Characteristic of porous media by means of magnetic resonance imaging with particular emphasis on analysis of the water diffusion tensor distributions and T1 and T2 relaxation times.

Summary of professional Accomplishments

Artur Tadeusz Krzyżak

November 2016

1. Introduction

1.1. Held diplomas, scientific degrees

PhD in physics obtained on 8 January 2001 r. at the H. Niewodniczański Nuclear Physics Institute in Cracow. The dissertation defended with distinction entitled: Investigation of water dynamics in biological systems by means of magnetic resonance imaging of the diffusion tensor, supervisor: prof. dr hab. A. Jasiński, reviewers: prof. dr hab. Jacek Hennel, prof. dr hab. Edward Szcześniak.

Master's degree in physics obtained in June 1993 r. at the Faculty of Physics Mathematics and Astronomy at Jagiellonian University in Cracow. Title of the thesis: 3D Phonocardiography, supervisor: Prof. dr hab. S. Micek.

1.2. Previous employment in the scientific units

- Assistant professor in Magnetic Resonance Imaging laboratory at Nuclear Physics Institute: January 2001 to September 2001.

- Intermission in the scientific work: September 2001 to March 2003.

- Adjunct professor at Nuclear Physics Institute: March 2003 to December 2012.

- Senior technical specialist at the Fossil Fuels Department at the faculty of Geology, Geophysics and Environmental Protection AGH-UST Cracow: from January 2013.

1.3. Research topics and interests

- The development of novel and existing methods for MR tomography and spectroscopy, imaging of water diffusion coefficient and diffusion tensor in porous systems: biological, geological, material with usage of the existing techniques (DWI, DTI), as well as, own innovative approaches,

- Research of the actual distributions of magnetic field gradients and b-matrices present during tomography experiments, and diffusion imaging in particular,

- Research of the systematic errors in tomography experiments caused by approximate calculation of diffusion tensor, revealing scale of such errors and development of the techniques to reduce them,

- Inventing the concept of anisotropic phantoms as a model of diffusion tensor and building their prototypes,

- Development of the BSD-DTI and sBSD-DTI methods, their theoretical underpinnings, mathematical formalism, and calibration of MR scanners with usage of the above techniques,

- Investigation of the petro-physical parameters of rock core samples (carbonates, sandstones and shales) by means of NMR,

- Determination of the 1H nuclei content in the synthetized silica materials: MCM-41 and SBA-15 as well as, model clay materials: illite, smectite, kaolinite, chlorite, illite-smectite.

1.4. Research plans

My future scientific activities will concern:

- Development of NMR methods for analysis of petro-physical parameters of carbonates, sandstones and shales, proposing innovative solutions and prototypes of inventions within NMR-ROCKS project in PBS2 program financed by the National Centre for Research and Development, which I am manager of the project,

- Development of the MRI diagnostic of the cardiac muscle and coronary arteries, proposing innovative solutions and invention prototypes within CIRCULATE project in STRATEGMED2 program, financed by National Centre for Research and Development, in which I am coordinator responsible for magnetic resonance tomography and spectroscopy tasks.

2. Presentation of scientific achievements forming the basis for habilitation proceeding.

As a scientific achievement within the meaning of Art. 16, par. 2 of the Act of 14 March 2003 “On Academic Degrees and Academic Title and on Degrees and Title in Art” (journal of Laws No. 65, item 595, as amended) I present a series of seven related publications, three international patent applications and one granted patent entitled together: **Characteristic of porous media by means of magnetic resonance imaging with particular emphasis on analysis of the water diffusion tensor distributions and T1 and T2 relaxation times.**

2.1 Published articles

[H1] **A. Krzyżak**, Z. Olejniczak. Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix. Magnetic Resonance Imaging 2015, 33(3): 286–295., DOI:10.1016/j.mri.2014.10.007 IF (2.09).

My contribution to this work was: development of a novel theory of diffusion tensor imaging, called BSD-DTI, carrying out the experiments, data analysis and writing the manuscript. I estimate my share in this work to 85%.

[H2] K. Kłodowski**, A. Krzyżak.** Innovative anisotropic phantoms for calibration of diffusion tensor imaging sequences. Magnetic Resonance Imaging 2016, 34(4): 404-409., DOI:10.1016/j.mri.2015.12.010 (IF-2.09).

My contribution to this work was: development of the novel theory of diffusion tensor imaging, called BSD-DTI, concept and design of the anisotropic phantoms, planning and carrying out the experiments. I also participated in writing of the manuscript. I estimate my share in this work to 67%.

[H3] W. Węglarz**, A. Krzyżak**, M. Stefaniuk. ZTE imaging of tight sandstone rocks at 9.4T - comparison with standard NMR analysis at 0.05 T. Magnetic Resonance Imaging 2016, 34(4): 492-495; DOI:10.1016/j.mri.2015.12.001 (IF-2.09).

My contribution to this work was: partial development of the general concept of the work, carrying out the experiments on 0.05 T scanner, data analysis. I participated in writing of the manuscript. I estimate my share in this work to 40%.

[H4] **A. Krzyżak**, A. Jasiński, W. Węglarz, D. Adamek, P. Sagnowski, M. Baj. Visualisation of the extent of damage in a rat spinal cord injury model using MR microsopy of the water diffusion tensor. Acta neurobiologiae experimentalis 02/2005; 65(3):255-64 (IF-1.43).

My contribution to this work was: development of the general concept of the work, development of the software for diffusion tensor calculation and control the DTI experiments, carrying out the DTI experiments, data analysis and writing the manuscript. I estimate my share in this work to 50%.

[H5] **A. Krzyżak**, A. Jasiński, D. Adamek. Qualification of the most statistically "sensitive" diffusion tensor imaging parameters for detection of spinal cord injury Acta Physica Polonica A vol. 108, 207-210 (2005) (IF-0.53).

My contribution to this work was: development of the general concept of the work, development of the software for diffusion tensor calculation and control the DTI experiments, carrying out the DTI experiments, data analysis and writing the manuscript. I estimate my share in this work to 70%.

[H6] **A. Krzyżak**, A. Jasiński, S. Kwieciński, P. Kozłowski, D. Adamek. Quantitative Assessment of Injury in Rat Spinal Cords In Vivo by MRI of Water Diffusion Tensor. Applied Magnetic Resonance 07/2008; 34(1):3-20. DOI:10.1007/s00723-008-0095-7 (IF-0.748).

My contribution to this work was: development of the general concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments, data analysis and writing the manuscript. I estimate my share in this work to 50%.

[H7] **A. Krzyżak,** I. Habina. Low field 1H NMR characterization of mesoporous silica MCM-41 and SBA-15 filled with different amount of water. Microporous and Mesoporous Materials 2016; 231:230-239. DOI:10.1016/j.micromeso.2016.05.032 (IF-3.45).

My contribution to this work was: development of the general concept of the work, carrying out the MRI experiments, data analysis. I participated in writing of the manuscript. I estimate my share in this work to 67%.

[H8] **A. Krzyżak**. Anisotropic diffusion phantom for calibration of diffusion tensor imaging pulse sequence used in MRI:

American patent number: Ref. No: US8643369 B2 (2014).

I am the only author of this work and my share is 100%.

2.2 Introduction

2.2.1 Nuclear Magnetic Resonance in porous media

Nuclear Magnetic Resonance (NMR) since its discovery by Bloch and Purcell in 1946 has found number of applications in numerous fields of scientific research and a broad use in the industry [1-2]. For last 40 years the investigation of porous media by means of NMR has become one of the most important issues in a wide range of scientific research and industry applications in medicine, biology, geology and chemistry [3-5]. A non-invasive insight into both qualitative and quantitative description of a measured sample is one of the biggest advantages of magnetic resonance imaging (MRI). The sample is influenced only by the static external magnetic field and low energy electromagnetic wave of radio wave frequency corresponding to the resonance, known also as Larmor frequency, a characteristic attribute of the sample in question containing nuclei with non-zero spins [6-7]. The most frequently investigated element is hydrogen (1H) being a component of water molecules, hydrocarbons, etc. The other popular nuclei in NMR are: carbon (13C), nitrogen (15N), oxygen (17O), fluorine (19F), sodium (23Na), phosphorus (31P), as well as deuterium (2H) [7]. The presented work focuses on magnetic resonance imaging of specimens abundant in hydrogen in low (0.05 – 0.5 T) and high (3 – 9.4 T) magnetic fields, with consideration of proposed by the author innovative solutions pertaining to diffusion tensor imaging of water and T1 and T2 relaxation times distributions, in particular.

2.2.2 Diffusion tensor imaging by means of NMR

Diffusion in porous media is a transport phenomenon in which matter is transferred between the compartments due to the random movements (Brownian motion) [8]. In case of macroscopic gradient of particles concentration, the diffusion can be described by classical Fick's law. However, in macroscopic equilibrium, when the concentration of the particles is homogenous and constant over time, a macroscopic change is not being observed. In such a case in order to derive a diffusion coefficient in a classical way, using Fick's law, one need to add contrast agents to the analysed medium. Usually radioactive or fluorescence contrast agents are used to derive the diffusion coefficient in medium, by tracking change of their concentration over time. Alternatively, the diffusion process can be described basing on the statistical approach. In 1926 A. Einstein and M. Smoluchowski [8] proved that conditional probability of finding a particle in particular position in space after time t, which movement is caused by Brownian motions, can be described by the same Gaussian function as the solution of Fick's equation.

In order to obtain a precise description of influence of diffusion on the NMR signal, in 1965 Stejskal and Tanner analysed the diffusion phenomenon for a spin-echo sequence described by Bloch equations [9]. For spins immersed in external magnetic field, which can be represented with vector $\vec{B}(\vec{r},t) = \vec{r}\vec{G}(\vec{r},t) + \vec{B}_o$ dependent from position: $\vec{r} = (x, y, z)$, and time t, where magnetic field gradient $\vec{G}(r,t) = (G_x(t), G_y(t), G_z(t))$, and $\vec{B}_o = (0,0,B_o)$ being static magnetic field in z direction, of magnitude Bo, the Bloch equation with additional diffusion term became:

$$\frac{\partial \vec{M}}{\partial t} = \gamma \vec{M} \times \vec{B} - \mathrm{T}\vec{M} + M_o \vec{T}' + \vec{\nabla}(\mathrm{D}\vec{\nabla}\vec{M}), \qquad (1)$$

where: magnetization vector $\vec{M}(r,t) = (M_x(t), M_y(t), M_z(t))$, matrix T= $\begin{pmatrix} 1/T_2 & 0 & 0 \\ 0 & 1/T_2 & 0 \\ 0 & 0 & 1/T_1 \end{pmatrix}$

vector $\vec{T}'$= $\begin{pmatrix} 0 \\ 0 \\ 1/T_1 \end{pmatrix}$, T1 – longitudinal relaxation time, T2 – transverse relaxation time, Mo – equilibrium magnetization in Bo direction, D – diffusion tensor.

After mathematical transformations we obtain:

$$\ln\left(\frac{M(t)}{M_0}\right) = -bD, \qquad (2)$$

where $\vec{k}(t) = \gamma \int_0^t \vec{G}(t')dt'$, and b is defined as: $b = \int_0^t \vec{k}(t')^T \vec{k}(t')dt'$.

The b-matrix (gradient matrix) appearing in the above equation plays a crucial role in description of the diffusion NMR sequences. It tells how sensitive is given NMR sequence in respect to the diffusion phenomenon. Thus the greater the b, the bigger the attenuation of the NMR signal due to the diffusion movement. The equation (2) was used 20 years later by P. Basser as a foundation of diffusion tensor imaging (DTI) method [10-11]. First maps of diffusion tensor elements appeared the same year. DTI is a technique capable to describe diffusion in the anisotropic media, in which measurement of just a diffusion coefficient does not suffice. The diffusion tensor is derived from diffusion weighted MR images from more general dependence (3) (Stejskal-Tanner equation) between measured signal for each voxel and set of imaging and diffusion gradients.

$$\ln\left(\frac{A(\mathbf{b})}{A(0)}\right) = -\sum_{i=1}^{3} \sum_{j=1}^{3} b_{ij} D_{ij}, \qquad (3)$$

where: b_{ij} is an element of a symmetrical b-matrix, and D_{ij} is an element of a symmetrical diffusion tensor D.

2.2.3 Measurement of T1 and T2 relaxation times distributions through NMR

The core idea of the investigation of porous media through NMR is based on the differences of T1 and T2 relaxation times of molecules in bound systems in comparison to free water. The relaxation of water molecules in pores is shortened due to hydrophobic and hydrophilic interactions with the surface. In case of fast diffusion, during the NMR experiment, it can be assumed all hydrogen nuclei did interact with the surface. In such a case, a simplified relation of T1, T2 and diffusion coefficient (D) can be derived from Bloch equation (1):

$$\frac{1}{T_i}=\frac{1}{T_{i,b}}+\frac{1}{T_{i,S}}+\frac{1}{T_{2,D}}, \tag{4}$$

where $T_{i,b}$ is a relaxation time for free water, $T_{i,s}$ is a relaxation time caused by surface interactions, and $T_{2,D}$ is a relaxation time caused by diffusion. Indices i = 1, 2 describe the spin-lattice (longitudinal) and spin-spin (transverse) relaxation, respectively. The influence of diffusion occurs only for the transverse relaxation, and for a low-field systems and CPMG sequence with short echo time is practically negligible. In contrary, for high-field systems, the diffusion phenomenon is the main cause of lack of reproducibility of T2 measurements of substances treated with para and ferromagnetic additions. This effect stems from high magnetic field gradients generated by locally large differences in magnetic susceptibility of analysed sample immersed in high external magnetic field. A porous system characterized by surface S, volume, V, radius R, and constant C (which defines the dominating shape of pores; it is equal to 1, 2 or 3 for planar, cylindrical and spherical pores, respectively), the distribution of relaxation times $T_{i,s}$ can be expressed as followed:

$$\frac{1}{T_{i,S}}=\rho_i\frac{S}{V}=\rho_i\frac{C}{r}, \tag{5}$$

Where surface relaxivity ρ_i quantifies a strength of interaction between liquid molecules' spins with spins of surface molecules. The parameter is crucial for a proper transformation of relaxation times distribution obtained from inverse Laplace transform (ILT) from NMR signal, into pore size distribution. Thus the relaxation times distribution depends on S/V ratio and pores' surface characteristic [12].

2.2.4 The aim of work

In the presented works various porous media (phantoms, biological, geological and material samples) were characterized by means of magnetic resonance imaging, using novel methods of diffusion tensor, T1 and T2 relaxation times distributions, in particular.

The most important part of the innovation was **theoretical development and implementation of a novel in the field of nuclear magnetic resonance method**, called **BSD-DTI** (B-matrix Spatial Distribution in Diffusion Tensor Imaging), concerning imaging of the diffusion phenomenon and diffusion tensor in DWI (Diffusion Weighted Imaging) and DTI (Diffusion Tensor Imaging) experiments [H1]. An integral part of BSD-DTI is a novel type of

anisotropic diffusion phantoms (ADP), characterized by well-defined structure and anisotropy of diffusion tensor required in BSD-DTI. The phantoms reveal broad research and commercial potential [H2]. The new method was precisely described in **Polish and international scientific articles, patent applications and granted patents**: national [Z1a, Z2a, Z3a], international PCT [Z1b, Z3b], European [Z1e], American [Z1c], Japanese [Z1d], American granted patent [H8].

MRI research incorporating the BSD-DTI method and/or the anisotropic diffusion phantoms was conducted for a number of various porous media. The results of investigation of the ADPs of laminar and capillary structure [H1-H2], biological systems, including spinal cord [H4-H6], sandstone rock cores from oil and gas reservoirs in Poland [H3] and mesoporous (nanometre radius) silica materials MCM-41 and SBA-15 [H7] were included in the work.

The publications contain a historical overview of development of BSD-DTI technique, ADPs and their application to porous systems in biology, medicine and geology in both low and high field MRI.

2.3 Presentation of scientific achievements forming the basis for habilitation proceeding.

2.3.1 **A. Krzyżak**, Z. Olejniczak: Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix. Magnetic Resonance Imaging; 2015. 33(3): 286–295.

Due to the anisotropic structure of biological tissues and geological rock cores, diffusion usually has to be described with a diffusion tensor in such cases.

The paper [H1] contains full theoretical basis of the novel BSD-DTI technique improving accuracy of diffusion tensor calculation in DTI experiments [10, 13-14]. The method takes into account spatial distribution of the B-matrix, which is derived with usage of phantoms of known geometrical structure. The phantoms characterized with anisotropic diffusion in at least one direction serve as models of diffusion tensor. On the contrary to standard procedure of numerical derivation of the B-matrix [15-16], which requires precise knowledge of amplitudes, shapes and time dependence of diffusion gradients, the BSD approach bases on direct measurement of spatial distribution of B-matrix components.

Proposed technique was validated on commercial Bruker Biospec 94/2-USR tomograph, through imaging of water isotropic phantom and anisotropic capillary phantom with usage of standard spin-echo sequence. The obtained improvement in accuracy of determination of diffusion tensor for the isotropic phantom was factor of 8.

The diffusion tensor is a symmetrical 3x3 matrix, consisting of six independent elements, which can be visualized as an ellipsoid of probability density [15-16], described by eigenvectors and eigenvalues of the tensor obtained through its diagonalization. Such a tensor describe the analysed object both qualitatively and quantitatively, independently of its position in the laboratory frame. The goal of the DTI experiment is obtaining such a precise description for each voxel of the MR image. In practise, a reference image obtained without a diffusion gradient and at least six diffusion weighted images, acquired for six linearly independent diffusion gradients, are required in order to derive the tensor. The parameters describing diffusion gradients for a particular imaging sequence and given diffusion gradient direction are collected in a so called B-matrix (gradient matrix). In commercial MRI systems, the B-matrices are calculated automatically, but in a simplified and imprecise way. Usually a number of effects occurring during the imaging are not taken into account: imaging gradients, cross terms between imaging and diffusion gradients, eddy currents. Furthermore, the B-matrix is assumed to be constant in the entire imaging volume, what is not true. Such approach leads to the systematic errors which cannot be ameliorated by accumulation or averaging of the signal. Some techniques reducing those unwanted effects were proposed, but they are either time consuming or their usage is limited to specific cases. As a result the accuracy of DTI is seriously limited.

