Construction and investigation of 3D vessels net of the brain according to MRI data using the method of variation of scanning plane

A A Cherevko\textsuperscript{1,2}, G S Yankova\textsuperscript{2}, S V Maltseva\textsuperscript{1,2}, D V Parshin\textsuperscript{1}, A E Akulov\textsuperscript{3}, A K Khe\textsuperscript{1,2} and A P Chupakhin\textsuperscript{1,2}

\textsuperscript{1} Lavrentyev Institute of Hydrodynamics of the Russian Academy of Sciences, Novosibirsk 630090, Russia
\textsuperscript{2} Novosibirsk State University, Novosibirsk 630090, Russia
\textsuperscript{3} Institute of Cytology and Genetics of the Russian Academy of Sciences, Novosibirsk 630090, Russia

E-mail: sv_maltseva@mail.ru

Abstract. The blood realizes the transport of substances, which are necessary for livelihoods, throughout the body. The assumption about the relationship genotype and structure of vasculature (in particular of brain) is natural. In the paper we consider models of vessel net for two genetic lines of laboratory mice. Vascular net obtained as a result of preprocessing MRI data. MRI scanning is realized using the method of variation of slope of scanning plane, i.e. by several sets of parallel planes specified by different normal vectors. The following special processing allowed to construct models of vessel nets without fragmentation. The purpose of the work is to compare the vascular network models of two different genetic lines of laboratory mice.

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.

Reconstructing the vasculature (and, in particular, that of the brain) of small laboratory animals is of interest by virtue of their wide using as objects of medical and biological research. However, this type of task is associated with the problem of insufficient sensitivity, even of high-field imaging devices, to the blood flow in cerebral blood vessels in non-enhanced imaging; images of some vessels appear fragmented. In the paper [1] suggested a constructive algorithm that allows for fragmentation-free reconstruction of models of complex vasculature without vessel fragmentation.

Method of variation of slope of scanning plane [1] allowing for reconstruction of geometrical models of vessel nets according to MRI data is briefly described in Section 2. On the basis of constructed models of vessel nets a comparison of the geometric configuration of blood net
models for animals under investigation are carried out in Section 3. Results of measurement of angles between the vessels of the Willis’ circle are shown and results of statistical analysis are presented. Results of numerical analysis of the blood flow in the constructed models are obtained using software ANSYS/CFX and presented in Section 4.

2. Method of variation of slope of the scanning plane
Let us formulate basic principles of investigation of the object using MRI. Object under investigation is scanned by the set of parallel planes given by the normal vector to this set. Elementary MRI investigation includes the following main stages.

(i) In accordance with specified set of scanning planes scanner discretizes the physical continuous three-dimensional space into elementary volumes — voxels.
(ii) MRI scanner registers summary NMR signal of hydrogen atoms being in the same voxel.
(iii) Voxels lying in the one scanning plane create image of the one section of the object.

Results of the scanning are saved by the scanner in the form of images of the section. Wherein the created image is grey-scaled so that level of grey is proportional to the level of NMR signal. Mathematically every this image is given by the numerical matrix and rows and columns of the matrix correspond to numeration of pixels in the image. Value of element of this matrix is defined by the level of NMR signal in the corresponding voxel.

Level of NMR signal in voxel, and consequently brightness of corresponding pixel of the image, depends on the scalar product \((v_{ijk}, n)\), \(v_{ijk}\) — velocity of the blood flow in voxel \((ijk)\), \(n\) — normal vector to the scanning plane. Dependence of the pixel brightness on the said scalar product is such that when it equals (or approximately equals) to zero, then scanner registers it as absence of the blood flow in voxel \((ijk)\). This is true only if \(v_{ijk} = 0\) and is false when \(v_{ijk} \perp n\).

The described feature of creation of image according to MRI data leads to the following. In models of vessel nets (created by such images) arise interrupts of vessels (vessels are fragmented) in voxels where \(v_{ijk} \perp n\). Fragmented models of nets are unsuitable for hemodynamic computation and are limitedly suitable for analysis of their geometric features. Obviously there is necessity of creation of the method oriented to building non-fragmented models of vessel nets.

In the paper [1] method of MRI data processing was proposed, it is called method of variation of the slope of scanning plane, it allows to build non-fragmented models of vessel net. This method consists of carrying out scanning using several sets of parallel planes, recalculation of all available data to the unit grid domain and combination (in some way) of recalculated data. Used sets of planes are given by different normal vectors. Direct building of vessel net is performed by obtained combined data using software for image segmentation [2, 5].

3. Comparison of models of nets for different genetic lines

3.1. Description of genetic lines
As comparing genetic lines of laboratory mice in this paper, we consider the following two lines.

(i) Genetic line with the pathology: the line with a knock-out on the tumour necrosis factor (TNF), more details about this genetic line, see [7].
(ii) Control genetic line: C57Bl/6; the knock-out line have been obtained on the basis of this genetic line. Line C57Bl/6 is usually used as standard one for majority pharmacological preclinical research.

