Reconstruction of the Cerebral Vascular Net of the Small Laboratory Animals According to the Data of High-field MRI-scanner

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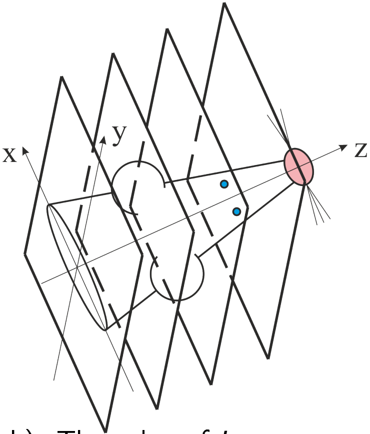
Introduction. MRI

MRI is a method of **inside-vision** that allows one to investigate internal structure of the object **without destruction**. This method is based on the nuclear magnetic resonance phenomenon.
MRI scanner registers the **flow through the cross-section** and creates output data according to its measurements.
In biological applications MRI may be used for reconstruction of the **vascular net**, for example vascular net of small laboratory animals such as mice and rats. This reconstruction has an important value for the **haemodynamic modelling**.

Problem statement. Physics



Data package is a **set of section images** (with metadata) obtained using the **set of parallel planes**. Pixel intensity in the image corresponds to the blood flow rate through the section. The scanner creates one data package for each set of parallel planes. The image of one section is a bitmap image in grey-scale from 1 up to I_{max}, where 1 corresponds to black color (there isn't information about the flow) and I_{max} corresponds to the white one (the flow is quick). The value of I_{max} depends on the scanner's shooting mode.

The problem is to reconstruct the model of the vasculature net useful for the further heamodynamic research.

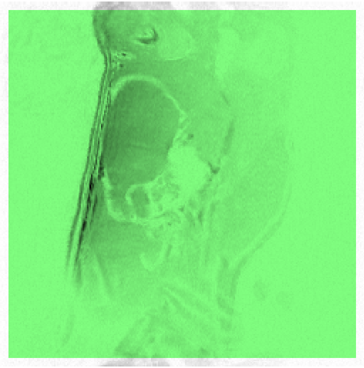
Problem statement. Experiment

MRI-scanner: Bruker BioSpec 117/16USR, field strength is **11.7 T**.
For comparison: the field strength of the "human" MRI-scanner is 1.5 T.

The problem is to reconstruct the model of the vascular net according to the tomography data of the head.

Tomography data features

1. Non-homogenuity of the slice images (both for the one slice itself and from the one slice to the other). This effect arises due to the non-homogenuity of the coil field.
2. Slice-by-slice normalization of the scanner reconstruction (slice images).The scanner detects “the brightest point” in each slice and assigns the intensity value at this point to I_{max}.
3. Data are noisy.
4. The vessels edges are blurred.



Problem statement. Mathematics

Tomography data are the scalar product $|(\vec{v}(x,y,z),\vec{n})| = A(x,y,z)$, where $\vec{v}(x,y,z)$ is a vector field describing the blood flow rate at point (x,y,z), $\vec{n}$ is the normal vector to the scanning plane, $A(x,y,z)$ is the value of the slice image brightness at point (x,y,z). Black pixels in the image may arise in two cases:

1) the flow is almost absent ($\vec{v} \approx 0$),

2) vectors $\vec{v}$ и $\vec{n}$ **are orthogonal** (their scalar product equals 0).

The smaller angle between vectors $\vec{v}$ and $\vec{n}$, the brighter point in the slice image.

The problem is to determine the boundary of the three-dimensional domain V such that

$$V = \{(x,y,z) : A(x,y,z) > A_0\},$$

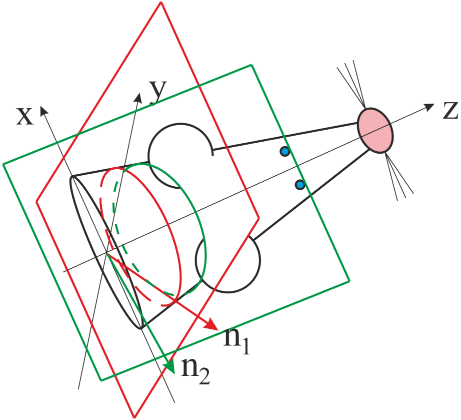
where A_0 is intensity value that separates vessels and domain without vessels.