The paper introduces so far unknown term of spatial distribution of the B-matrix, which was experimentally proved to exist. The spatial distribution of the B-matrix was obtained through completely alternative method of its derivation. It was pointed out, that the equation (3) from which usually the diffusion tensor is derived, can be solved with respect to the B-matrix. Thus for a known distribution of the diffusion tensor $\mathbf{D_{klm}}$ of discrete coordinates k, l, m in a laboratory frame, the elements of the B-matrix $\mathbf{b'_{klm}}$ can be derived from the following set of equations:

$$\begin{bmatrix} \ln\left(\frac{S^1(\mathbf{b_{klm}})}{S(\mathbf{bo_{klm}})}\right) \\ \ln\left(\frac{S^2(\mathbf{b_{klm}})}{S(\mathbf{bo_{klm}})}\right) \\ \cdot \\ \cdot \\ \cdot \\ \ln\left(\frac{S^N(\mathbf{b_{klm}})}{S(\mathbf{bo_{klm}})}\right) \end{bmatrix} = -\begin{bmatrix} \mathbf{b'_{klm}} : \mathbf{D}^1{}_{\mathbf{klm}} \\ \mathbf{b'_{klm}} : \mathbf{D}^2{}_{\mathbf{klm}} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{b'_{klm}} : \mathbf{D}^{N-1}{}_{\mathbf{klm}} \\ \mathbf{b'_{klm}} : \mathbf{D}^N{}_{\mathbf{klm}} \end{bmatrix}. \qquad (6)$$

The elements $\mathbf{D}^l{}_{klm}$ represent the diffusion tensor elements of the model phantom (Fig. 1) after subsequent rotations by given Euler angle. The l index marks subsequent positions of the phantom, and takes values from 1 to 6, which is a minimal value needed to solve the set of equations (6). If the tensor elements $\mathbf{D_{klm}}$ in the principal axis frame and set of Euler angles are known, the subsequent $\mathbf{D}^l{}_{klm}$ elements can be easily derived. For a precisely manufactured model phantom, as in the case (standard deviation of the diffusion tensor elements below 1%) the spatial distribution $\mathbf{D}^l{}_{klm}$ can be substituted with $\mathbf{D}^l$.

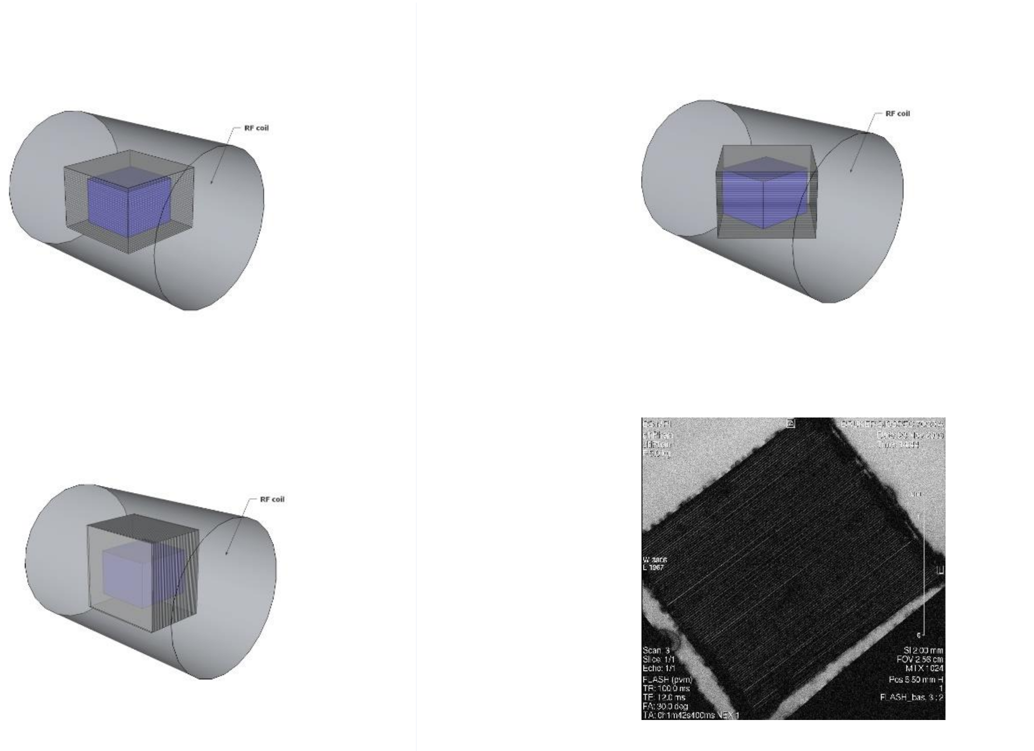


Fig 1. Three exemplary positions (out of six) of the model phantom (grey cube), after subsequent rotations by Euler angles. The region of interest (depicted in blue) is a constant (with respect to the laboratory frame) volume inside the RF coil and always encompassed by the phantom for every position. A scout image of the laminar (100 um thick glass plates separated with 20 um layers of water) phantom serving as a model of diffusion tensor was depicted in the lower right corner.

As a result of application of the BSD-DTI technique the spatial distribution of the B-matrix was obtained (Fig 2.). Furthermore, the obtained distribution was used to derive diffusion tensor elements of the isotropic and anisotropic phantoms with a precision much greater than offered by the manufacturer. For the former a vast reduction of the standard deviation of the diffusion tensor elements was obtained (3 times in axial direction to about 14 times in coronal). For the latter position of the anisotropic phantom was defined much more precisely in comparison with the standard method, for which the error of rotation angles in coronal and sagittal planes reached over a dozen degrees.

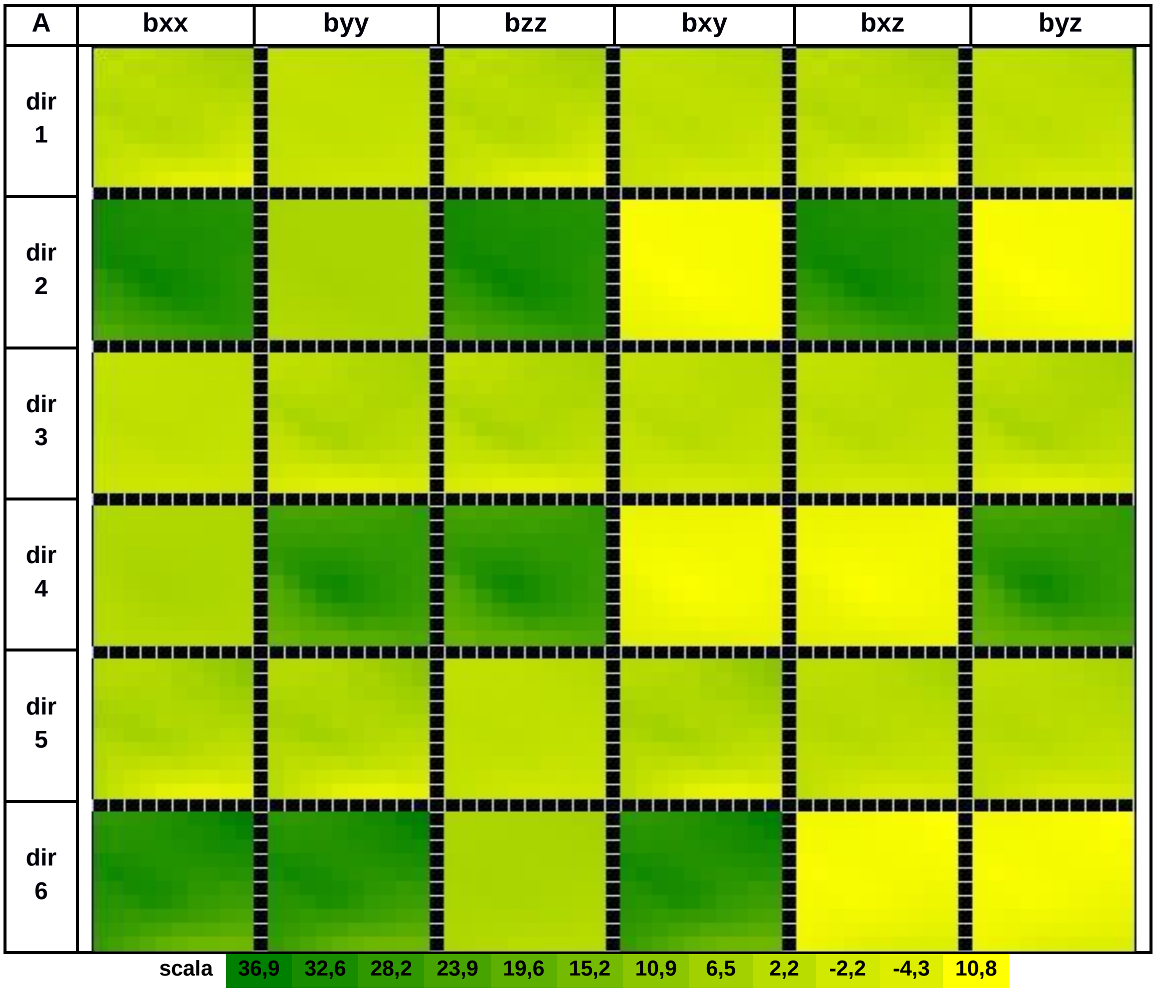
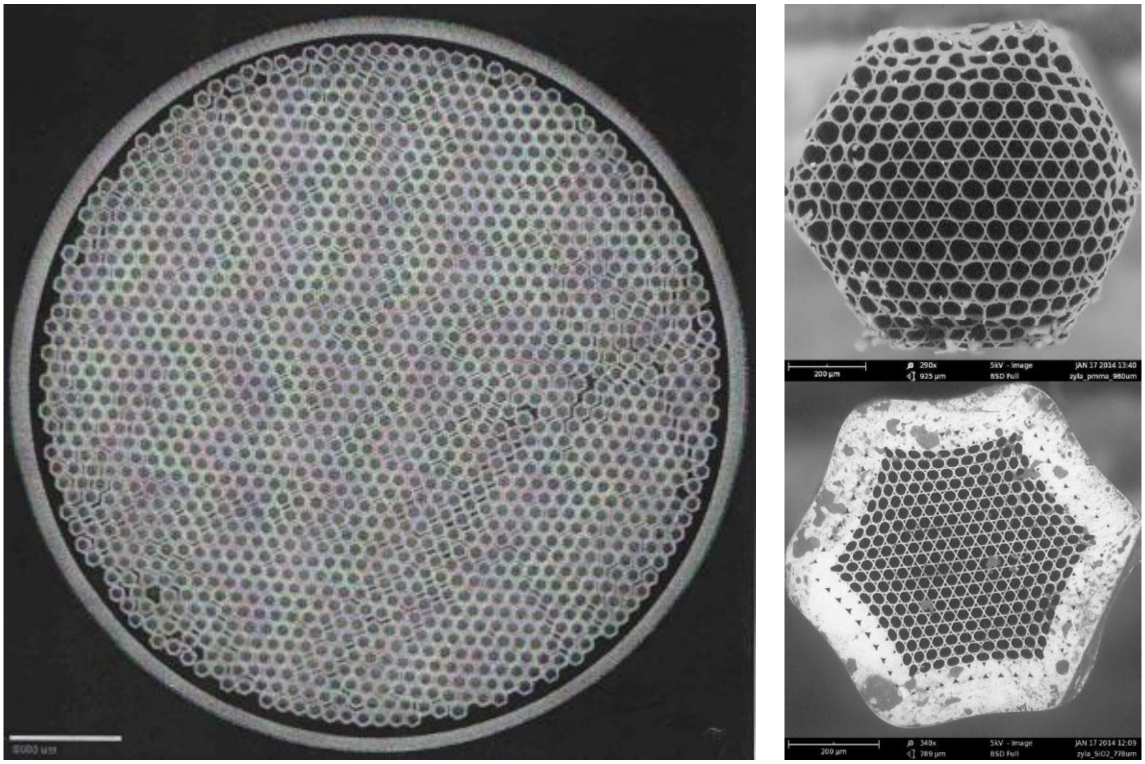


Fig. 2. Differential B-matrix elements (deviations from the constant values given by the manufacturer) for six directions of diffusion gradient in coronal plane.

2.3.2 K. Kłodowski, **A. Krzyżak:** Innovative anisotropic phantoms for calibration of diffusion tensor imaging sequences. Magnetic Resonance Imaging 2016, 34(4): 404-409., DOI:10.1016/j.mri.2015.12.010. (IF-2.09) (WoS).

The paper summarizes the long process of construction of anisotropic phantoms serving as models of diffusion tensor for porous media. After years of development, prof. Z. Raszewski with his team at Military University of Technology in Warsaw manufactured in accordance to the idea of the author set of anisotropic phantoms of capillary and laminar structure with minimized variations of the magnetic susceptibility inside the phantom. The set of phantoms made possible application of BSD-DTI to clinical scanners most frequently using echo planar imaging (EPI) based techniques [17]. EPI protocols are fast, but generate large magnetic field gradients and very sensitive to magnetic field inhomogeneity. Large differences in magnetic susceptibilities in the analysed sample cause distortions of the acquired images and thus limit the applications of EPI. Development of the novel type of phantoms profoundly extends possible applications of BSD-DTI. The results presented in the paper were obtained on a 3 T tomograph with usage of SE-EPI imaging sequence.



A – cross section of capillary phantom. Bundles of capillaries are visible.

B – single bundle of capillaries made of: PMMA – top and glass – bottom.

Fig. 3. Phantom consists of bundles of capillaries made either of PMMA or glass. Bundles of 0.8 mm diameter are filled with capillaries of internal diameter of about 30 um.

The phantoms were tested on a 3T Siemens clinical scanner. The observed improvement of diffusion tensor distribution from isotropic phantom, which was defined as a ratio of the standard deviations obtained in a standard way to derived through BSD-DTI, ranged from 2.8 to 5.3. The biggest improvement was observed for coronal plane, and the smallest for axial. It confirms previous conclusions that commercial tomographs achieve the best accuracy in transverse plane. Furthermore, the BSD-DTI was for the first time applied to a clinical system using demanding in terms of magnetic field homogeneity, EPI imaging sequence.

A – isotropic (water) B – anisotropic (glass plates) C – anisotropic (capillaries)

Fig. 4. Set of phantoms for derivation of the spatial distribution of b-matrix. The phantoms are made of glass ball filled with water (either distilled or doped with $CuSO_4$ ions). Inside phantoms B and C anisotropic laminar (thin glass plates separated with water) or capillary structures were added.

2.3.3 W. Węglarz, **A. Krzyżak,** M. Stefaniuk: ZTE imaging of tight sandstone rocks at 9.4T - comparison with standard NMR analysis at 0.05 T. Magnetic Resonance Imaging 2016, 34(4): 492-495; DOI:10.1016/j.mri.2015.12.001

A complementary analysis of sandstone rocks by means of high field 9.4T and low field 0.05T systems, was the subject of this work. Due to locally high magnetic field gradients occurring in the high field systems, they are no longer in use in the research of the porous rock cores [5]. The analysis of the samples with para and ferromagnetic admixtures are not reliable in the high fields. The common standard for such analysis became low field systems providing very short echo times, which are practically insensitive to such admixtures. The analysis of the relaxation time distributions (especially T2) after inverse Laplace transform is a reliable description of pore size distribution. Additionally developed with accordance to our requirements RF coil allowed for reliable measurement of mesoporous and microporous (tight sandstones, shales) media. In this work, the precise results obtained through the low field NMR (Fig. 6.) were compared with the high field results obtained with usage of a novel ZTE (zero echo time) imaging sequence, which makes possible imaging of some rock samples in the high field (Fig. 5.). The results approve the correlation of the high field ZTE signal with the low field total porosity calculated from T2 distributions measured with CPMG sequence for the sandstones (Fig. 7.). It has to be noted that the abundances of para and ferromagnetic admixtures in the sandstones were low. In case of higher abundances (e.g. in shale samples), the ZTE signal was highly distorted.

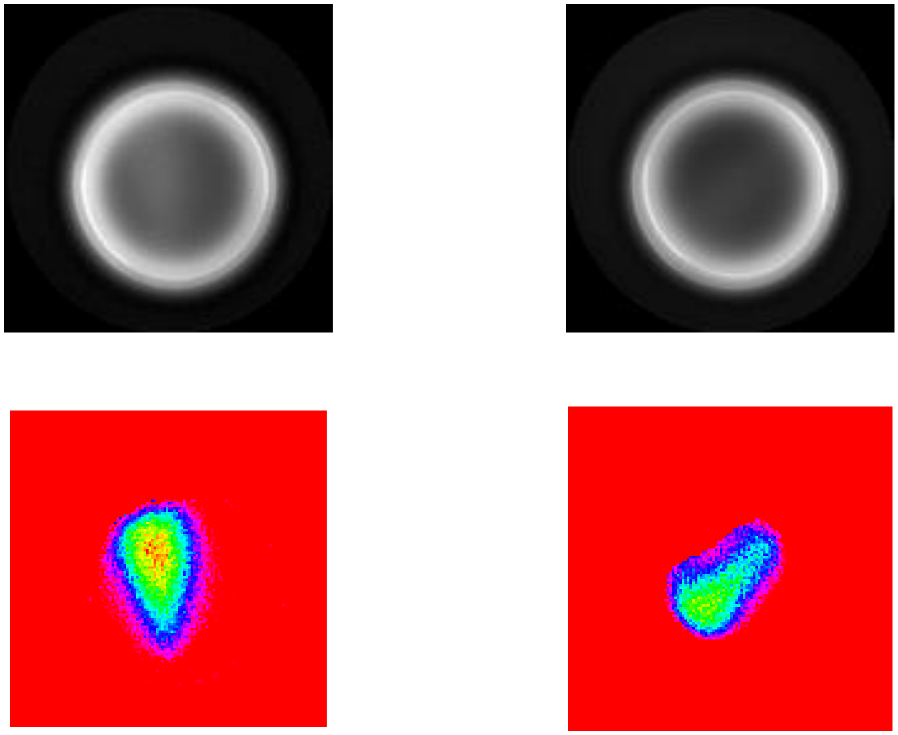


Fig. 5. MR images of tight sandstones obtained with ZTE sequence. Images of saturated (top left) and native (top right) sample. The bottom row depicts corresponding intensity distributions.

The main achievement of the work, besides approving the low field methods, is drawing attention towards spatial quantitative imaging of some rock samples in the high field systems, with usage of novel ZTE sequence in a relatively short time (about 1h). The existing low field alternative, i.e. single point imaging (SPI) usually takes much more time. Due to much better signal to noise ratio in the high field systems (linear increase with the field strength), such spatial imaging may find use in the investigation of particular rock samples.

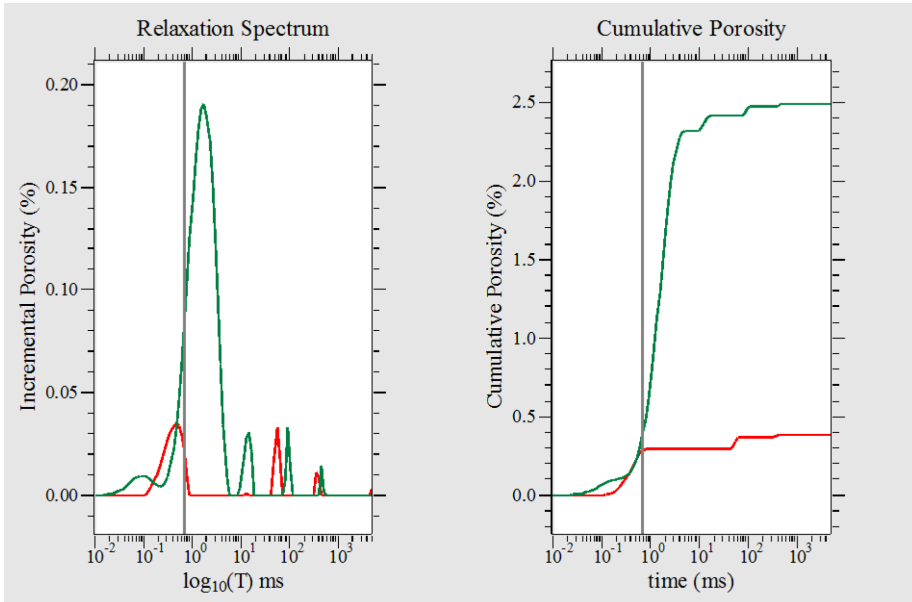


Fig. 6. T2 relaxation spectrum and cumulative porosity of the dried (red) and saturated (green) sandstone sample, acquired with the CPMG sequence.

