure 4.** Measured angles of the circle of Willis.

Results of measurements of angles between the vessels of Willis’ circle (being the part of build three-dimensional models) shown in Table 1. In the table rows correspond to condition numbers of investigated animals. The values of angles between blood vessels in places of their confluence adduce in columns. The angles between left and right anterior cerebral arteries (ACA) are adduced in the second column. The angles between left and right ACA and posterior communication arteries (PCoA) are adduced in the third and fourth columns. The angle between left and right posterior cerebral arteries (PCeA) is adduced in the fifth column. The angle between left and right anterior cerebral arteries (ACA) and middle cerebral artery (MCA) is adduced in the sixth and seventh column. The angle between left and right carotid arteries (CA) and posterior communication arteries (PCoA) is adduced in the eighth and ninth column.

Selected sections of vessels are shown in Figure 5.
Table 1. Angles of Willis’ circle (in degrees).

| Animal | ACA | ACA and PCoA (l.) | ACA and PCoA (r.) | PCeA | ACA and MCA (l.) | ACA and MCA (r.) | CA and PCoA (l.) | CA and PCoA (r.) |
|--------|-----|------------------|------------------|------|-----------------|-----------------|-----------------|-----------------|
| F4d    | 41  | 157              | 162              | 126  | 80              | 86              | 53              | 53              |
| F9d    | 48  | 162              | 161              | 131  | 86              | 78              | 55              | 42              |
| F11    | 46  | 165              | 164              | 165  | 115             | 64              | 57              | 59              |
| F13    | 46  | 160              | 170              | 157  | 87              | 82              | 43              | 66              |
| F14    | 23  | 163              | 165              | 134  | 68              | 79              | 58              | 55              |
| F15    | 39  | 164              | 164              | 146  | 44              | 74              | 61              | 58              |
| F16    | 39  | 162              | 160              | 145  | 88              | 76              | 53              | 57              |
| F17    | 35  | 159              | 161              | 124  | 65              | 64              | 51              | 58              |
| F38d   | 55  | 161              | 158              | 139  | 79              | 57              | 49              | 58              |
| M20d   | 46  | 166              | 158              | 135  | 72              | 57              | 57              | 55              |
| M21d   | 50  | 163              | 151              | 125  | 59              | 72              | 54              | 50              |
| M25d   | 35  | 166              | 165              | 118  | 54              | 56              | 62              | 51              |
| M26d   | 64  | 151              | 156              | 140  | 86              | 57              | 58              | 54              |
| M28    | 36  | 160              | 152              | 133  | 73              | 114             | 62              | 55              |
| M29    | 38  | 168              | 160              | 94   | 56              | 61              | 51              | 45              |
| M30d   | 37  | 160              | 161              | 142  | 65              | 78              | 54              | 60              |
| M33    | 42  | 167              | 157              | 114  | 76              | 75              | 57              | 51              |
| M34    | 37  | 162              | 151              | 128  | 58              | 76              | 52              | 53              |
| M35    | 42  | 163              | 160              | 129  | 66              | 64              | 58              | 57              |
| M36    | 50  | 160              | 158              | 132  | 67              | 52              | 47              | 54              |
| M37    | 41  | 163              | 151              | 137  | 69              | 57              | 55              | 57              |

4. Numerical analysis of hemodynamics

Software ANSYS/CFX is used for numerical analysis of hemodynamics [6, 7]. Computation carried out on the base of supercomputer centre of Novosibirsk State University. Model of incompressible viscous liquid (viscosity and density of liquid is given equal to viscosity and density of blood) is used for numerical modelling. Walls of blood vessels considered to be rigid and no-slip condition is given to them. Flow considered to be laminar, so the mathematical model of the blood flow consists of four equations expressing conservation laws of mass and three pulse component.

At the inlets of vertebral arteries and common carotid arteries we set blood flowrate, obtained on the basis of NMR phase velocimetry. In outlets we set volumetric rate different from the vessel outlet in the cross-section area.

As a result of numerical calculations were obtained values of velocity and pressure in the
**Figure 5.** Selected sections of vasculature.

Vasculature. Examples of these results of numerical simulations are shown below. In Figures 6, 7 you can see streamlines and variations in mean pressure distribution of the vessel wall near Willis’ circle respectively.

**Figure 6.** Streamlines of the velocity vector.

5. **Statistical analysis**

Using results of numerical calculations we found the values of flowrate, average pressure and maximum speed for all inputs, outputs, and highlighted in Figure 5 cross sections.