Common approach to the vascular net reconstruction

Data: the packet obtained by object scanning along one axis (usual along the symmetry axis) and the normal is parallel to the chosen axis. We call this scanning as a "standard" one.
Usual approach is to build the vascular net according to the data of one standard scanning.
The **main disadvantage** of the net reconstruction obtained this way: vessels interruptions.
Causes of the vessels interruptions:
1. The vessel becomes such narrow that the scanner sensitivity is not enough to recognize it: the whole flow rate ($\vec{v}(x, y, z)$) is small.
2. The vessel is **parallel to the scanning plane**: the normal component of the flow rate ($|(\vec{v}(x, y, z), \vec{n})|$) is small.
These interruption causes are typical for all objects under investigation. In the case of small laboratory animals it arises more. Approximate diameter of the vertebral artery for mouse is 0.29 mm and for rat is 0.67 mm. For comparison: approximate diameter of the human vertebral artery is 3.7 mm.

Problem solving. **Method of the scanning plane angle variation**

Several scannings are performed using **different directions of the normal vector** of the scanning planes set. One data packet is scanning data corresponding to one normal vector. Problem solution uses several data packages differing from each other by the normal vector.



Packages choice for the net reconstruction. Unsuitable packages

Data packages are different from each other by the normal vector to the scanning planes. Not all data packages are suitable for the net reconstruction.

1. Unsuitable packages of the first type (unsuitability caused by physics of the process): scanning planes are located such that at the object section defined by these planes **flow is almost absent**. Disadvantage: **high noise level**.

2. Unsuitable packages of the second type (unsuitability caused by the scanner specificity): **scanner rotates the image** then the angle between scanning plane and one of the coordinate planes is greater than or equal to 45 degrees. Disadvantage: **impossibility of the registration (matching)** of the data from different packages.

Packages choice for the net reconstruction. Suitable packages

1, 2, 3 — the scanning planes with angles of 0, 15, 30 degrees to the x axis respectively.
1, 4, 5 — the scanning planes with angles of 0, 15, 30 degrees to the y axis respectively.

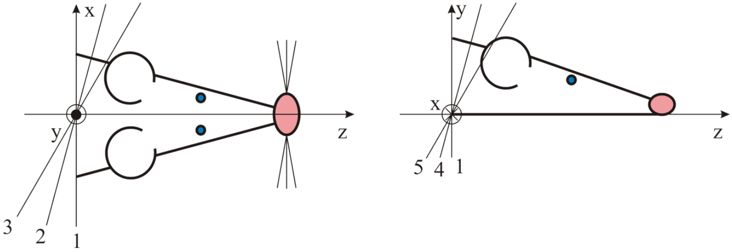


Figure: Schematic representation of the scanning planes for suitable packages

These five packages are used for the vascular net reconstructions.

Unified domain for all packages

Consider n **data packages** A^i, $i = 1, ..., n$. Data of the ith package is known in three-dimensional cube K_i. For different packages cubes are different.