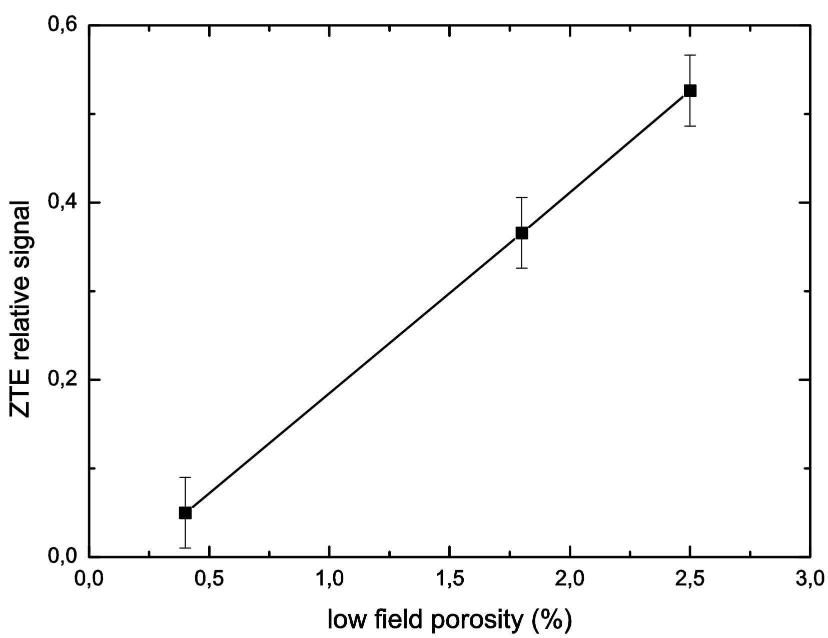


Fig. 7. Dependence of the ZTE signal intensity (measured in 9.4 T) vs. Cumulative porosity (measured in 0.05 T).

2.3.4 **A. Krzyżak,** A. Jasiński, W. P Węglarz, D. Adamek, P. Sagnowski, M. Baj: Visualisation of the extent of damage in a rat spinal cord injury model using MR microsopy of the water diffusion tensor. Acta neurobiologiae experimentalis 2005, 65(3):255-64.

The papers [H4-H6] focused on diffusion tensor imaging of a spinal cord constituent the basis for the patent application [Z1a] in which general description of a method incorporating spatial distribution of the b-matrix was described. The method later on was called BSD-DTI and its complete theoretical underpinning together with the experimental validation was described in [H1]. In this paper calculations and analysis of the diffusion tensor elements of the rat neural tissues (considered as biological porous systems) were presented. The tissue analysis was twofold; in a physiological (control), and pathological (after precisely controlled damage) state. Diffusion tensor elements, and the derivative parameters, such as: trace, isotropy index, transverse and longitudinal diffusion index, were analysed for various regions of interest. For various diffusion tracts along the spinal cord (Fig. 8A) histopathological analysis (Fig. 8B) was conducted and tensor elements were analysed. Figure 9A depicts maps of the symmetric diffusion tensor calculated for each image voxel. After diagonalization the derivative parameters were calculated as well (Fig. 9B). Statistically significant increase of the isotropy index and concomitant decrease of the longitudinal diffusion coefficient were noted in the neighbourhood of the damage. The analysis revealed correlations between changes of the diffusion tensor and damage of the neural tissue of the spinal cord. The DTI experiments and DTI results were done with usage of the software developed by the author. Difficulties in calculating the b matrices independent of the orientation of the acquired in vitro images were not published in this paper, but triggered further research focused on independent derivation of the b matrix in the DTI experiments.

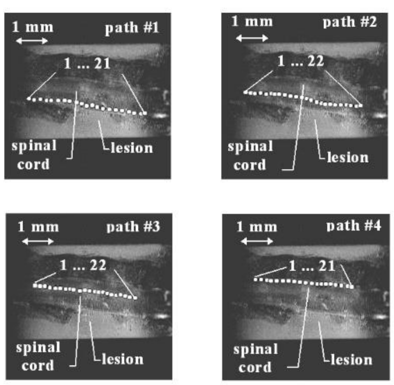


Fig. 8A. Tracts along the spinal cords for which tensor elements were analysed and histopathological analysis was conducted.

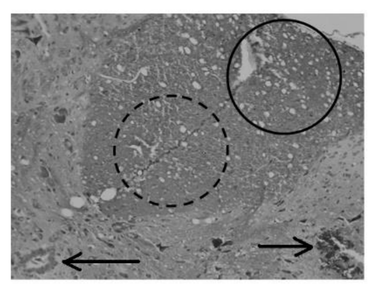
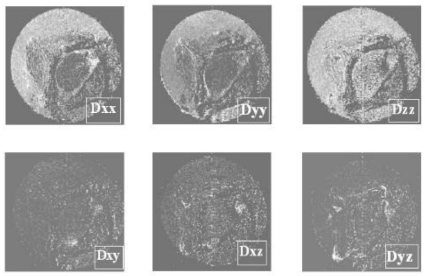


Fig. 8B. Optical microscopy of the damaged spinal cord. In the marked regions changes in the structure of tissue are visible.



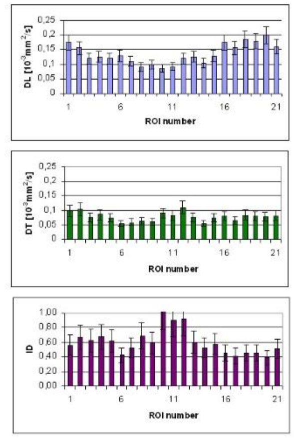


Fig. 9A Elements of the symmetrical diffusion tensor in a laboratory frame.

Fig. 9B Parameters calculated from the eigenvalues of the diffusion tensor (after diagonalization in the principal axis frame): DT – transverse diffusion, DL – longitudinal diffusion, ID – isotropy index.

2.3.5 **A. Krzyżak**, A. Jasiński., D. Adamek.: Qualification of the most statistically "sensitive" diffusion tensor imaging parameters for detection of spinal cord injury Acta Physica Polonica A vol. 108, 207-210 (2005).

The paper [H5] continued the research begun in [H4] and focused on the search for parameters (derived from the diffusion tensor) most effectively detecting damages in the spinal cord. Several experiments of the rat spinal cord, both in vitro and in vivo, carried out on 6.4 T NMR scanner were analysed. For control and damaged at Th12 and Th13 vertebras spinal cord samples DTI experiments were carried out. The calculated diffusion tensor elements were analysed in several regions of interest encompassing both, white and grey matter of the spinal cord. The results were analysed statistically. The lowest predictive potential of the damage was observed for the trace of diffusion tensor, which takes into account information from 3 orthogonal directions. The other parameters, i.e. longitudinal and transverse diffusion, isotropy index and fractional anisotropy give complementary description. A graphical comparison of the results for various region of interest are presented in figure 10. In the table 1. statistically significant change of the parameters derived from the diffusion tensor were collected.

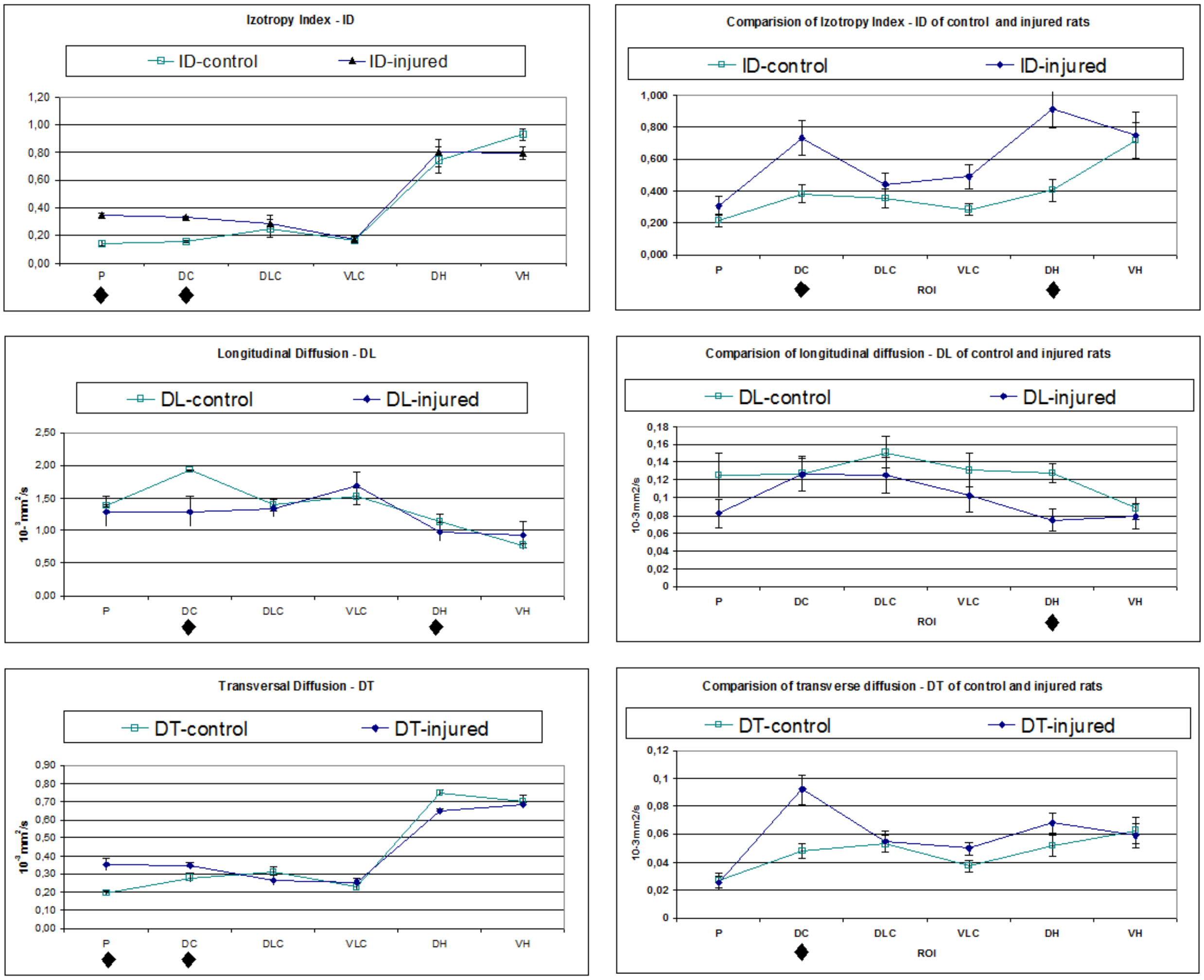


Fig. 10. Plots of the: isotropy index ID, transverse diffusion DT, longitudinal diffusion DL of the control and damaged samples for in vivo (left column) and in vitro (right column) experiments. Statistically significant changes ($p < 0.05$) were marked with diamond.

ROI	ID_A	ID_X	DL_A	DL_X	DT_A	DT_X	Tr_A	Tr_X	FA_A	FA_X
P	+	-	-	-	+	-	-	-	+	-
DC	+	+	+	+	+	-	+	+	-	+
DLC	-	-	-	-	-	-	-	-	-	-
VLC	-	-	-	-	-	-	-	-	-	-
DH	-	-	+	-	-	-	-	-	+	-
VH	-	+	-	-	-	+	-	-	-	-

Table 1. Statistically significant ($p < 0.05$) results of the in vivo (A index) and in vitro (X index) DTI experiments. Statistically significant changes ($p < 0.05$) between control and damaged in a particular regions (P - pyramidal tracts; DC - Dorsal Column; DLC - Dorsal Lateral Column; VLC - Ventral Lateral Column; DH - Dorsal Horn; VH - Ventral Horn) samples were marked with "+".

2.3.6 **A. Krzyżak,** A. Jasiński, S. Kwieciński, P. Kozłowski, D. Adamek: Quantitative Assessment of Injury in Rat Spinal Cords In Vivo by MRI of Water Diffusion Tensor. Applied Magnetic Resonance 2008, 34(1):3-20.

The experience gained as a result of the in vitro experiments on biological porous systems imaging [H4-H5] allowed to carry out much more difficult in vivo research. The effects of these experiments are included in this publication [H6]. As in the work of the [H4-H5] there were examined the diffusion tensor factors changes of neural tissue of the spinal cord of the rat in two groups: the control one and after controlled injury. In order to correctly measure the diffusion weighted images being the data source for tensor map calculation, MR measurements were synchronized by ECG pulses and respiration sensor placed on the chest. It allowed to make high-quality measurements of the spinal cord without movement artifacts and consequently, it made possible the calculation of the diffusion tensor components. Figure 11 shows diffusion weighted spinal cord MR images in two different sections: in the center of the damage, and 5 mm above. Appropriate maps for diffusion tensor components are shown in Figure 12. Figure 13 shows maps of FA (Fractional Anisotropy) anisotropy coefficient and diffusion tensor principal component maps presented in the RGB form.

The main achievement was to show the capabilities of in vivo imaging for posttraumatic spinal cord changes, using diffusion tensor. Diffusion changes in neural tissue occur much earlier than the swelling and bleeding, this gives the potential for earlier diagnosis and treatment of any injuries to the spinal cord, which in the early stages do not produce, for example, swelling. The emergence of such swelling, for example, after 2-3 days is potentially dangerous and is also related to the extra pressure on the core.

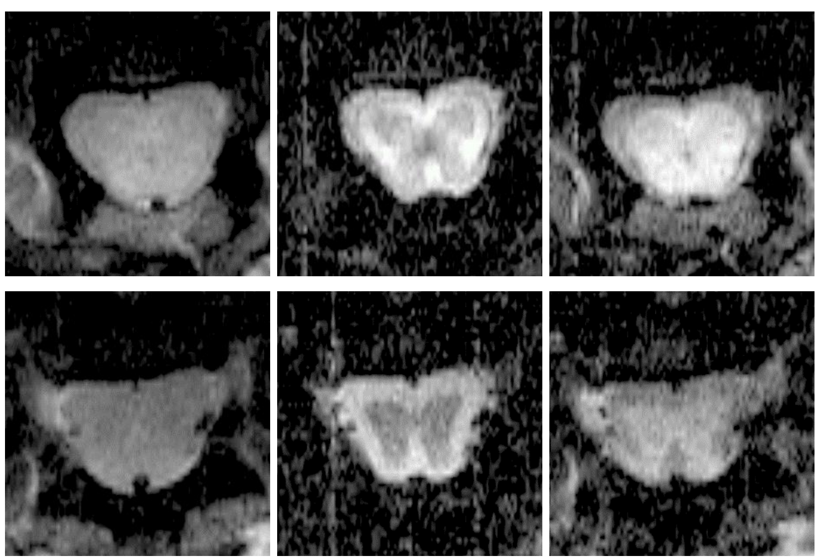


Fig. 11. Sample images of the spinal cord: in the center of the injury - the first line and 5 mm above – the second line. First column - without the diffusion gradient and another with diffusion gradients, in the Y and Z direction.

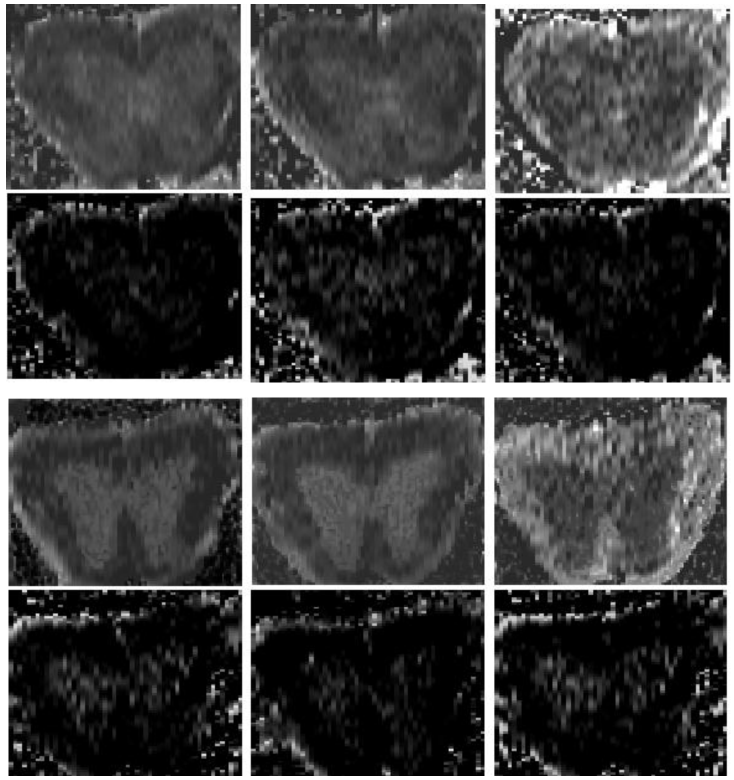


Fig. 12. Diffusion tensor components for the layer in the center of the damage (the first 2 rows) and 5 mm above (2 rows).

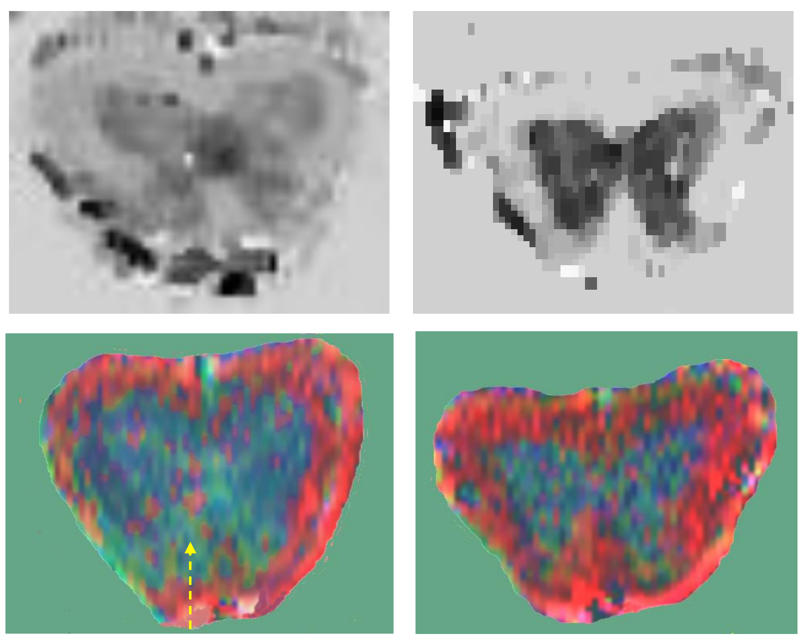


Fig. 13. Images of the fractional anisotropy FA and diffusion tensor components presented in a RGB form: in the center of the damage - first column and 5 mm above – the second column.

2.3.7 **A. Krzyżak**, I. Habina: Low field 1H NMR characterization of mesoporous silica MCM-41 and SBA-15 filled with different amount of water. Microporous and Mesoporous Materials 2016, 231: 230-239. DOI:10.1016/j.micromeso.2016.05.032 (IF-3.45) (WoS).