3.2. Building of models of vessel nets
Building of geometric models of vessel nets of investigated animals was realised using method of variation of the slope of scanning plane with five sets of scanning planes. Scanning planes are deviated from the axial one (i.e. from the standard scanning direction being the axis of
symmetry of the object) on 15 and 30 degree in two orthogonal directions. Choice of these angles of deviation is caused by the following. When the deviation angle of the scanning plane from the axial one is increased, relation signal/noise is decreased and becomes unacceptably small when the angle is near 90 degree. In addition when scanning plane is turned on 45 degree or more, MRI scanner recalls coordinate axes leading to the turning of the image.

Non-fragmented three-dimensional models of vessel nets of all animals under investigation have been constructed using method of variation of the slope of the scanning plane with the usage of software ITK-Snap [2]. In Figure 1 you can see images of three-dimensional models of vessel nets for animals of genetic line with TNF knock-out, in Figure 2 — for animals of genetic line C57Bl/6.

Figure 1. Models of vessel nets for animals of genetic line with TNF knock-out.

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 raws correspond to condition numbers of investigated animals, wherein prefix 661 corresponds to animals from genetic line with TNF knock-out, and prefix BL — to animals from genetic line C57Bl/6. 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.
Figure 2. Models of vessel nets for animals of genetic line C57Bl/6.

Table 1. Angles of Willis’ circle (in degrees).

| Animal | ACA | ACA and PCoA (l.) | ACA and PCoA (r.) | PCeA |
|--------|-----|--------------------|--------------------|------|
| 661-3  | 75  | 145                | 145                | 80   |
| 661-4  | 88  | 153                | 150                | 96   |
| 661-5  | 58  | 160                | 150                | 110  |
| 661-6  | 65  | 145                | 144                | 90   |
| 661-7  | 60  | 150                | 145                | 95   |
| 661-8  | 60  | 150                | 150                | 92   |
| BL-3   | 60  | 145                | 150                | 96   |
| BL-4   | 70  | 145                | 135                | 90   |
| BL-5   | 45  | 155                | 155                | 85   |
| BL-6   | 60  | 155                | 158                | 100  |
| BL-7   | 50  | 160                | 150                | 90   |
| BL-8   | 70  | 150                | 145                | 95   |
Table 2. Boundary conditions for blood flow velocity (in $cm^3/s$) in numerical simulation.

|               | CCA (l.) | CCA (r.) | VA (l.) | VA (r.) |
|---------------|----------|----------|---------|---------|
| Velocity (cm$^3/s$) | 8.0      | 8.0      | 5.      | 5.      |

Statistical analysis of the measured angles between the arteries of Willis’ circle was performed. No statistically significant distinctions in construction of Willis’ circle between the two genetic lines were found. In spite of normal distribution of the mark but in connection with small sample the data analysis was carried out using parametric and non-parametric method. Application of Mann–Whitney–Wilcoxon test gives statistical significance of distinctions between the genetic lines less than 0.4 (despite the fact that values are statistically significant if they are less than 0.05). Results of analysis using Student’s t-test considered to be similar and statistical significance is no less than 0.2.

4. Numerical analysis of hemodynamics

Software ANSYS/CFX is used for numerical analysis of hemodynamics. 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 water) is used for numerical modelling. Walls of blood vessels considered to be rigid and condition of adhesion 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.

Figure 3. Stream lines of the velocity vector.

At the inlets of vertebral and carotid arteries we set blood flow velocity, at the outlet of others cerebral arteries we set flowrate. Values of the blood flow velocity used in numerical simulations
are shown in Table 2. Values of the blood flow velocity in left and right Common cerebral artery (CCA) are adduced in the first and second columns. Values of the blood flow velocity in left and right Vertebral artery (VA) are adduced in the third and forth columns. In outlets we set volumetric rate different from the vessel outlet in the cross-section area.

Results of numerical simulations are shown below. In Figures 3, 4 you can see stream lines and variations in mean pressure distribution of the vessel wall near Willis’ circle. In both figures the first and second models correspond to the animals of the genetic line with TNF knock-out, third and forth correspond to the animals of the genetic line C57Bl/6.

5. Conclusions
In the paper the construction of the models of vascular channel for the laboratory animals of two genetic lines realised using the method of variation of slope of scanning plane. The method showed its efficiency and allowed for construction of the models of vascular channel suitable for hemodynamic calculations and statistical analysis of vessel architectonics. Also it was shown that there is no influence of TNF knock-out on morphological and hydrodynamical characteristics of Willis’ circle of adult animals.

Acknowledgments
The study was completed thanks to the support of Russian Science Foundation (project No. 14-35-00020, all MRI experimentation studies using Bruker BioSpec 117/16 USR scanner), Russian Foundation for Basic Research (project No.14-01-00036, mathematical modelling) at the site of the Centre for Laboratory Animal Genetic Resources, Institute of Cytology and Genetics, Siberian Branch of the Russian Academy of Sciences (RFMEFI61914X0005 and RFMEFI62114X0010).

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