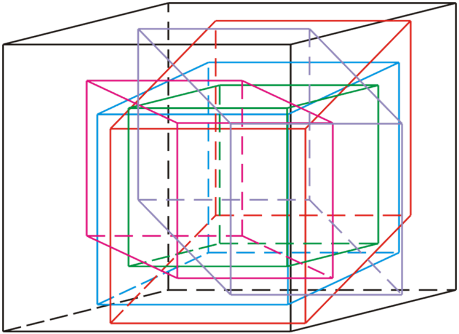
For cubes K_i, $i = 1, ..., n$ we define a unified domain K as follows:

1. K is cube.

2. Faces of the cube K are parallel to the coordinate planes.

3. K contains all cubes K_i, $i = 1, ..., n$.

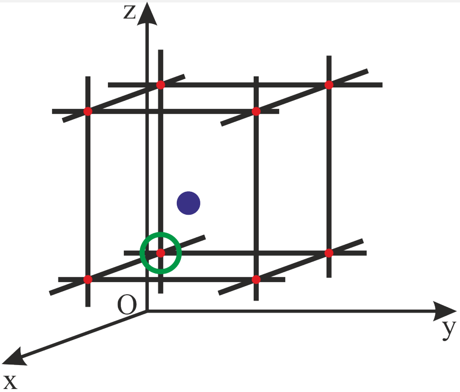
4. K is minimal cube with all previous conditions.



Cube K "carries" all tomography information under consideration.

Data recalculation at the unified domain grid

Let data of the s-th package be known in the cube K_s. Let A^s be a three-dimensional array containing **digital information about slice images** of this package: the number A^s_{ijk} is digital value of the **brightness** of the pixel (i, j) at the k-th package slice. We uses the following rule to approximate array A^s at the mesh node $P \in K$



$$A^s(P) = \begin{cases} 1, & P \notin K_s, \\ A^s_{[x][y][z]}, & P \in K_s, \end{cases}$$

where (x, y, z) are coordinates of the node P in the coordinate system of the s-th package, $[\cdot]$ integer part of the number.

Registration is automatized method that combines several data with each other.
After previous stage we have five arrays (of unified size) known at the same three-dimensional grid: A^i, $i = 1, ..., 5$.
Array Z containing information about vessels location according to five packages is constructed as follows.
(ijk)-th element of array Z defined by the following formula

$$Z_{ijk} = \max\left(A^s_{ijk},\ s = 1, ..., 5\right).$$

Thus, an element of Z is equal to 1 only in the case if no data package contains information about vessel location at the this node.

Stages. Layerwise data processing

Substages of the layerwise processing.

1. Vertical intensity alignment of the slice image.
2. Horizontal intensity alignment of the slice image.
3. Contrast and brightness adjustment.
4. Denoising, smoothing with Fourier-filter.

The stage of layerwise processing allows to decrease disadvantages of MRI-data.
After layerwise data processing we have: 256 greyscale bitmap images.
Pixel amount in each image is 256×256.
Remark: existence of MRI-data disadvantages depends on the several scanning parameters, for example on the choice of receiver coil.

Stages. Segmentation

Segmentation is automated methods that create suitable models of anatomy from slice images.

This stage is realized in ITK-Snap. Segmentation consists of two substages.

Threshold parameter is a digital value that characterizes the distinction between vessels and domain without vessels.

1. Segmentation with threshold parameter which is **uniformly suitable** for the whole domain.

2. Segmentation in small regions with another value of the threshold parameter. As a rule, the threshold parameter value is **less** than once at previous substage.

Method approbation. Mouse

Character diameter of the vertebral artery: 0.29 mm.
Receiving coil: type 1 ("mouse coil").

Mouse. Layerwise data processing

The stage aim is to transform array Z so that slice images composed of this array satisfy following conditions

1. Image intensity is uniform along the vertical and along the horizontal.
2. Noise level is not significant.
3. Vessels boundaries are legible.