The motivation for the paper [H7] was to characterize the mesoporous systems (nanoporous diameters) built with silicate compounds of large surfaces and a uniform hexagonal pore structure by NMR method in the low field of 50mT with short echo time. As low field enabled the results, which are not affected by differences in the magnetic susceptibilities of the investigated medium, which in turn is the main problem of the NMR application for porous systems in high magnetic fields. In [H7] we explored the transverse T2 and longitudinal T1 relaxation times their quotients and T1T2 maps depending on water content in both samples, from the overfilled to partially filled mesopores' states (Fig. 14). In earlier work carried out using MAS technique by D'Agostino et al [18], it has been shown that the T1/T2 ratio correlates with the maximum activation energy of desorption, which gives information about the water interaction on the surface (fig. 15). The results presented in this work in a complementary manner confirms earlier reports of Grunberg et al. [19], in which the stronger binding of water molecules were observed for SBA-15 as compared with MCM-41. A unique achievement of the work is to observe nuclear resonance of the hydrogen nuclei both in water that fills the pore spaces and the water in-between pores, and also in water associated with the surface of the particles of calcium-silicate MCM-41 and SBA-15, and finally the hydroxyl groups present on the surface of the systems being researched.

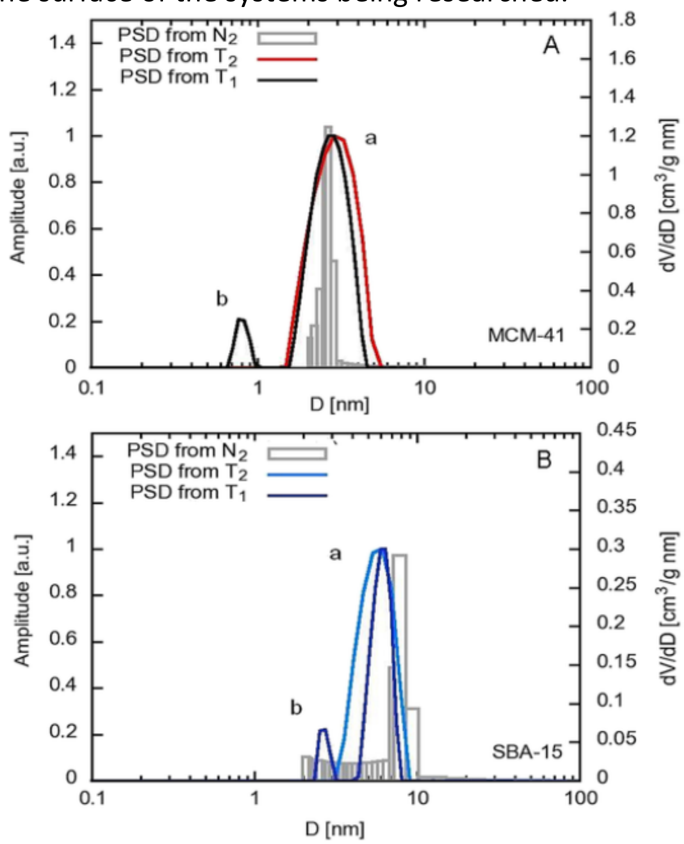


Fig. 14. Pore distribution obtained for T1 and T2 experiments and for N2 isotherm.

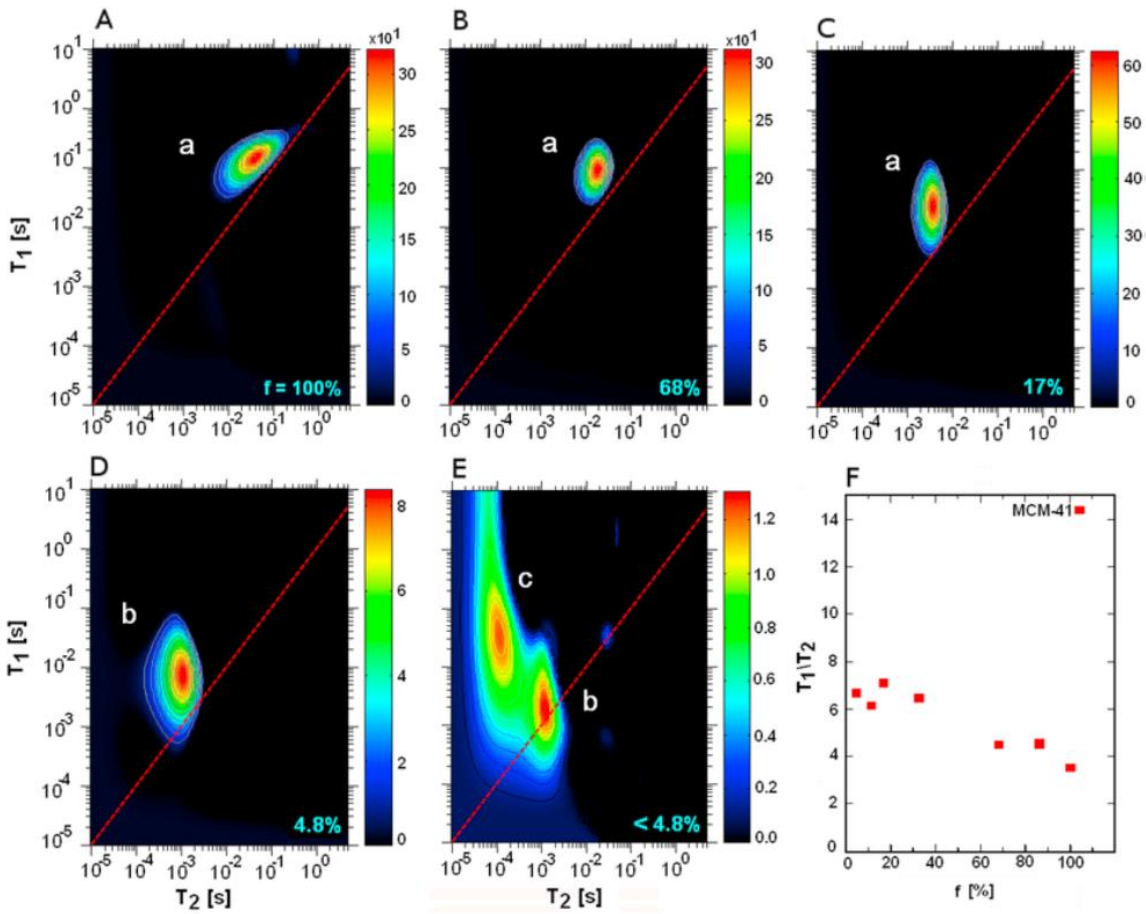


Fig. 15. T1T2 distribution maps, for the signals: a – free water, b – surface-bound water, c – hydroxyl groups.

In conclusion, the results of work [H7] demonstrate the possibility of effective (correct) NMR imaging of porous systems in a micro- and mesopore- scale (2nm) according to IUPAC classification (in fact, we are also able to image microporous systems in shales [B1, B3]). So far in the work of the [H4-H6] we studied biological macro-pores sizes from several to tens of micrometers. Work [H3] is, in turn, an example of NMR application to the meso- and macroporous systems found in the solids (sandstone). The work [H1] and [H2] in addition to the innovative parts, are also the examples of the NMR application to standard macroporous capillary and laminar structures.

2.3.8 **A. Krzyżak.** Anisotropic diffusion phantom for calibration of diffusion tensor imaging pulse sequence used in MRI.

Publication of [H8] provides a description of the American patent granted in February 2014 at number: US8643369 B2. The patent description includes the protection of calibration methods which constitutes a development of the claims 6-9 described in Polish patent application. For the American Office and in response to the comments of the reviewers, some of the records were reformulated and developed. However, the substance of this is the protection of the calibration method described above. Detailed records are present at given numbers of applications and patents, which are reference publications.

The subject matter of the invention concerns the anisotropic diffusion phantom for the calibration of any diffusion MR DTI imaging sequence and a method for the calibration of all the MRI scanners by using anisotropic diffusion models based on the “b” matrix, which is a quantity specific for every magnetic resonance (MR) imaging sequence and the MRI scanner used. It has application in the study of solids, amorphous materials, liquids and biological tissues.

In the prior art, the values of the “b” matrix that were needed to calculate the diffusion tensor were determined analytically and separately for every diffusion MR imaging sequence and MRI scanner; the results were approximate only due to the complex formulae used in the calculation. Alternatively, a single value of the “b” matrix that was assumed for the entire volume of the object in question Was used for the calculation of the diffusion tensor.

A disadvantage of the diffusion tensor calculation methods known in the art is the large contribution of calculation errors as the approximate “b” matrix values are used and a lack of any spatial distribution of the “b” matrix is assumed. Therefore, it is rather difficult to determine the water diffusion fluctuations in the object examined by using an MRI scanner properly, precisely and quantitatively, and the reproducibility of the results is non-existent. Distinct MR sequences occur for various MRI scanners; in consequence, the results are discrepant and hardly comparable. The results are fraught with errors as it is impossible to precisely determine the “b” matrix values.

A calibration method of the invention for any MRI scanner eliminates these shortages and enables the precise and spatial determination of “b” matrix values for any MRI scanner and any imaging sequence, in particular DTI.

Detailed examples of the BSD-DTI method application for commercial MR scanners are shown in the works [H1] and [H2]. Figure 16 illustrates the possible scale of accuracy improvement for determining diffusion tensor components.

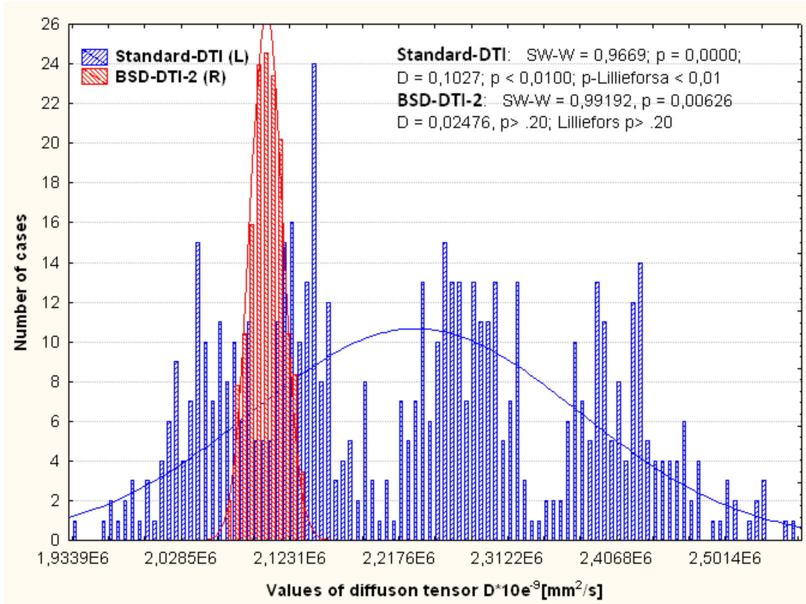


Fig. 16. The value of diffusion tensor components obtained with the standard method DTI (blue) for an isotropic and methods according to the invention (red), named BSD-DTI (B matrix Spatial Distribution in DTI). The standard deviation of the distribution obtained by BSD-DTI is several times smaller in relation to the distribution obtained by standard method.

2.4 Summary

The actual issues linking works [H1-H8] are the innovative solutions in the NMR field, allowing for a significant increase in the estimation accuracy of biophysical parameters for porous systems in the various fields of science and technology such as biology, geology and engineering. Some of the solutions, in particular concerning the diffusion and diffusion tensor imaging was covered by patent protection [H8,Z1,Z2,Z3].

The most important achievements covered by publications [H1-H8], include:

- The development of theory for new methods of diffusion coefficients and tensor components imaging in DWI and DTI experiments:
    - BSD-DTI-B-matrix Spatial Distribution in DTI,
    - SBS-DTI-simplified BSD-DTI
- The development of objectives and implementation fora new line of anisotropic phantoms of laminar and capillary structures, being patterns of diffusion tensor.
- Phantom prototypes implementation for application of BSD-DTI method in practice and their use for experiments executed on commercial systems, such as Bruker 9.4 T, GE 3T, Siemens 3T.
- The development of the theory and its experimental verification concerning imaging of hydrogen in the following states: liquid water, surface-bound water and hydroxyl groups in mesoporous systems.
- Obtaining patent protection for BSD-DTI methods of in the U.S. Patent Office.

Literature

1. Bloch F, Hansen WW, Packard M. Nuclear Induction. Phys Rev 1946; 69:127 (The original announcement by Bloch's group)
2. Purcell EM, Torrey HC, Pound RV. Resonance absorption by nuclear moments in a solid. Phys Rev 1946; 69:37-38. (The original announcement by Purcell's group)
3. Simpson MJ, Simpson AJ. NMR Spectroscopy. A Versatile Tool for Environmental Research. 1st ed. Chichester : John Wiley & Sons Ltd, 2014.
4. Stapf S, Han S-J. NMR Imaging in Chemical Engineering Research. 4th ed. Weiheim : Wiley-VCH Verlag GmbH & Co., 2006
5. George R. Coates, Lizhi Xiao, and Manfred G. Prammer, NMR Logging Principles and Applications, Halliburton Energy Services, 1999.
6. E.L.Hahn, Phys. Rev., 780,580(1950).

7. P.T. Callaghan, *Principles of Nuclear Magnetic Resonance Microscopy*, Clarendon Press, Oxford, 1993
8. A. Einstein *Investigation on the theory of the Brownian movement* . New York: Dover; 1926
9. EO. Stejskal, JE. Tanner, Spin diffusion measurements: spin echoes in presence of time dependent field gradient. Journal of Chemical Physics 1965;42:288-292.
10. Basser PJ, Mattiello J, LeBihan D.. Estimation of the effective self-diffusion tensor from the NMR spin echo. J Magn Reson B 1994;103:247–254.
11. Basser PJ, Mattiello J, Le Bihan D.. MR diffusion tensor spectroscopy and imaging. Biophys J1994;66:259–267.
12. M. Vogel, Eur. Phys. J. Spec. Top. 189 (2010) 47- 64.
13. Le Bihan D, Editor. Magnetic Resonance Imaging of Diffusion and Perfusion: Applications to Functional Imaging. Lippincott-Raven Press, New York, 1995..
14. Le Bihan D & Fukuyama H, Editors. Water: The forgotten Biological Molecule. Pan Stanford Publishing, Singapore, 2011.
15. Peter B. Kingsley. Introduction to diffusion tensor imaging mathematics: Part II. Anisotropy, diffusion-weighting factors, and gradient encoding schemes. Concepts in Magnetic Resonance Part A 2006; 101–122.
16. Peter B. Kingsley. Introduction to diffusion tensor imaging mathematics: Part III. Tensor Calculation, Noise, Simulations, and Optimization. Concepts in Magnetic Resonance Part A 2006; Volume 28A, Issue 2: 155–179.
17. Le Bihan D. Looking inside the brain: The power of neuroimaging. Princeton University Press, Princeton, 2014.
18. B. Grünberg, T. Emmler, E. Gedat, I. Shenderovich, G.H. Findenegg, H.H. Limbach, G. Buntkowsky, Chem. Eur. J. 10 (2004) 5689-5696.
19. C. D'Agostino, J. Mitchell, M.D. Mantle, L.F. Gladden, Chem. Eur. J. 20 (2014) 13009 - 13015.
20. M. Fleury, E. Kohler, F. Norrant, S. Gautier, J.M'Hamdi, L. Barree, J. Phys. Chem. C 117 (2013) 4551-4560.
21. M. Fleury, M. Romero-Sarmiento, J. Petr. Sci. Eng. 137 (2016) 55-62.

3. List of research and scientific achievements (not included in the work discussed in section 2.), and indicators of scientific achievements.

3.1 An indication of your factual and percentage participation for publications in the Journal Citation Reports (JCR) list.

I am a co-author of 19 papers published in journals from the JCR list, with 11 of these published after obtaining a PhD degree, and another 8 before. For a complete compilation please refer to list A at the end of this auto-presentation

After PhD thesis.

[A1] K. Borkowski, K. Kłodowski, H. Figiel, A. Krzyżak. A theoretical validation of the B-matrix Spatial Distribution approach to Diffusion Tensor Imaging. Magnetic Resonance Imaging 2016, (IF-1.98).

My contribution to this work was: development of the general concept of the work, carrying out the NMR experiments, data analysis. I participated in writing of the manuscript. I estimate my share in this work to 35%.

[A2] G. Stoch, A. Krzyżak. Parameterized signal calibration for NMR cryoporometry experiment without external standard. Journal of Magnetic Resonance 2016, 269:97-103. Doi:10.1016/j.jmr.2016.05.015, (IF- 2.89).

My contribution to this work was discussion: of general concept of the work, carrying out the NMR experiments, data analysis. I participated in correction of the manuscript. I estimate my share in this work to 10%.

[A3] A. Fheed, A. Świerczewska, A. KRZYŻAK: The isolated Wuchiapingian (Zechstein) Wielichowo Reef and its sedimentary and diagenetic evolution, SW Poland. Geological Quarterly 12/2015; 59(4):762-780. DOI:10.7306/gq.1266 (IF-1.0).

My contribution to this work was: discussion of general concept of the work in the field of NMR, carrying out the NMR experiments, data analysis. I estimate my share in this work to 15%.

[A4] K. Borkowski, A. Krzyżak: Simulations of rotation of the anisotropic phantom in BSD-DTI. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 10/2015; 28(1 Supplement):467-468. Doi:10.1007/s10334-015-0490-7 (IF-2.87).

My contribution to this work was: development of the general concept of the work. I participated in writing of the manuscript. I estimate my share in this work to 50%.

[A5] K. Kłodowski, A. Krzyżak: Pattern recognition and filtering of the b-matrix spatial distribution in the BSD-DTI technique. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 10/2015; 28(1 Supplement):468-469. Doi:10.1007/s10334-015-0490-7 (IF-2.87).

My contribution to this work was: partial development of the general concept of the work. I participated in writing of the manuscript. I estimate my share in this work to 50%.

[A6] A. Krzyżak: Application of anisotropic diffusion phantom for DTI experiments. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 10/2012; 25(1 Supplement):231-232. DOI:10.1007/s10334-012-0324-9 (IF-1.86).

I am the only author of this work and my share is 100%.

[A7] A. Krzyżak, Leszek Jaroszewicz: Anisotropic diffusion phantom - application for DTI. Molecular Imaging & Biology 12/2010; 12 (Suppl 2). DOI:10.1007/s11307-010-0453-3 (IF-3.14).

My contribution to this work was: development of the novel theory of diffusion tensor imaging, called BSD-DTI, carrying out the experiments, data analysis, concept and design of the anisotropic phantoms and writing the manuscript. I estimate my share in this work to 85%.

[A8] A. Krzyżak: The comparison of statistically significant alterations of the water diffusion tensor parameters for injured rats' spinal cords in vivo and in vitro. European Journal of Neurology 09/2010; 17(SI):313-313, (IF-3.76).

I am the only author of this work and my share is 100%.

[A9] A. Krzyżak: Assessment of white and grey matter injury in rats spinal cord using alterations of the water diffusion tensor parameters. Journal of the Neurological Sciences 08/2009; 283(1-2):279-279, (IF- 2.32).