Also, the hydraulic resistances of all parts of the bloodstream were computed between selected sections in Figure 5.
All data in the form of averages by groups are presented in the following Table:

|       | female          | male          |
|-------|-----------------|---------------|
|       | control (mean ± S.E.) | sick (mean ± S.E.) | p       |
|       | control (mean ± S.E.) | sick (mean ± S.E.) | p       |
| $R_{L,1-2}$ | 187.19 ± 48.76 | 174.56 ± 40.86 | 0.87   |
| $R_{L,3-4}$ | 49.43 ± 5.21  | 66.24 ± 4.08  | 0.08   |
| $R_{L,5-6}$ | 55.75 ± 6.35  | 81.99 ± 9.13  | 0.05   |
| $R_{L,7-8}$ | 25.09 ± 6.67  | 37.92 ± 2.63  | 0.24   |
| $R_{L,9-10}$ | 49.05 ± 12.68 | 40.83 ± 4.10  | 0.67   |
| $R_{L,11-12}$ | 164.40 ± 45.02 | 81.52 ± 17.93 | 0.26   |
| $R_{L,13-14}$ | 84.16 ± 13.99 | 171.44 ± 71.48 | 0.13   |
| $R_{L,15-16}$ | 139.05 ± 28.50 | 235.86 ± 40.59 | 0.09   |
| $R_{L,17-18}$ | 128.69 ± 38.46 | 158.49 ± 55.59 | 0.67   |
| $R_{L,19-22}$ | 201.16 ± 35.10 | 158.90 ± 37.52 | 0.48   |
| $R_{L,20-21}$ | 268.32 ± 110.74 | 212.14 ± 57.29 | 0.75   |
| $\Sigma R^L$ | 635.94 ± 167.00 | 556.30 ± 56.31 | 0.76   |
| $\Sigma R^R$ | 529.17 ± 68.84 | 689.01 ± 92.63 | 0.22   |
| $\Sigma R^L - \Sigma R^R$ | 106.77 ± 107.60 | -132.71 ± 75.38 | 0.19   |
| $\Sigma L$ | 0.65 ± 0.06   | 0.53 ± 0.03   | 0.23   |
| $\Sigma R$ | 0.56 ± 0.04   | 0.50 ± 0.02   | 0.32   |
| $\Sigma L - \Sigma S^R$ | 0.08 ± 0.04 | 0.03 ± 0.05 | 0.47 |
| $\Sigma O^L$ | 0.02 ± 0.01 | 0.03 ± 0.00 | 0.61 |
| $\Sigma O^R$ | 0.02 ± 0.01 | 0.01 ± 0.00 | 0.69 |
| $\Sigma O^L - \Sigma O^R$ | 0.00 ± 0.02 | 0.02 ± 0.00 | 0.64 |
| $\Sigma V^L$ | 216.06 ± 49.46 | 119.09 ± 11.76 | 0.22   |
| $\Sigma V^R_{max}$ | 208.34 ± 55.69 | 135.05 ± 10.35 | 0.40   |
| $\Sigma V^L_{max}$ | 7.72 ± 22.91 | -15.96 ± 8.91 | 0.51   |

Figure 7. Variations from mean pressure distribution on the vessel wall.
In this Table we denote $R$ – vascular hydraulic resistance, $R[10^3 \cdot Pa \cdot s/m^3] = \Delta P/Q$, where $\Delta P$ – pressure difference; $Q$ – volume flow rate; $S$ – vascular cross-section area, $[mm^2]$; $Q$ – blood volume flow rate $[cm^3/s]$; $V_{max}$ – maximum blood velocity, $[cm/s]$.

Upper indices denote: $R$ – right vasculature, $L$ – left vasculature, $M$ – medium vasculature. Number indices denote numbers of cross-section planes highlighted in Figure 5. The $\Sigma$ sign denote sum of certain parameters on all left or right vasculature.

Statistical analysis has performed on the basis of the Student’s t-criterion.

Using these data and the geometric characteristics of the vasculature. Statistical analysis was performed which showed that mainly significant differences between the control group of animals and sick one not identified. But in group of sick animals there is a otherwise relationship of indicators in the right and left vasculature in comparison with the control group. This applies primarily to summary resistance and summary maximum speed.

6. Conclusions

In the paper the construction of the models of vascular channel for the laboratory animals with and without diabetes are studied. MRI data is it possible to construct models of the vascular system, suitable for hemodynamic calculations and statistical analysis of vascular architectonics.

It was shown that there is influence of diabetes on morphological and hydrodynamical characteristics of Willis’ circle of adult animals is weakly expressed and manifests itself only in the another relationship of indicators in the right and left vasculature.

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