Mouse. Layerwise data processing. Vertical intensity alignment

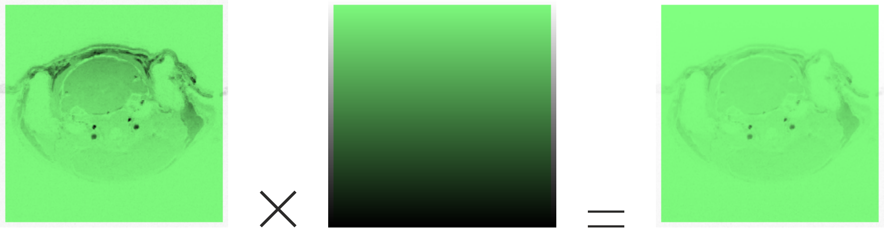


Figure: Initial slice, mask, multiplication result

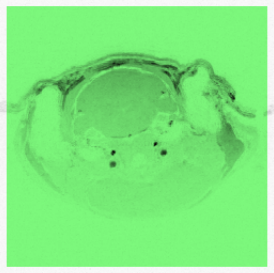
Before: intensity decreases from top of the image to the bottom.
After: vertical image intensity is more uniform.

Mouse. Layerwise data processing. Horizontal intensity alignment

Figure: Image with vertical intensity alignment, mask, multiplication result

Before: intensity decreases from the boundary to the center.
After: horizontal image intensity is more uniform.

Mouse. Layerwise data processing. Image intensity alignment



$\Rightarrow$

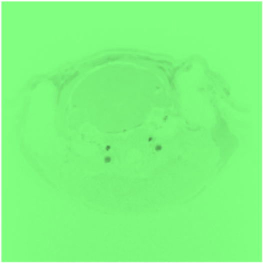


Figure: Initial slice image, image after masks multiplications

Before: image intensity decreases from top to the bottom and from the boundary to the center.
After: vertical and horizontal image intensity is more uniform.
Disadvantage: low contrast.

Mouse. Layerwise data processing. Contrast and brightness adjustment

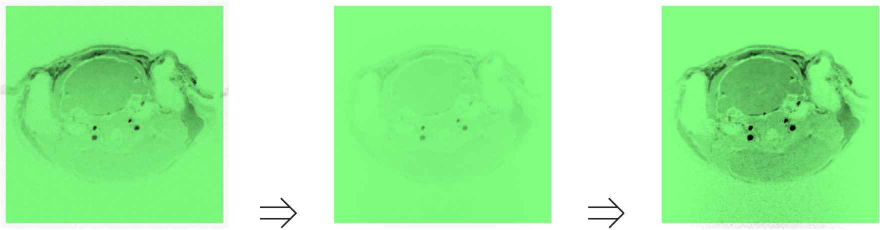


Figure: Initial slice image; slice image after masks multiplication, contrast and brightness adjustment

Before: low contrast.
After: high contrast.
Disadvantage: noise.

Mouse. Layerwise data processing. Denoising

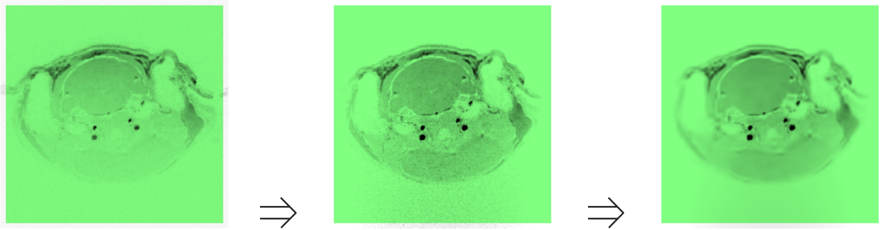


Figure: Initial slice image; slice image after masks multiplication, contrast and brightness adjustment; slice image after masks multiplication, contrast and brightness adjustment, using the Fourier filter

Before: high contrast and high noise level.
After: high contrast and low noise level.

Mouse. Layerwise data processing.

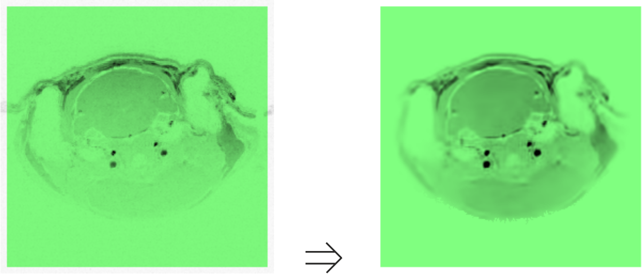


Figure: Initial slice image; slice image after masks multiplication, contrast and brightness adjustment, using the Fourier filter

Before: non-uniform image intensity, high noise level, illegible vessels boundaries.
After: uniform intensity, low noise level, legible vessels boundaries.