I am the only author of this work and my share is 100%.

[A10] A. Krzyżak, A. Jasiński: Application of statistical analysis of diffusion tensor parameters for assessment of spinal cord injury. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 09/2005; 18(S1):116-117. DOI:10.1007/s10334-005-0002-2, (IF-1.72).

My contribution to this work was: development of the novel theory of diffusion tensor imaging, carrying out the experiments, data analysis and writing the manuscript. I estimate my share in this work to 85%.

[A11] A. Jasiński, A. T. Krzyżak, D. Adamek, J. Pindel, W. P. Węglarz, P. Kozłowski, A. Urbanik: Investigation of spinal cord structures using water diffusion tensor imaging in a rat model of mechanical injury "in vivo". Neurologia i neurochirurgia polska 01/2001; 35(3):85-85, (IF-0.74).

My contribution to this work was: collaborating in the concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis. I estimate my share in this work to 30%.

Before PhD thesis.

[A12] J. Pindel, A. Jasiński, A. Krzyżak, W. Węglarz, D. Adamek, P. Sagnowski, P. Kozłowski, A. Urbanik: Temporal studies of water diffusion tensor in an injured spinal cord of the rat. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/2000; 11(Sl):121-121, (IF-0.87).

My contribution to this work was: development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis. I estimate my share in this work to 25%.

[A13] D. Adamek, A. Jasiński, A. Krzyżak, J. Pindel, P. Kozłowski, P. Sagnowski, W. Węglarz: The distribution and spatial relations of damage to the spinal cord after mechanical injury may suggest a narrow potential therapeutical "window".. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/2000; 11(Sl):10-10, (IF-0.87).

My contribution to this work was: development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis. I estimate my share in this work to 25%.

[A14] A. Jasiński, A.T. Krzyżak, P. Kozłowski, W. Węglarz, J. Pindel, D. Adamek, P. Sagnowski, A. Urbanik: Investigation of spinal cord injury on a rat model - effects of formaline fixation on water diffusion tensor. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/1999; 8(Sl):181-182, (IF-0.8).

My contribution to this work was: collaborating in the concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments, data analysis and writing the manuscript. I estimate my share in this work to 40%.

[A15] W. P. Węglarz, A. Jasiński, A. T. Krzyżak, P. Kozłowski, D. Adamek, P. Sagnowski, J. Pindel: MR microscopy of water diffusion tensor in biological systems. Applied Magnetic Resonance 12/1998; 15(3):333-341. DOI:10.1007/BF03162019, (IF-0.93).

My contribution to this work was: development of the general concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments, data analysis and writing the manuscript. I estimate my share in this work to 50%.

[A16] A. Jasiński, P. Kozłowski, A.T. Krzyżak, D. Adamek, P. Sagnowski: Water diffusion tensor imaging in an injured spinal cord of the rat in vivo at 9.4 T. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/1998; 6(Sl):119-120, (IF-0.2).

My contribution to this work was: collaborating in the concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis. I estimate my share in this work to 40%.

[A17] D. Adamek, J. Kałuża, P. Sagnowski, A. Krzyżak, A. Jasiński, M. Baj, W. Węglarz, A. Urbanik: In the search of better insight into pathology of spinal cord injury. Investigation of water diffusion in relation to the expression of ubiquitin and glial fibrillary acidic protein in spinal cord of rat after experimental weight drop injury. Zentralblatt für Neurochirurgie 01/1998; 58(3):211-211, (IF-0.3).

My contribution to this work was: development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis. I estimate my share in this work to 20%.

[A18] A. Krzyżak, A. Jasiński, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski, W. Węglarz: Monitoring injury in a rat spinal cord using MR Microscopy of a water diffusion tensor. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/1997; 5(2):161-162, (IF-0.2).

My contribution to this work was: development of the general concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments, data analysis and writing the manuscript. I estimate my share in this work to 50%.

[A19] B. Tomanek, A. Jasiński, Z. Sułek, J. Muszynska, P. Kulinowski, S. Kwieciński, A. Krzyżak, T. Skórka, J. Kibiński: Magnetic resonance microscopy of internal structure of drone and queen honey bees. J Apic. Res. Journal of Apicultural Research 01/1996; 35(1):3-9, (IF-0.774).

My contribution to this work was: development of part of the software, carrying out part of the experiments. I estimate my share in this work to 5%.

3.2 Authorship or co-authorship of monographs, scientific publications in international journals or domestic journals other than ones in databases or list referred to in 3.1.

In addition to the works of [H1-H8] and works in magazines featured in the JCR list of [A1-A20] I am the author or co-author of twenty [B1-B20] published papers in other journals, and more than one hundred conference presentations [C1-C108]. In addition to the below works, another 6 work is under review in the high-ranked magazines in the JCR list. These works and conference presentations are enumerated in C and D lists at the end of this document, respectively.

[B1] S. Bednarczyk, A. KRZYŻAK, G. MACHOWSKI. Comparative analysis of measurements and estimation of permeability of shales in selected well sections from Baltic Basin (Northern Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:769-776. DOI 10.5593/SGEM2016/B13/S06.097.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B2] J. Górka, A. Świerczewska, A. KRZYŻAK. Controls of pressure solution structures on fluid migration – nuclear magnetic resonance studies from Struga-1 well (Zechstein Main Dolomite; W Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:785-792. DOI 10.5593/SGEM2016/B13/S06.099.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B3] E. PUSKARCZYK, P. KRAKOWSKA, A. KRZYŻAK, G. MACHOWSKI. Correlation of nuclear magnetic resonance and mercury intrusion porosimetry data for the best petrophysical parameters estimation in shales. SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:793-800. DOI 10.5593/SGEM2016/B13/S06.100.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B4] A. PSTRUCHA, G. MACHOWSKI, A. KRZYŻAK. Petrophysical characterization of the Miocene sandstones of the Carpathian Foredeep (South-East Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:891-898. DOI 10.5593/SGEM2016/B13/S06.112.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B5] E. PSTRUCHA, G. MACHOWSKI, A. KRZYŻAK. Porosity and permeability of the Main Dolomite oil-bearing rocks in the S-1 well (Western Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:905-912. DOI 10.5593/SGEM2016/B13/S06.114.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B6] N. Radzik, A. KRZYŻAK, A. Świerczewska, G. MACHOWSKI. The complex characterization of sandstone cores using low-field NMR SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:963-970. DOI 10.5593/SGEM2016/B13/S06.122.

My contribution to this work was: development of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B7] K. Kłodowski, P. Łukasik, A. Krzyżak. Approximation of the actual spatial distribution of the b-matrix in diffusion tensor imaging with bivariate polynomials. Annals of Computer Science and Information Systems 2016; 8:943-946. DOI: 10.15439/2016F457.

My contribution to this work was: partial development of the general concept of the work, development of the novel theory of diffusion tensor imaging, called BSD-DTI, , planning and carrying out the experiments. I estimate my share in this work to 40%.

[B8] K. Borkowski, A. Krzyżak. Improving precision and accuracy of DTI experiments with the simplified BSD calibration – computer simulations. Annals of Computer Science and Information Systems 2016; 8:935-938. DOI: 10.15439/2016F403.

My contribution to this work was: development of the general concept of the work, development of the novel theory of diffusion tensor imaging, called sBSD-DTI, planning and carrying out the experiments. I estimate my share in this work to 60%.

[B9] A. Krzyżak, P. Łukasik, K. Janc. Determination of the quality of results obtained by various numerical methods for BSD. Annals of Computer Science and Information Systems 2016; 8:955-958. DOI: 10.15439/2016F458.

My contribution to this work was: development of the general concept of the work, development of the novel methods of diffusion tensor imaging, called BSD-DTI and sBSD-DTI, planning and carrying out the experiments. I estimate my share in this work to 60%.

[B10] J. Górka, A. Świerczewska, A. Krzyżak. Significance of pressure solution structures analysis for fluid flow studies – examples from Struga-1 well (Zechstein Main Dolomite; W Poland): first results. Geology, Geophysics & Environment 01/2015; 41(1):82-83. DOI:10.7494/geol.2015.41.1.82.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B11] N. Radzik, A. Świerczewska, A. Krzyżak. Identification of tectonic microstructures in flysch sandstones of the Outer Carpathians using X-ray nanotomography and nuclear magnetic resonance – first results. Geology, Geophysics & Environment 01/2015; 41(1):127-128. DOI:10.7494/geol.2015.41.1.127.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 30%.

[B12] A. Krzyżak, K. Kłodowski, Z. Raszewski. Anisotropic phantoms in Magnetic Resonance Imaging. IEEE Engineering in Medicine and Biology Society Conference Proceedings 2015; 414-417. DOI: 10.1109/EMBC.2015.7318387.

My contribution to this work was: development of the novel theory of diffusion tensor imaging, called BSD-DTI, concept and design of the anisotropic phantoms, planning and carrying out the experiments. I also participated in writing of the manuscript. I estimate my share in this work to 60%.

[B13] A. Krzyżak, K. Borkowski. Theoretical analysis of phantom rotations in BSD-DTI. IEEE Engineering in Medicine and Biology Society Conference Proceedings 2015; 410-413. DOI:10.1109/EMBC.2015.7318386.

My contribution to this work was: development of the novel theory of diffusion tensor imaging, called BSD-DTI, planning and carrying out the experiments. I also participated in writing of the manuscript. I estimate my share in this work to 60%.

[B14] A. Krzyżak, K. Kłodowski. The B Matrix Calculation Using the Anisotropic Phantoms for DWI and DTI Experiments. IEEE Engineering in Medicine and Biology Society Conference Proceedings 2015; 418-421. DOI:10.1109/EMBC.2015.7318388.

My contribution to this work was: development of a novel theory of diffusion tensor imaging, called BSD-DTI, carrying out the experiments, data analysis and writing the manuscript. I estimate my share in this work to 90%.

[B15] Ł. Kaczmarek, M. Maksimczuk, T. Wejrzanowski, A. Krzyżak. Use of X-ray computed microtomography in the heterogeneity analysis of Polish Zechstein carbonate rocks. SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:1027-1034. DOI 10.5593/SGEM2016/B13/S06.130.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 20%.

[B16] Ł. Kaczmarek, M. Maksimczuk, T. Wejrzanowski, A. Krzyżak. High-resolution x-ray microtomography and Nuclear Magnetic Resonance study of a carbonate reservoir rock. SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2015; 1:779-786. DOI 10.5593/SGEM2015/B11/S6.099.

My contribution to this work was: discussion of the general concept of the work, carrying out the NMR experiments, data analysis. I estimate my share in this work to 20%.

[B17] A. Krzyżak, A. Jasiński, W. Węglarz, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski. Quantitative assessment of injury in the spinal cord of a rat using MR Microscopy of water diffusion tensor, Proceedings of ISMRM, 6th Scientific Meeting in Sydney 1998, vol 3, p. 1931.

My contribution to this work was: development of the concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis, writing manuscript. I estimate my share in this work to 50%.

[B18] A. Jasiński, P. Kozłowski, A. Krzyżak, D. Adamek, P. Sagnowski, and J. Pindel. Investigation of spinal cord injury on a rat model using water diffusion tensor imaging. Proceedings of the IV Annual Meeting of the British Chapter of the ISMRM, p. B8, Nottingham, December 1998.

My contribution to this work was: collaborating in the concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis, writing manuscript. I estimate my share in this work to 40%.

[B19] A. Krzyżak, A. Jasiński, P. Kozłowski, D. Adamek, P. Sagnowski, and J. Pindel, "Diffusion tensor imaging of the injured spinal cord of a rat *in vivo*. A comparison with *in vitro* experiments", Proceedings of VII Meeting of ISMRM, p. 327, Philadelphia, May 1999.

My contribution to this work was: development of the concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis, writing manuscript. I estimate my share in this work to 50%.

[B20] A. Krzyżak, A. Jasiński, P. Kozłowsk, D. Adamek, P. Sagnowski, and J. Pindel, "Quantitative assessment of injury in the spinal cord of a rat *in vivo* using MRI of water diffusion tensor", Proceedings of VII Meeting of ISMRM, p. 1810, Philadelphia, May 1999.

My contribution to this work was: development of the concept of the work, development of the software for diffusion tensor calculation, carrying out the DTI experiments and data analysis, writing manuscript. I estimate my share in this work to 50%.

3.3 Authorship or co-authorship of collective studies, collections, research documentation, expert opinions, works of art.

I am the author of the know-how documentation presented in the following three sections.

3.3.1 Know-how documentation concerning the use of the invention prototype [Z1].

Documentation of the invention in the field of nuclear magnetic resonance of a protected patent applications [Z1] or patent [H8] containing development in the following areas:

- publication of the principles that are protected by patent and patent applications,
- technological principles for the construction of innovative anisotropic phantoms and BSD-DTI method implementation for a few commercial MRI systems (0.05T, 0.5T Magritek and 3T),
- new theoretical solutions,
- concepts and algorithms for data analysis from standard and innovative DWI and DTI experiments, using BSD-DTI method for MRI systems by Bruker, GE, working name for the program: BSD-DTI,
- concepts and algorithms for data multiple storage, working name: Geo Lab-Log,
- business model for the invention use and the principles of spin-off company creation.

3.3.2 Know-how documentation concerning the use of the invention [Z2].

Documentation of the invention in the field of nuclear magnetic resonance, protected by patent applications [Z2], containing development in the following areas:

- publication of patent applications’ protected principles
- new theoretical solutions

3.3.3 Know-how documentation concerning the use of the invention prototype [Z3].

Documentation of the invention in the field of nuclear magnetic resonance, protected by patent applications [Z3], containing development in the following areas:

- publication of patent applications’ protected principles,
- new theoretical solutions,
- concepts and algorithms for data analysis from standard and innovative DWI and DTI experiments, using sBSD-DTI method for MRI systems by Bruker, GE, Siemens.

3.4 Inventions, utility and industrial models, which obtained protection and have been exposed to international or national exhibitions or fairs

I am the author of the three families of inventions listed below and described in publications [H8, Z1, Z2, Z3].

3.4.1 The first group of inventions – [Z1].

The first group is protected by Polish, European, Japanese patent applications and American patent granted and applies to:

- the construction of various models of anisotropic phantoms of laminar and capillary structures being the diffusion tensor patterns,
- the method, called BSD-DTI, of calculating the actual spatial distribution of magnetic field gradient and matrix b for DWI and DTI experiments,
- the calibration method for any diffusion imaging sequence for MR scanners and the calculation method for actual distribution of the coefficients and diffusion tensors in DWI and DTI.

3.4.2 The second group of inventions – [Z2].

The second group protected by Polish patent application applies to:

- the method, called TSD-DTI, of calculating (as previously) the actual spatial distribution of magnetic field gradient and matrix b for DWI and DTI experiments, using a set of (matrix) anisotropic phantoms,
- the calibration method for any diffusion imaging sequence for MR scanners and the calculation method for actual distribution of the coefficients and diffusion tensors in DWI and DTI.

3.4.3 The third group of inventions – [Z3].

The third group of inventions protected by Polish and international patent applications (PCT) applies to:

- method simplified in relation to BSD-DTI, for determination (as previously) the actual spatial distribution of magnetic field gradient and matrix b for DWI and DTI experiments, called sBSD-DTI,
- method to shorten calibration time length twice for any diffusion imaging sequence performed on MR scanners, in comparison to BSD-DTI.

[Z1] **A. Krzyżak.** Anisotropic diffusion phantom for calibration of any diffusion tensor imaging pulse sequence used in MRI, DTI and the calibration manner for any MR scanner:

a) Polish patent application number: P.385276 (26.05 2008).
b) Extension of patent application in international PCT mode: PCT/PL2009/000051, WO/2009/145648 (2009).
c) USA patent application number US2011074423 (2011).
d) Japan patent application number JP2011520582 (2011).
e) European patent application number EP09755104.8 (2011).

The method foundation - later named as BSD-DTI - and construction foundations for anisotropic phantoms described in detail in [H1], are protected by patent path [Z1] and covered by patent protection in May 2008 as one of the results of the own research grant [G5}. In subsequent years the patent path has been enriched with the international application PCT and then USA, Japanese, and European application. The choice of the patent paths was based on the feasibility study developed by Strategor under grant Patent Plus [G4]. The Polish, Japanese and European paths are still in the proceeding phase, and the American path ended in February of 2014 with the assignment of a patent [H8]. Each of the national paths is separately proceeded and differs more or less from the first, and most comprehensive description in the publication for patent application, number P. 385276.

Principal patent claims, the application of P.385276:

1. An anisotropic diffusion phantom for the calibration of any MR imaging sequence, characterized in that it is formed by any volume densely filled with non-magnetic capillary elements (1) free of hydrogen nuclei, filled with H2O, hydrogel or another substance that contains hydrogen nuclei or it is formed by an array of thin glass plates (1) separated with layers of H2O, hydrogel or another substance that contains hydrogen nuclei (2), wherein the diffusion phantom can also be formed by anisotropic liquid crystals (LC) or others for other elements, such as for example 2H, 3He, 13C, 14N, 17O, 19F, 29Si, 31P etc.

2. An anisotropic phantom according to Claim 1, characterized in that it is formed by a cylindrical volume densely filled with non-magnetic cylindrical rods free of hydrogen nuclei, separated with layers of H2O, hydrogel or another substance that contains hydrogen nuclei.

3. An anisotropic phantom according to Claims 1 and 2, characterized in that by adjusting the capillary diameters, the cylindrical rod diameters or the thickness of the layers of H2O, hydrogel or any other substance that contains hydrogen nuclei between thin glass plates, the diffusion limit is determined for specified diffusion times Δ and temperature.

4. An anisotropic phantom according to Claim 1, characterized in that the densely non-magnetic capillaries or other elements of the diffusion phantom are made of glass, Teflon or any other material with similar properties.

5. An anisotropic phantom according to Claim 1, characterized in that it is a pipe with a bundle of suitable capillaries filled with H2O, hydrogel or any other substance that contains hydrogen nuclei so that the restriction of the diffusion at a given temperature in the direction perpendicular to the capillary axis is significant with respect to the range of diffusion times Δ in the diffusion MR imaging sequence.

6. A method for the calibration of any MR tomograph that consists in the spatial determination of the “b” matrix values, characterized in that for the calibration of any MR tomograph sequence by using the anisotropic diffusion phantom, the anisotropic diffusion phantom is placed in the interaction area of an RF coil in the volume of the MR tomograph tested, wherein subsequently, for the calculation of the diffusion tensor, the required number of “b” matrices are calculated based on the anisotropic diffusion model, which makes no less than six “b” matrices determined for each voxel and for each diffusion gradient vector direction required, and the “b” matrix values for the direction of the diffusion gradient vector are determined by solving a system of no less than six equations for the distinct diffusion tensor D values, wherein for the direction of the diffusion gradient vector various diffusion tensor values are obtained, preferably by rotating the anisotropic diffusion phantom in the volume of the MR tomograph tested, being the diffusion model for which the diffusion tensor in the system of principal axes has known values, wherein the diffusion model is rotated by various Euler angles, so that the determinant DM of the matrix whose columns correspond to the components of the diffusion tensor D after successive rotations of the diffusion model by specific Euler angles is defined by the matrix

$$D_M = \begin{pmatrix} D_{11} & D_{12} & D_{13} & D_{14} & D_{15} & D_{16} \\ D_{21} & D_{22} & D_{23} & D_{24} & D_{25} & D_{26} \\ D_{31} & D_{32} & D_{33} & D_{34} & D_{35} & D_{36} \\ D_{41} & D_{42} & D_{43} & D_{44} & D_{45} & D_{46} \\ D_{51} & D_{52} & D_{53} & D_{54} & D_{55} & D_{56} \\ D_{61} & D_{62} & D_{63} & D_{64} & D_{65} & D_{66} \end{pmatrix},$$

whose determinant is different from zero; subsequently, for the calculation of “b” matrix values for the direction of the diffusion gradient vector, the following system of equations is solved:

$$\mathbf{L = b\, D_M},$$

and this operation is repeated for the required number of diffusion gradient vector directions, i.e. for no less than six non-collinear directions of diffusion gradients and no less than one for the direction without a diffusion gradient.

7. A method according to Claim 6, characterized in that for the anisotropic diffusion phantom, the diffusion tensor values in the system of principal axes D1, D2, D3 as a function of temperature T and diffusion time Δ are determined in the typical unidimensional measurements of the diffusion coefficients for anisotropy directions.

8. A method according to Claim 6, characterized in that for the calibrated MR tomograph volume a diffusion model is formed and selected for an RF coil depending on its shape and parameters.

9. A method according to Claim 6, characterized in that the calibration of any MR tomograph is repeated every time before a change of imaging sequence parameters, in particular when changing diffusion gradients.

[Z2] **A. Krzyżak.** The method for imaging sequence calibration of diffusion tensor and tensor coefficients imaging in DWI, DTI, fMRI-DTI imaging experiments.

The elaboration in publication [Z2] applies to the patent application in the Polish Patent Office number p. 403172 of March of the year. 2013. The innovation is one of the results of the own grant realized in the years 2010-2013 in the IFJ PAN. The subject of the invention is a way of diffusion sequence calibration in MRI diffusion type experiment conducted for MR scanner, especially for DWI, DTI, FMRI-DTI experiments. The present invention provides an alternative for BSD-DTI solutions described above. The way of calibration for any diffusion imaging NMR sequence according to the invention eliminates the disadvantages described above, allowing for accurate measurement for the diffusion tensor and coefficients with any imaging sequence in particular for DWI, DTI, FMRI-DTI experiments.

Its essence is a calibration method of imaging sequence for MRI diffusion experiment conducted with MR scanner, which consists of the following steps for the specific locations in RF field. In the tested area of MR scanner it is subsequently placed the anisotropic diffusion phantom, that is diffusion-constraint at least in one direction along one of the principal axis associated with the phantom, and that has the diffusion tensor known previously. After placing the anisotropic diffusion phantom in a particular place, the measurements of diffusion tensor are carried out, by specifying the diffusion tensor components for the principal axes. After such measurements the spatial distribution for anisotropic diffusion phantom tensor is obtained, whose values are characterized by a pre-calibration value of the standard deviation. The next step is the correction for the diffusion tensor parameters on the basis of diffusion tensor spatial tensor distribution in order to lower the standard deviation to post-calibration value, less than the pre-calibration one.

An example of the use of the invention is presented in Figure 17.

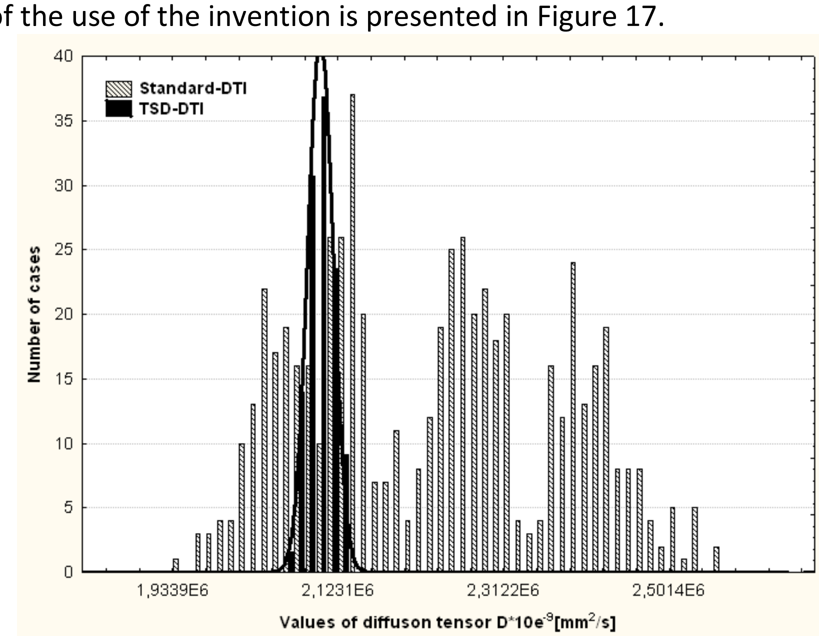


Fig. 17 Distributions obtained for principal values of isotropic diffusion phantom: by means of standard DTI method (dotted) and the invented method (filled) called TS-DTI (Tensors

Spatial Distribution in DTI), respectively. The standard deviation for distribution obtained by TSD-DTI is several times smaller in relation to standard method and it is comparable to BSD-DTI results.

Main claims for patent application P.403172:

1. Calibration method of imaging sequence for MRI diffusion experiment conducted with MR scanner, which consists of the following steps: in the tested area of MR scanner it is subsequently placed the anisotropic diffusion phantom, that is diffusion-constraint at least in one direction along one of the principal axis associated with the phantom, and that has the diffusion tensor known previously. After placing the anisotropic diffusion phantom in a particular place, the measurements of diffusion tensor are carried out, by specifying the diffusion tensor components for the principal axes. After such a measurements the spatial distribution for anisotropic diffusion phantom tensor is obtained, whose values are characterized by a pre-calibration value of the standard deviation. The next step is the correction for the diffusion tensor parameters on the basis of diffusion tensor spatial tensor distribution in order to lower the standard deviation to post-calibration value, less than the pre-calibration one.

2. A method according to Claim 1, characterized in that measurements of diffusion tensor is performed for various diffusion sequence parameters, in particular, for various values of diffusion gradients, diffusion times, matrix b values, directions and amplitudes for diffusion gradient vector.

3. A method according to Claim 1, characterized in that adjustments for diffusion tensor parameters are made by experimental changes to sequence parameters, in particular the value of the array "b", again by doing the measurements of diffusion tensor phantom anisotropic in the same locations, and the adjustment of parameters the sequence shall be made until the standard deviation for spatial distribution of diffusion tensor equals the desired post-calibration value.

5. A method according to Claim 1, characterized in that validates the parameters obtained by measurements of diffusion tensor using the same experiment with the revised parameters for the homogeneous water phantom.

6. A method according to Claim 5, characterized in that if the standard deviation of the diffusion tensor spatial distribution for homogeneous water phantom exceeds the desired value, then the correction of measurement parameters for anisotropic diffusion tensor phantom is repeated.

7. A method according to Claim 1, characterized in that adjusted parameters for diffusion tensor measurements are the final part of calibration for any diffusion tensor imaging sequence and it is used in diffusion tensor imaging for any object.

8. A method according to Claim 1, characterized in that calibration is performed before any change of imaging sequence parameters, in particular for changes in values and directions of diffusion gradient vectors.

[Z3] **A. Krzyżak**. The way of sequence calibration for imaging in an DMRI experiment using MR scanner.

Publication [Z3] applies to the last, third patent applications path presented in this work. Initial application number P. 413306 was made in the Polish Patent Office in July 2015, and another one extending protection to all countries of the world in PCT mode, a year later in July 2016. This invention is partially dependent on the invention [H8], and its essence is faster MR scanner calibration process by double and simplification of the calibration itself, which is of fundamental importance, especially for large commercial MR systems. These works are one of the results of the grant from the second competition of the Applied Research Program carried out in the period 2013-2017 on AGH.

3.5 Total impact factor of publications according to the Journal Citation Reports (JCR) list, in accordance with the year of publication

Total impact factor for all work is: 40,79.

3.6 The number of citations of publications by Web of Science (WoS) database

The total number of citations for publications is 77*, in this 52 without auto-citations.

3.7 Hirsch Index according to Web of Science database

Hirsch index, h = 6*.

(*) As of October 30, 2016. There are 15 published articles of my co-authorship in the WoS database under the in-process indexing, and 5 publications of other authors. The expected Hirsch index associated with this fact is 8, and the number of citations exceeds 105.

3.8 Managing of international and national research projects and the participation in such projects

Leadership in research projects at present or in the past, after PhD degree:

[G1]. **Task Coordinator** for AGH project in 2015-2018, on the basis of a NCBiR contract No. STRATEGMED2/265761/10/NCBR/2015 within the **STRATEGMED** framework, titled: *The regeneration of ischemic damage of the cardiovascular system using the Wharton's Jelly as a limitless source of therapeutic stem cells*. The subject of the task for AGH is the development of imaging methods using the phenomenon of nuclear magnetic resonance in order to quantify the regenerative potential WJMSC in studies of cardiac and skeletal muscles

[G2]. **Grant Leader** in the period 2013-2017 under a contract NCBiR No. PBS2/A2/0/2013 in the frame of Applied Research Program, titled: *The development of an innovative method that uses the phenomenon of nuclear magnetic resonance and its application to petrophysical parameters estimation for shale rocks, terygenic and carbonate Polish oil formations*.

[G3]. **Own grant leader** of its own in the years 2010-2013, on the basis of a contract with MNiSzW N N518413238 titled: *Development of the method for significant improvement the relationship to the noise in fMRI-DTI studies of human brain and spinal cord.*

[G4]. **Task Coordinator** in period 2010-2012, on the basis of a contract with MNiSzW No. PP 54001 under the Patent Plus program. Subject related to *elaboration of feasibility study and the national invention applications*.

[G5]. **Own grant leader** in period 2006-2008 ,on the basis of a contract with MNiSzW No. N518 006 31/0406 titled: *Developing a comprehensive method for determining component values of b matrix with MR diffusion tensor.*

In addition, I attended as a contractor in the following research projects:

[G6]. Project implemented in 2013-2017 under the direction of Prof. Dr hab. M. Stefaniuk in the frame of Blue Gas I, titled *Seismic research, and their application for detection of the presence of gas zones from shales. Selection of optimal parameters of acquisition and processing in order to render the structural construction and distribution of geomechanical and petrophysical parameters for rocks.*

[G7]. Project implemented in 2014-2017 under the direction of Prof. Dr hab. M. Stefaniuk in the frame of Blue Gas II, titled *Identification, location, and sharing of the optimal zones for unconventional occurrence of hydrocarbon accumulations of a "shale gas" type in the flysch Carpathians and technological aspects of the exploitation*.

3.9 International or national awards for scientific activities

- **Magna Cum Laude Award** (first award for the team from Poland on Europe's largest Conference on NMR) A. Krzyżak, A. Jasiński, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski, W. Węglarz: Monitoring injury in a rat spinal cord using MR Microscopy. Abstr. of 14th Ann. Meeting of ESMRMB'97 MAGMA Suppl. V(II):161-162. 1997.

- **Second prize** at the prestigious ISMRM Conference in Nottingham Nottingham A. Jasiński, P. Kozłowsk, A. Krzyżak, D. Adamek, Sagnowski P, and Pindel J. Investigation of spinal cord injury on a rat model using water diffusion tensor imaging. Proc. of the IV Meeting of the British Chapter of the ISMRM, p. B8, Nottingham (1998)

- **Distinction of IFJ PAN**, A. Krzyżak, Badanie wody w układach biologicznych metodą obrazowania MR tensora dyfuzji wody, PhD thesis, IFJ PAN (2001)

- **Fellowships** sponsored by ISMRM and ESMRMB and presentation of research results at prestigious conferences in 1998 (Sydney, Australia) and 1999 (Philadelphia, USA) by **ISMRM San Diego, USA**, and from 1997 to 1999 (Brussels, Geneva, Seville) by **ESMRMB, Vienna, Austria**.

- **Rector of AGH University Award**, II degree, for scientific achievements, 2016

3.10 Speeches on international or national thematic conferences

I am the author or co-author of more than a hundred presentations on 49 international and 27 national conferences. Out of this number I presented 9 papers personally [C17, C19, C28, C33, C41, C53, C78, C80, C98]. For a complete list of presentations, together with an indication of the conference subject please refer to part C at the end of the presentation.

4. Didactic and popularizing achievements and international cooperation

4.1 Participation in European programmes and other international and national programmes

- Program Of Applied Research PBS2 [G2] – implemented in the years 2013-2017.
- Strategic program STRATEGMED2 [G1] – implemented in the years 2015-2018.
- Strategic program Blue Gas 1 [G6] i Blue Gas 2 [G7] implemented in the years 2013-2017.

Projects [G1], [G2], [G6] and [G7] have been widely described in section 3.8.

4.2 Active participation in international and national scientific conferences

I am a co-author of 108 conference presentations enumerated in list C. This number contains 34 speeches presented at national and international conferences, after obtaining a doctoral degree (20), before obtaining a doctoral degree (14). The number of poster presentations is 74, after obtaining a doctoral degree (32), before obtaining a doctoral degree (42).

4.3 Participation in the organizational committees of national and international scientific conferences

- Participation in the Organization Committee of the National Seminar on Nuclear Magnetic Resonance And Its Applications, Kraków 1994 – 2012

4.4 Received prizes and awards

Prizes and awards are described in section 3.9.

4.5 Participation in consortia and research networks

Within the framework of the grant [G2] the manager of a consortium made up of the following universities and companies:

- AGH University of Science and Technology, Kraków,

- Warsaw University of Technology,
- Jarosław Dąbrowski Military Technical Academy , Warsaw,
- The Henryk Niewodniczański Institute of Nuclear Physics PAS,
- Polish Oil and Gas SA.

Within the framework of the grant [G1] participant of a consortium made up of the following universities and companies:

- Collegium Medicum, Jagiellonian University
- Jan Paweł II Cracow Specialist Hospital
- Polish Bank Of Stem Cells SA
- Jagiellonian Innovation Centre sp. z o. o.
- AGH University of Science and Technology, Kraków
- Medical University Of Silesia, Katowice

4.6 Project leadership carried out in collaboration with researchers from other Polish and foreign centers and in cooperation with businesses, other than those referred to in section 3.9 and 4.5.

Within the framework of the grant [G1] AGH cooperation with the following centres and entrepreneurs:

- RWTH Aachen – prof. Bernharda Blumicha group
- ETH Zurych – dr Franciszek Hennel
- Magritek Gmbh – dr Federico Casanova, dr Mark Hunter, dr Jurgen Koltz.

Within the framework of the grant [G2] AGH cooperation with the following centers and entrepreneurs:

- Magritek Gmbh – dr Federico Casanova, dr Juan Perlo, MSc Sean Buchannan.

4.7 Participation in committees, editorial and scientific boards of magazines

4.8 Membership in international and national organizations and scientific societies

- IEEE - Institute of Electrical and Electronics Engineers (od 2015).
- WMIS - World Molecular Imaging Society (od 2010).
- ESMRMB - European Society for Magnetic Resonance in Medicine and Biology (1997 – 2001, 2005-2006, 2012-2015).
- ISMRM - International Society for Magnetic Resonance in Medicine (1997-2000).

4.9 Achievement of the teaching and popularization of science

- Preparing and conducting (from 2010) lectures and experimental exercises to promote physics in primary school for children.
- Preparing and conducting (2000) lectures seminar concerning the application of the nuclear magnetic resonance tomography for imaging, in particular diffusion and diffusion tensor imaging for students, PhD candidates and academics IFJ PAN.
- Preparing and conducting presentations (from 2006 to 2012) concerning the application of tomography and NMR spectroscopy during open days IFJ MR.
- Preparing and conducting (from 2014) lectures and experimental exercises to promote physics of nuclear magnetic resonance for students of applied geology.

4.10 Scientific care of students

Promoter of the MSc theses, AGH technical physics:

- Mgr inż. Michał Radwan, The development of rapid Imaging sequences based on spin ech to study the diffusion in vivo-2010.
- Mgr inż. Iwona Habina, The spatial determination of matrix (b) for any sequence of diffusion tensor imaging using magnetic resonance master anisotropic diffusion – 2010.
- Mgr inż. Karol Borkowski, Development of imaging methods for human brain using fMRI-DTI – 2014.
- Weronika Mazur, Diffusion tensor imaging for anisotropic systems using NMR methods, planned to defend the thesis in June 2017.

4.11 Scientific care of PhD students as a scientific guardian or secondary promoter

Secondary promoter of PhD theses on Technical Physics or Geology, AGH:

- Mgr inż. Krzysztof Kłodowski – the planned defence of doctoral thesis - January 2017.
- Mgr inż. Karol Borkowski – the planned defence of doctoral thesis - June 2018.
- Mgr inż. Adam Fheed – the planned defence of doctoral thesis – June 2019.
- Mgr inż. Natalia Radzik – the planned defence of doctoral thesis – June 2019.

4.12 Internships in foreign and domestic science or academic centers

Monthly internships combined with scientific research:

- Institute for Biodiagnostic of National Research Council, Winnipeg, Canada – April 1999.
- FORENAP Institue, Rouffach, France, September 1998 .

I participated in training on the various aspects of spectroscopy and NMR tomography organized by the biggest companies, European (ESMRMB) and global (ISMRM):

- ESMRM - Brussels, September 1997, Genewa, September 1998, Seville, September 1999, Lizbona, September 2012.
- ISMRM – Sydney, April 1998, Philadelphia, April 1999.

I participated in training on NMR application to petrophysics hole and laboratory studies carried out by well-known companies:

- NMR Petrophysics INC – Marseille, France, March 2014.
- Magritek Gmbh – Aachen, Germany, October 2014.

4.13 Expertises or other development on request (free of charge)

- The elaboration of three publication of patent applications for patent attorneys, H.Drelichowski and A.Pawlowski (2009-2015)
- The development of the business model of the invention [H8] for MARR (2009)
- The development of the business model of the invention [H8] for the feasibility study prepared by Strategor from Poznan (2010).
- Preparation of know-how documentation for AGH described in section 3.4 (2015-2016).

4.14 Participation in expert and competition teams

4.15 Reviewing international and national projects

4.16 Review of publications in international and national journals

- Reviewer of several works (from 2008) in *NMR in Biomedicine* and *Neuroradiology*.

4.17 Other achievements and performed functions not mentioned so far

- Leader and creator of the concept of Laboratory of *Tomography And Nuclear Magnetic Resonance Spectroscopy* at the Faculty of Geology, Geophysics and Environmental Protection to study geological, biological and material porous systems in low and medium fields (2014-2016).

List of publications

Published articles

[H1] A. Krzyżak, Z. Olejniczak. Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix. Magnetic Resonance Imaging 2015, 33(3): 286–295., DOI:10.1016/j.mri.2014.10.007 IF (2.09).

[H2] K. Kłodowski, A. Krzyżak. Innovative anisotropic phantoms for calibration of diffusion tensor imaging sequences. Magnetic Resonance Imaging 2016, 34(4): 404-409., DOI:10.1016/j.mri.2015.12.010 (IF-2.09).