Reconstruction according to the standard scanning

Connectedness: 18 components.

Figure: Vascular net obtained according to the one (standard) scanning

Reconstruction according to five data packages

Connectedness: 11 components.

Figure: Vascular net obtained according to five data packages

Reconstruction according to five data packages with refinement at small fields

Connectedness: 2 components.

Figure: Vascular net obtained according to five data packages with refinement at small fields

Mouse. Conclusions

The algorithm proposed allows to reconstruct connected vascular net of the mouse head.

Advantages of the **net obtained using the algorithm proposed** as compared with the net obtained according to the standard scanning:

1. Contains vessels which **does not exist** in the standard scanning reconstruction.

2. **Connectedness is more** that the connectedness of the standard scanning reconstruction.

Disadvantages:

1. Overestimation of the vessel diameters.

2. Segmentation of the vessels passing through the cerebrospinal fluid (CSF).

Method approbation. Rat

Character diameter of the vertebral artery: 0.67 mm (mouse — 0.29 mm).
Receiving coil: type 2 (“rat coil”).
Sensitivity of the rat coil is less than sensitivity of the mouse once.

Reconstruction according to the standard scanning

Connectedness: 37 components.

Figure: Vascular net obtained according to the one (standard) scanning

Reconstruction according to five data packages

Connectedness: 12 components.

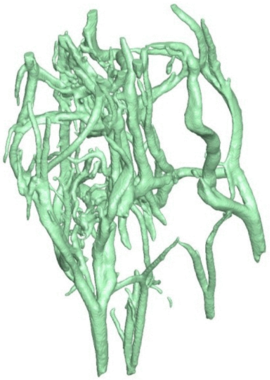


Figure: Vascular net obtained according to five data packages

Reconstruction according to five data packages with refinement at small fields

Connectedness: 1 component.

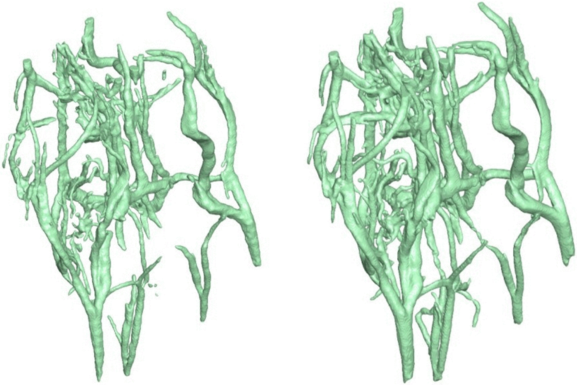


Figure: Comparison of the vascular nets: standard-packet and five-packet

Rat. Conclusions

The algorithm proposed allows to obtain connected vascular net of the rat head.
Advantages of the **net obtained using the algorithm proposed** as compared with the net obtained according to the standard scanning are similar to the mouse case:
1. Contains vessels which **does not exist** in the standard scanning reconstruction.
2. **Connectedness is larger** than the connectedness of the standard scanning reconstruction.
Remarks:
1. “Rat net” contains more vessels that “mouse net”.
2. It was found that masks which are useful for the intensity alignment of the mouse slice images are not useful for the rat one. Vascular net for the rat data are obtained without layerwise data preprocessing. Masks for the “rat” coil may be obtained and applied to the tomography data.

Conclusions

Procedure complex for the vascular net reconstruction is developed and realized.
The algorithm proposed based on the method of the scanning plane angle variation and is applied to the tomography data of two small laboratory animals. It shows satisfactory results on these test materials.
In the future the vascular net obtained such way may be used for the haemodynamics modelling in the brain vessels of the small laboratory animals.

Literature

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Thank you for attention!