[H3] W. Węglarz, A. Krzyżak, M. Stefaniuk. ZTE imaging of tight sandstone rocks at 9.4T - comparison with standard NMR analysis at 0.05 T. Magnetic Resonance Imaging 2016, 34(4): 492-495; DOI:10.1016/j.mri.2015.12.001 (IF-2.09).

[H4] A. Krzyżak, A. Jasiński, W. Węglarz, D. Adamek, P. Sagnowski, M. Baj. Visualisation of the extent of damage in a rat spinal cord injury model using MR microsopy of the water

[H5] A. Krzyżak, A. Jasiński, D. Adamek. Qualification of the most statistically “sensitive” diffusion tensor imaging parameters for detection of spinal cord injury Acta Physica Polonica A vol. 108, 207-210 (2005) (IF-0.53).

[H6] A. Krzyżak, A. Jasiński, S. Kwieciński, P. Kozłowski, D. Adamek. Quantitative Assessment of Injury in Rat Spinal Cords In Vivo by MRI of Water Diffusion Tensor. Applied Magnetic Resonance 07/2008; 34(1):3-20. DOI:10.1007/s00723-008-0095-7 (IF-0.748).

[H7] A. Krzyżak, I. Habina. Low field 1H NMR characterization of mesoporous silica MCM-41 and SBA-15 filled with different amount of water. Microporous and Mesoporous Materials 2016; 231:230-239. DOI:10.1016/j.micromeso.2016.05.032 (IF-3.45).

[H8] A. Krzyżak. Anisotropic diffusion phantom for calibration of diffusion tensor imaging pulse sequence used in MRI:

American patent Ref. No: US8643369 B2 (2014).

Publications of patent applications

[Z1] A. Krzyżak. Anizotropowy fantom dyfuzji dla kalibracji dowolnej sekwencji obrazowania MR, DTI oraz sposób kalibracji dowolnego tomografu MR:

a) numer zgłoszenia polskiego: P.385276 (26.05 2008),
b) rozszerzenie zgłoszenia patentowego w międzynarodowym trybie PCT PCT/PL2009/000051, WO/2009/145648 (2009),
c) numer zgłoszenia amerykańskiego US2011074423 (2011),
d) numer zgłoszenia japońskiego JP2011520582 (2011) i JP2014223546 (2014),
e) numer zgłoszenia europejskiego EP09755104.8 (2011).

[Z2] A. Krzyżak. Metoda kalibracji sekwencji obrazowania współczynników dyfuzji i tensora dyfuzji w eksperymentach obrazowania DWI, DTI, fMRI – DTI:

a) numer zgłoszenia polskiego: P.403172 (15.03.2013).

[Z3] A. Krzyżak. Sposób kalibracji sekwencji obrazowania w eksperymencie typu DMRI przeprowadzanym w tomografie MR:
a) numer zgłoszenia polskiego: P. 413306 (30.07.2015),
b) numer zgłoszenia międzynarodowego PCT/EP2016/067964 (07.2016).

A Scientific publications in journals from Journal Citation Reports (JCR) database.

[A1] K. Borkowski, K. Kłodowski, H. Figiel, A. Krzyżak. A theoretical validation of the B-matrix Spatial Distribution approach to Diffusion Tensor Imaging. Magnetic Resonance Imaging 2016, (IF-1.98).
[A2] G. Stoch, A. Krzyżak. Parameterized signal calibration for NMR cryoporometry experiment without external standard. Journal of Magnetic Resonance 2016, 269:97-103. Doi:10.1016/j.jmr.2016.05.015, (IF- 2.89).
[A3] A. Fheed, A. Świerczewska, A. KRZYŻAK. The isolated Wuchiapingian (Zechstein) Wielichowo Reef and its sedimentary and diagenetic evolution, SW Poland. Geological Quarterly 12/2015; 59(4):762-780. DOI:10.7306/gq.1266 (IF-1.0).
[A4] K. Borkowski, A. Krzyżak. Simulations of rotation of the anisotropic phantom in BSD-DTI. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 10/2015; 28(1 Supplement):467-468. Doi:10.1007/s10334-015-0490-7 (IF-2.87).
[A5] K. Kłodowski, A. Krzyżak. Pattern recognition and filtering of the b-matrix spatial distribution in the BSD-DTI technique. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 10/2015; 28(1 Supplement):468-469. Doi:10.1007/s10334-015-0490-7 (IF-2.87).
[A6] A. Krzyżak. Application of anisotropic diffusion phantom for DTI experiments. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 10/2012; 25(1 Supplement):231-232. DOI:10.1007/s10334-012-0324-9 (IF-1.86).

[A7] A. Krzyżak, Leszek Jaroszewicz. Anisotropic diffusion phantom - application for DTI. Molecular Imaging & Biology 12/2010; 12 (Suppl 2). DOI:10.1007/s11307-010-0453-3 (IF-3.14).

[A8] A. Krzyżak. The comparison of statistically significant alterations of the water diffusion tensor parameters for injured rats' spinal cords in vivo and in vitro. European Journal of Neurology 09/2010; 17(SI):313-313, (IF-3.76).

[A9] A. Krzyżak: Assessment of white and grey matter injury in rats spinal cord using alterations of the water diffusion tensor parameters. Journal of the Neurological Sciences 08/2009; 283(1-2):279-279, (IF- 2.32).

[A10] A. Krzyżak, A. Jasiński: Application of statistical analysis of diffusion tensor parameters for assessment of spinal cord injury. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 09/2005; 18(S1):116-117. DOI:10.1007/s10334-005-0002-2, (IF-1.72).

[A11] A. Jasiński, A. T. Krzyżak, D. Adamek, J. Pindel, W. P. Węglarz, P. Kozłowski, A. Urbanik: Investigation of spinal cord structures using water diffusion tensor imaging in a rat model of mechanical injury "in vivo". Neurologia i neurochirurgia polska 01/2001; 35(3):85-85, (IF-0.74).

[A12] J. Pindel, A. Jasiński, A. Krzyżak, W. Węglarz, D. Adamek, P. Sagnowski, P. Kozłowski, A. Urbanik: Temporal studies of water diffusion tensor in an injured spinal cord of the rat. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/2000; 11(Sl):121-121, (IF-0.87).

[A13] D. Adamek, A. Jasiński, A. Krzyżak, J. Pindel, P. Kozłowski, P. Sagnowski, W. Węglarz: The distribution and spatial relations of damage to the spinal cord after mechanical injury may suggest a narrow potential therapeutical "window".. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/2000; 11(Sl):10-10, (IF-0.87).

[A14] A. Jasiński, A.T. Krzyżak, P. Kozłowski, W. Węglarz, J. Pindel, D. Adamek, P. Sagnowski, A. Urbanik: Investigation of spinal cord injury on a rat model - effects of formaline fixation on water diffusion tensor. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/1999; 8(Sl):181-182, (IF-0.8).

[A15] W. P. Węglarz, A. Jasiński, A. T. Krzyżak, P. Kozłowski, D. Adamek, P. Sagnowski, J. Pindel: MR microscopy of water diffusion tensor in biological systems. Applied Magnetic Resonance 12/1998; 15(3):333-341. DOI:10.1007/BF03162019, (IF-0.93).

[A16] A. Jasiński, P. Kozłowski, A.T. Krzyżak, D. Adamek, P. Sagnowski: Water diffusion tensor imaging in an injured spinal cord of the rat in vivo at 9.4 T. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/1998; 6(Sl):119-120, (IF-0.2).

[A17] D. Adamek, J. Kałuża, P. Sagnowski, A. Krzyżak, A. Jasiński, M. Baj, W. Węglarz, A. Urbanik: In the search of better insight into pathology of spinal cord injury. Investigation of water diffusion in relation to the expression of ubiquitin and glial fibrillary acidic protein in spinal cord of rat after experimental weight drop injury. Zentralblatt für Neurochirurgie 01/1998; 58(3):211-211, (IF-0.3).

[A18] A. Krzyżak, A. Jasiński, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski, W. Węglarz: Monitoring injury in a rat spinal cord using MR Microscopy of a water diffusion

tensor. MAGMA Magnetic Resonance Materials in Physics Biology and Medicine 01/1997; 5(2):161-162, (IF-0.2).

[A19] B. Tomanek, A. Jasiński, Z. Sułek, J. Muszynska, P. Kulinowski, S. Kwieciński, A. Krzyżak, T. Skórka, J. Kibiński: Magnetic resonance microscopy of internal structure of drone and queen honey bees. J Apic. Res. Journal of Apicultural Research 01/1996; 35(1):3-9, (IF-0.774).

B Scientific publications in international or domestic journals other than listed in the JCR database

[B21] S. Bednarczyk, A. KRZYŻAK, G. MACHOWSKI. Comparative analysis of measurements and estimation of permeability of shales in selected well sections from Baltic Basin (Northern Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:769-776. DOI 10.5593/SGEM2016/B13/S06.097.

[B22] J. Górka, A. Świerczewska, A. KRZYŻAK. Controls of pressure solution structures on fluid migration – nuclear magnetic resonance studies from Struga-1 well (Zechstein Main Dolomite; W Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:785-792. DOI 10.5593/SGEM2016/B13/S06.099.

[B23] E. PUSKARCZYK, P. KRAKOWSKA, A. KRZYŻAK, G. MACHOWSKI. Correlation of nuclear magnetic resonance and mercury intrusion porosimetry data for the best petrophysical parameters estimation in shales. SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:793-800. DOI 10.5593/SGEM2016/B13/S06.100.

[B24] A. PSTRUCHA, G. MACHOWSKI, A. KRZYŻAK. Petrophysical characterization of the Miocene sandstones of the Carpathian Foredeep (South-East Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:891-898. DOI 10.5593/SGEM2016/B13/S06.112.

[B25] E. PSTRUCHA, G. MACHOWSKI, A. KRZYŻAK. Porosity and permeability of the Main Dolomite oil-bearing rocks in the S-1 well (Western Poland). SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:905-912. DOI 10.5593/SGEM2016/B13/S06.114.

[B26] N. Radzik, A. KRZYŻAK, A. Świerczewska, G. MACHOWSKI. The complex characterization of sandstone cores using low-field NMR SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:963-970. DOI 10.5593/SGEM2016/B13/S06.122.

[B27] K. Kłodowski, P. Łukasik, A. Krzyżak. Approximation of the actual spatial distribution of the b-matrix in diffusion tensor imaging with bivariate polynomials. Annals of Computer Science and Information Systems 2016; 8:943-946. DOI: 10.15439/2016F457.

[B28] K. Borkowski, A. Krzyżak. Improving precision and accuracy of DTI experiments with the simplified BSD calibration – computer simulations. Annals of Computer Science and Information Systems 2016; 8:935-938. DOI: 10.15439/2016F403.

[B29] A. Krzyżak, P. Łukasik, K. Janc. Determination of the quality of results obtained by various numerical methods for BSD. Annals of Computer Science and Information Systems 2016; 8:955-958. DOI: 10.15439/2016F458.

[B30] J. Górka, A. Świerczewska, A. Krzyżak. Significance of pressure solution structures analysis for fluid flow studies – examples from Struga-1 well (Zechstein Main Dolomite; W Poland): first results. Geology, Geophysics & Environment 01/2015; 41(1):82-83. DOI:10.7494/geol.2015.41.1.82.

[B31] N. Radzik, A. Świerczewska, A. Krzyżak. Identification of tectonic microstructures in flysch sandstones of the Outer Carpathians using X-ray nanotomography and nuclear magnetic resonance – first results. Geology, Geophysics & Environment 01/2015; 41(1):127-128. DOI:10.7494/geol.2015.41.1.127.

[B32] A. Krzyżak, K. Kłodowski, Z. Raszewski. Anisotropic phantoms in Magnetic Resonance Imaging. IEEE Engineering in Medicine and Biology Society Conference Proceedings 2015; 414-417. DOI: 10.1109/EMBC.2015.7318387.

[B33] A. Krzyżak, K. Borkowski. Theoretical analysis of phantom rotations in BSD-DTI. IEEE Engineering in Medicine and Biology Society Conference Proceedings 2015; 410-413. DOI:10.1109/EMBC.2015.7318386.

[B34] A. Krzyżak, K. Kłodowski. The B Matrix Calculation Using the Anisotropic Phantoms for DWI and DTI Experiments IEEE Engineering in Medicine and Biology Society Conference Proceedings 2015; 418-421. DOI:10.1109/EMBC.2015.7318388.

[B35] Ł. Kaczmarek, M. Maksimczuk, T. Wejrzanowski, A. Krzyżak. Use of X-ray computed microtomography in the heterogeneity analysis of Polish Zechstein carbonate rocks. SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2016; 3:1027-1034. DOI 10.5593/SGEM2016/B13/S06.130.

[B36] Ł. Kaczmarek, M. Maksimczuk, T. Wejrzanowski, A. Krzyżak. High-resolution x-ray microtomography and Nuclear Magnetic Resonance study of a carbonate reservoir rock. SCIENCE AND TECHNOLOGIES IN GEOLOGY, EXPLORATION AND MINING, SGEM 2015; 1:779-786. DOI 10.5593/SGEM2015/B11/S6.099.

[B37] A. Krzyżak, A. Jasiński, W. Węglarz, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski. Quantitative assessment of injury in the spinal cord of a rat using MR Microscopy of water diffusion tensor, Proceedings of ISMRM, 6th Scientific Meeting in Sydney 1998, vol 3, p. 1931.

[B38] A. Jasiński, P. Kozłowsk, A. Krzyżak, D. Adamek, P. Sagnowski, and J. Pindel. Investigation of spinal cord injury on a rat model using water diffusion tensor imaging. Proceedings of the IV Annual Meeting of the British Chapter of the ISMRM, p. B8, Nottingham, December 1998.

[B39] A. Krzyżak, A. Jasiński, P. Kozłowski, D. Adamek, P. Sagnowski, and J. Pindel, "Diffusion tensor imaging of the injured spinal cord of a rat *in vivo*. A comparison with *in vitro* experiments", Proceedings of VII Meeting of ISMRM, p. 327, Philadelphia, May 1999.

[B40] A. Krzyżak, A. Jasiński, P. Kozłowsk, D. Adamek, P. Sagnowski, and J. Pindel, "Quantitative assessment of injury in the spinal cord of a rat *in vivo* using MRI of water diffusion tensor", Proceedings of VII Meeting of ISMRM, p. 1810, Philadelphia, May 1999.

C Conference presentations

[C1]. N. Radzik, A. Świerczewska, A. KRZYŻAK. 2D and 3D Magnetic Resonance Imaging of cataclastic deformation bands. CETEG 2016 : 14th meeting of the Central European Tectonic Groups, 21th meeting of the Czech Tectonic Studies Group (ČTS) : Predná Hora, Slovakia, April 28–May 1, 2016.

[C2]. K. KŁODOWSKI, A. T. KRZYŻAK. Analytical description of the B-matrix spatial distribution in Diffusion Tensor Imaging. AMPERE NMR School: 12th–18th June 2016, Zakopane.

[C3]. K. BORKOWSKI, A. KRZYŻAK. Improving precision and accuracy of DTI experiments with the simplified BSD calibration – computer simulations. FedCSIS: the Federated Conference on Computer Science and Information Systems : 11–14 September, 2016, Gdansk, Poland.

[C4]. E. PSTRUCHA, G. MACHOWSKI, A. KRZYŻAK. Porosity and permeability of the Main Dolomite oil-bearing rocks in the S-1 well (Western Poland). 16th International multidisciplinary scientific geoconference: 28 June – 6 July, 2016. Albena, Bulgaria.

[C5]. S. Bednarczyk, A. KRZYŻAK, G. MACHOWSKI. Comparative analysis of measurements and estimation of permeability of shales in selected well sections from Baltic Basin (Northern Poland). 16th International multidisciplinary scientific geoconference: 28 June – 6 July, 2016. Albena, Bulgaria.

[C6]. J. Górka, A. Świerczewska, A. KRZYŻAK. Controls of pressure solution structures on fluid migration – nuclear magnetic resonance studies from Struga-1 well (Zechstein Main Dolomite; W Poland). 16th International multidisciplinary scientific geoconference: 28 June – 6 July, 2016. Albena, Bulgaria.

[C7]. E. PUSKARCZYK, P. KRAKOWSKA, A. KRZYŻAK, G. MACHOWSKI. Correlation of nuclear magnetic resonance and mercury intrusion porosimetry data for the best petrophysical parameters estimation in shales and. 16th International multidisciplinary scientific geoconference: 28 June – 6 July, 2016. Albena, Bulgaria.

[C8]. A. PSTRUCHA, G. MACHOWSKI, A. KRZYŻAK. Petrophysical characterization of the Miocene sandstones of the Carpathian Foredeep (South-East Poland). 16th International multidisciplinary scientific geoconference: 28 June – 6 July, 2016. Albena, Bulgaria.

[C9]. N. Radzik, A. KRZYŻAK, A. Świerczewska, G. MACHOWSKI. The complex characterization of sandstone cores using low-field. 16th International multidisciplinary scientific geoconference: 28 June – 6 July, 2016. Albena, Bulgaria.

[C10]. Ł. Kaczmarek, M. Maksimczuk, T. Wejrzanowski, A. Krzyżak. Use of X-ray computed microtomography in the heterogeneity analysis of Polish Zechstein carbonate rocks. 16th International multidisciplinary scientific geoconference: 28 June – 6 July, 2016. Albena, Bulgaria.

[C11]. E. PSTRUCHA, G. MACHOWSKI, A. T. KRZYŻAK. The porous-fractured space of the oil- and gas-bearing carbonates in the S-1 well (western Poland). IGSC Katowice: 7th International Geosciences Student Conference : Katowice, 11–14 July 2016

[C12]. A. FHEED, A. ŚWIERCZEWSKA, A. KRZYŻAK. Sulphate-induced porosity reduction in Permian Reef, SW Poland in the scope of nuclear magnetic resonance studies. Vienna 2016 - efficient use of technology – unlocking potential : 78th EAGE conference & exhibition : 30 May – 2 June 2016, Vienna, Austria.

[C13]. K. KŁODOWSKI, P. Łukasik, A. KRZYŻAK. Approximation of the actual spatial distribution of the b-matrix in diffusion tensor imaging with bivariate polynomials. FedCSIS: the Federated Conference on Computer Science and Information Systems : 11–14 September, 2016, Gdansk, Poland.

[C14]. P. Łukasik, A. KRZYŻAK, K. JANC. Determination of the quality of results obtained by various numerical methods for BSD. FedCSIS: the Federated Conference on Computer Science and Information Systems : 11–14 September, 2016, Gdansk, Poland.

[C15]. A. PSTRUCHA, G. MACHOWSKI, A. KRZYŻAK. Characterization of the pore space of the Carboniferous gas-bearing deposits in the P-29. Vienna 2016 - efficient use of technology – unlocking potential : 78th EAGE conference & exhibition: 30 May – 2 June 2016, Vienna, Austria.

[C16]. A. Szymocha, Z. Olejniczak, G. Stoch, A. KRZYŻAK, K. Góra-Marek. Analysis of pore size distribution by NMR techniques. XLVII Ogólnopolskie Kolokwium Katalityczne. Kraków 16–18.03.2015.

[C17]. A. KRZYŻAK , K. KŁODOWSKI. The B matrix calculation using the anisotropic phantoms for DWI and DTI experiments. 37th annual international conference of the IEEE Engineering in Medicine and Biology Society : August 25–29 2015, Milano, Italy.

[C18]. A. KRZYŻAK, K. KŁODOWSKI, Z. RASZEWSKI. Anisotropic phantoms in magnetic resonance imaging. EMBC 2015: 37th annual international conference of the IEEE Engineering in Medicine and Biology Society: Milano, Italy, August 25–29 2015.

[C19]. A. KRZYŻAK. Application of diffusion techniques in fMRI . Innovative technologies in biomedicine : 2nd international conference. Krakow, Poland, October 12–14, 2015.

[C20]. A. KRZYŻAK, K. KŁODOWSKI. B-matrix spatial distribution in diffusion tensor imaging. Innovative technologies in biomedicine : the 2nd International conference : October 12–14, 2015, Krakow, Poland.

[C21]. Ł. Kaczmarek, M. Maksimczuk, T. Wejrzanowski, A. KRZYŻAK. High-resolution X-ray microtomography and nuclear magnetic resonance study of a carbonate reservoir rock. SGEM 2015 : Science and technologies in geology, exploration and mining : 15th International multidisciplinary scientific geoconference: 18–24, June, 2015. Albena, Bulgaria.

[C22]. N. Radzik, A. Świerczewska, A. KRZYŻAK. Identification of tectonic microstructures in flysch sandstones of the Outer Carpathians using X-ray nanotomography and nuclear magnetic resonance – first results. XVIth International conference of young geologists: Herl'any 2015.

[C23]. J. Górka, A. Świerczewska, A. KRZYŻAK. Significance of pressure solution structures analysis for fluid flow studies – examples from Struga-1 well (Zechstein Main Dolomite; W

Poland): first results . Geology, Geophysics & Environment. XVIth International conference of young geologists: Herl'any 2015.

[C24]. K. KŁODOWSKI, A. KRZYŻAK. Pattern recognition and filtering of the b-matrix spatial distribution in the BSD-DTI technique. ESMRMB 2015 : 32nd annual scientific meeting : Edinburgh, UK, 1–3 October.

[C25]. K. BORKOWSKI, A. KRZYŻAK. Simulations of rotation of the anisotropic phantom in BSD-DTI. ESMRMB 2015 : 32nd annual scientific meeting : Edinburgh, UK, 1–3 October.

[C26]. A. KRZYŻAK, BORKOWSKI K.. Theoretical analysis of phantom rotations in BSD-DTI. 37th annual international conference of the IEEE Engineering in Medicine and Biology Society : August 25–29 2015, Milano, Italy.

[C27]. A. Krzyżak. Application of anisotropic diffusion phantom for DTI experiments. 29th Annual Meeting of ESMRMB, Lizbona, Portugalia, October 2012.

[C28]. A. Krzyżak. The application of the spatial distribution of the B matrix - a new approach to determine the diffusion tensor in DTI. the XLIV Polish Seminar on Nuclear Magnetic Resonance and Its Applications, Kraków, 3-4 December 2012, in IFJ Report, 2056/AP 2012.

[C29]. A. Krzyżak, Z. Raszewski, I. Habina, W. Węglarz, L. Jaroszewicz. Usefulness of anisotropic diffusion phantom for DTI, Abstr. of Advanced Bioimaging Technologies, Krakow, Poland, 7-9 September 2011.

[C30]. A. Krzyżak. The comparison of statistically significant alterations of the water diffusion tensor parameters for injured rats' spinal cords in vivo and in vitro. 14th Congress of European-Federation-of-Neurological-Societies. Geneva, SWITZERLAND, September 2010.

[C31]. A. Krzyżak, Z. Raszewski. Anisotropic diffusion phantom – application for DTI. World Molecular Imaging Annual Congress, Kyoto, Japan, September 8-11, 2010.

[C32]. A. Krzyżak. ANISOTROPIC DIFFUSION PHANTOM FOR B-MATRIX CALCULATION. XLI Polish Seminar on Nuclear Magnetic Resonance and Its Applications, Kraków, 1-2 December 2009.

[C33]. A. Krzyżak. The space b-matrix calculation using model phantoms of anisotropic diffusion, Proceedings of Bat Sheva Seminar on „Frontiers of Biomedical Magnetic Resonance“, Safed, Israel, September 2008.

[C34]. A. Krzyżak, A. Jasiński, S. Kwieciński, P. Kozłowski, D. Adamek. Quantitative assesment of injury in the spinal cord of rat in vivo using MRI of water diffusion tensor, XXII Int. Conf. on Radio and Microwave Spectroscopy, Poznań-Będlewo, Poland, 22-25 April 2007.

[C35]. A. Krzyżak. Assessment of white and grey matter injury in rats spinal cord using alterations of the water diffusion tensor parameters. 5th International Congress on Vascular Dementia Location: Budapest, HUNGARY, November 08-11, 2007.

[C36]. K. Banaś, A. Jasiński, A. Banaś, T. Banasik, T. Skórka, A. Krzyżak, P. Brzegowy, K. Majcher, D. Adamek, Application of linear discriminant analysis in evaluation of diffusion-weighted MRI results of spinal cord, Abstr. of the XXXIX Polish Sem. on Nuclear Magnetic Resonance and Its Applications, Kraków, Poland, 30 November - 1 December 2006.

[C37]. A. Krzyżak, A. Jasiński. The b-matrix calculation using liquid crystal model. Abstr. of the XXXIX Polish Sem. on Nuclear Magnetic Resonance and Its Applications, Kraków, Poland, 30 November - 1 December 2006.

[C38]. A. Krzyżak, A. Jasiński. Assessment of spinal cord injury using statistically significant changes in diffusion tensor parameters, 22nd Annual Scientific Meeting of ESMRMB, Basel, Switzerland, 15-18 September 2005.

[C39]. A. Krzyżak, A. Jasiński. Assessment of Spinal Cord Injury Using Diffusion Tensor Parameters, 3rd Kraków-Winnipeg Workshop on Magnetic Resonance and molecular Imaging, Kraków, September 20-23, 2005.

[C40]. A. Krzyżak, A. Jasiński, D. Adamek. Qualification of the Most Statistically „Sensitive" Diffusion Tensor Imaging Parameters for Detection of Spinal Cord Injury Ramis 2005, Poznań-Będlewo, April 24-28, 2005.

[C41]. A. Krzyżak, A. Jasiński. Oszacowanie wielkości uszkodzenia rdzenia kręgowego przy użyciu parametrów tensora dyfuzji V Zjazd Polskiego Medycznego Towarzystwa Rezonansu Magnetycznego, Szczyrk, 17-19 czerwiec 2005.

[C42]. A. Krzyżak, A. Jasiński. Parametrization of the Extent of Spinal Cord Injury using Water Diffiusion Tensor Ogólnopolskie Sympozjum Magnetyczny Rezonans Jądrowy w Chemii, Biologii i Medycynie, Warszawa 2005.

[C43]. A. Krzyżak, A. Jasiński. Oszacowanie wielkości uszkodzenia tkanki nerwowej rdzenia kręgowego szczura in vivo poprzez analizę zmian parametrów tensora dyfuzji wody XXXVIII Ogólnopolskie Seminarium na Temat Magnetycznego Rezonansu i Jego Zastosowań, Kraków, 1-2 grudzień 2005

[C44]. A. Jasiński, A. Krzyżak, A. Urbanik, D. Adamek, W. Węglarz, J. Pindel. Obrazowanie MR tensora dyfuzji w badaniach i diagnostyce urazów rdzenia kręgowego. XXXVI Zjazd Radiologów Polskich, Lublin, 2001.

[C45]. J. Pindel, A. Jasiński, A. Krzyżak, W. Węglarz, D. Adamek, P. Sagnowski, P. Kozłowski, A. Urbanik. Temporal studies of water diffusion tensor in an injured spinal cord of the rat. 17th Annual Scientific Meeting of ESMRMB, Paryż, Francja, September 2000.

[C46]. A. Jasiński., A. Krzyżak., Urbanik A., D. Adamek., P. Kozłowski, Węglarz W., Pindel J.:MRI tensora dyfuzji w badaniach i wczesnej diagnostyce urazów rdzenia kręgowego. Sympozjum - Diagnostyka Obrazowa w Chorobach Kręgosłupa i Kanału Kręgowego, Wrocław, 2000.

[C47]. D. Adamek, A. Jasiński, A. Krzyżak, J. Pindel, P. Kozłowski, P. Sagnowski, W. Węglarz. The distribution and spatial relations of damage to the spinal cord after mechanical injury may suggest a narrow potential therapeutical "window". 17th Annual Scientific Meeting of ESMRMB, Paryż, Francja, September 2000.

[C48]. A. Jasiński., A. Krzyżak, A. Urbanik, D. Adamek., P. Kozłowski, P. Sagnowski, W. Węglarz, J. Pindel. Badanie urazów rdzenia kręgowego na modelu szczura metodą obrazowania tensora dyfuzji. III Kongres Polskiego Medycznego Rezonansu Magnetycznego, Lądek Zdrój, 1999.

[C49]. A. Jasiński, P. Kozłowski, A. Krzyżak, D. Adamek, P. Sagnowski, J. Pindel and W. Węglarz. *Effects of Formaline Fixation on Water Diffusion in Tissues of Normal and Injured Spinal Cord of the Rat.* Symposium on „Applications of Magnetic Resonance to Chemistry and Related Areas", 09.06 - 11.06.1999, Warszawa.

[C50]. W. Węglarz, A. Krzyżak, A. Jasiński, P. Kozłowski, D. Adamek, P. Sagnowski, J. Pindel. *Is Diffusion Tensor Imaging useful in characterization of the Spinal Cord Injury?* AMPERE VII NMR School, Zakopane 30.05 - 4.06. 1999.

[C51]. A. Jasiński, A. Krzyżak, A. Urbanik, D. Adamek, P. Kozłowski, P. Sagnowski, W. Węglarz, J. Pindel. Investigation of the spinal cord injury on a rat model using diffusion tensor imaging. III Zjazd Polskiego Medycznego Towarzystwa Rezonansu Magnetycznego, Lądek Zdrój 7.10 - 9.10. 1999.

[C52]. A. Jasiński, A. Krzyżak, P. Kozłowski, A. Urbanik. Investigation of spinal cord injury on a rat model - effects of formaline fixation on water diffusion tensor. 16th Annual Scientific Meeting of ESMRMB, Sewilla, Hiszpania, September 1999.

[C53]. A. Krzyżak, A. Jasiński, P. Kozłowski, D. Adamek, P. Sagnowski and J. Pindel. "Diffusion tensor imaging of the injured spinal cord of a rat *in vivo*. A comparison with *in vitro* experiments", VII Meeting of ISMRM, Philadelphia, May 1999.

[C54]. A. Krzyżak, A. Jasiński, P. Kozłowski, D. Adamek, P. Sagnowski and J. Pindel. "Quantitative assessment of injury in the spinal cord of a rat *in vivo* using MRI of water diffusion tensor", VII Meeting of ISMRM, Philadelphia, May 1999.

[C55]. J. Pindel, A.T. Krzyżak, W.P. Węglarz, D. Adamek, P. Sagnowski, P. Kozłowski, A. Urbanik *Zależność tensora dyfuzji od czasu po urazie rdzenia kręgowego szczura.* XXII Ogólnopolskie Seminarium na temat Magnetycznego Rezonansu Jądrowego i jego Zastosowań, Kraków 1 - 2. 12.1999, IFJ Raport Nr 1834/PS p. 25.

[C56]. D. Adamek, A. Jasiński, A. Krzyżak, J. Pindel, P. Sagnowski, A. Urbanik, W. Węglarz *Patomorfologia zmian pourazowych w rdzeniu kręgowym szczura w relacji do obrazowania dyfuzji MR.* XXII Ogólnopolskie Seminarium na temat Magnetycznego Rezonansu Jądrowego i jego Zastosowań, Kraków 1 - 2. 12.1999. IFJ Raport Nr 1834/PS p. 40.

[C57]. A. Jasiński, F. Hennel, A. Krzyżak, J. Nedelec, A. Urbanik. Dyfuzyjno-zależne obrazowanie MR rdzenia kręgowego człowieka III Kongres Polskiego Medycznego Rezonansu Magnetycznego, Lądek Zdrój, 1999.

[C58]. A. Krzyżak, A. Jasiński, W. Węglarz, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski Quantitative assessment of injury in the spinal cord of a rat using MR Microscopy of water diffusion tensor. ISMRM Sixth Scientific Meeting, April 18-24, 1998 Sydney, Australia.

[C59]. A.Jasiński, W. Węglarz. „Diffusion Tensor Imaging in an Injured Spinal Cord of the Rat *in vivo*." 29th AMPERE - 13th ISMAR Satellite Symposium on Spatially Resolved Magnetic Resonance; July 30 - August 1 1998, Leipzig.

[C60]. A. Jasiński, P. Kozłowski, A. Krzyżak, D. Adamek and P. Sagnowski. „Water diffusion tensor imaging in an injured spinal cord of the rat *in vivo* at 9.4T. 15th Annual Scientific Meeting of ESMRMB, Genewa, Szwajcaria, September 1998.

[C61]. D. Adamek, P. Sagnowski, A. Krzyżak, A. Jasiński, P. Kozłowski, J. Kałuża „In the search of better insight into pathology of spinal cord injury. Investigations on nuclear magnetic resonance (NMR) water diffusion imaging in relation to patomorphological changes in spinal cord of rat after experimental weight drop injury", European Meeting 1998 Neurutrauma, Magdeburg, 30.09 - 3.10. 1998.

[C62]. A. Jasiński, P. Kozłowski, A. Krzyżak, D. Adamek, P. Sagnowski, J. Pindel „Obrazowanie MR zmian tensora dyfuzji wody zachodzących pod wpływem urazu mechanicznego w rdzeniu kręgowym szczura *in vivo*." Materiały XXXI Ogólnopolskiego Seminarium Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków 1-2 grudnia 1998.

[C63]. A. Jasiński, F. Hennel, A. Krzyżak, K. Szybiński, A. Urbanik „Obrazowanie MR dyfuzji wody w rdzeniu kręgowym człowieka." Materiały XXXI Ogólnopolskiego Seminarium Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków 1-2 grudnia 1998 .

[C64]. K. Szybiński, A. Jasiński, J. Kozub, B. Sobiecka, A. Urbanik „Obrazowanie MR wysokiej rozdzielczości rdzenia kręgowego człowieka na systemie SIGNA 1.5 T." Materiały XXXI Ogólnopolskiego Seminarium Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków 1-2 grudnia 1998.

[C65]. A. Jasiński, P. Kozłowski, A. Krzyżak, D. Adamek, P. Sagnowski and J. Pindel. „Investigation of Spinal Cord Injury on a Rat Model Using Water Diffusion Tensor Imaging." IVth Annual Meeting of the British Chapter of the ISMRM Nottingham, 18^{th}-19^{th} December 1998.

[C66]. A. Jasiński, P. Kozłowski, A. Krzyżak, D. Adamek and P. Sagnowski „Water diffusion tensor imaging in an injured spinal cord of the rat *in vivo* at 9.4 T." Ogólnopolskie Sympozjum"Application of Magnetic Resonance in Chemistry and Related Areas", 24-26 June 1998, Warszawa.

[C67]. W. Węglarz, A. Jasiński and A. Krzyżak. „MR Microscopy of Water Diffusion Tensor in Biological Systems." Proc. of the Joint 29^{th} AMPERE – 13^{th} ISMAR International Conference on Magnetic Resonance and Related Phenomena, Berlin, Germany, August 2-5 1998.

[C68]. P. Sagnowski, D. Adamek, A. Krzyżak., A. Jasiński, A. Urbanik. Zmiany rozkładu przestrzennego dyfuzji wody na skutek urazu rdzenia kręgowego w obrazowaniu MR dyfuzji wody (D-MRI). 2 XXXV Zj. Rad. Pol., Katowice, 1998.

[C69]. P. Sagnowski, A. Krzyżak, D. Adamek, M. Baj, A. Jasiński, A. Urbanik. Różnice anizotropii dyfuzji wody w istocie białej i szarej rdzenia kręgowego w obrazowaniu MR tensora dyfuzji wody (DT-MRI). XXXV Zj. Rad. Pol., Katowice, 1998.

[C70]. A. Krzyżak, et al., Quantitative assessment of injury in the spinal cord of a rat using MR Microscopy of water diffusion tensor. ISMRM, 6th Scientific Meeting in Sydney 1998.

[C71]. A. Krzyżak, A. Jasiński, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski and W. Węglarz. „Monitoring injury in a rat spinal cord using MR Microscopy of a water diffusion tensor", 14th Annual Scientific Meeting of ESMRMB, Brussels, 18-21.09.1997.

[C72]. A. Krzyżak, W. Węglarz, A. Jasiński. „MRI visualisation of a water diffusion tensor in a rat spinal cord" V NMR School, Zakopane, Poland, June 1-5, 1997.

[C73]. A. Jasiński, A. Krzyżak, D. Adamek, M. Baj, J. Kuśmiderski, P. Sagnowski, W. Węglarz. Diffusion tensor imaging in an excised spinal cord of the rat Kraków-Winnipeg Workshop on Biomedical Applications of MRI and MRS, Kraków 1997.

[C74]. A. Jasiński, A. Krzyżak, D. Adamek, M. Baj, P. Sagnowski, W. Węglarz. „Diffusion Tensor Imaging in an Excised Spinal Cord of the Rat”, 1st Kraków - Winnipeg Workshop on Biomedical Applications of MRI and MRS, 6-8 November 1997, Kraków, Poland.

[C75]. D. Adamek, P. Sagnowski, A. Krzyżak, M. Baj, W. Węglarz, J. Kałuża, A. Jasiński, J.Kuśmiderski. „Assessment of Post-Traumatic Morphological Changes in Spinal Cord of a Rat After Experimental Dynamic Injury in Correlation with MR Water Diffusion Tensor Imaging”, 1st Kraków - Winnipeg Workshop on Biomedical Applications of MRI and MRS, 6-8 November 1997, Poland.

[C76]. A. Krzyżak, A. Jasiński, W. Węglarz. „Data Processing for Diffusion Tensor Imaging”, 1st Kraków - Winnipeg Workshop on Biomedical Applications of MRI and MRS, 6-8 November 1997, Kraków, Poland

[C77]. W. Węglarz, A. Jasiński, A. Krzyżak, Z. Sułek. ”Metoda obrazowania MR tensora dyfuzji wody w układach biologicznych”, Materiały XXX Ogólnopolskiego Seminarium MRJ i Jego Zastosowań, Kraków 1-3 grudnia 1997.

[C78]. A. Krzyżak, A. Jasiński, W. Węglarz, M. Baj, D. Adamek, P. Sagnowski, J. Kuśmiderski. „Badanie uszkodzeń rdzenia kręgowego szczura metodą obrazowania MR tensora dyfuzji wody in vitro” Materiały XXX Ogólnopolskiego Seminarium MRJ i Jego Zastosowań, Kraków 1-3 grudnia 1997.

[C79]. P. Sagnowski, A. Krzyżak, D. Adamek, M. Baj, A. Jasiński, J. Kuśmiderski „MR microscopy of water diffusion tensor in rat spinal cord injury model.” 10th European Congress of Radiology, Vienna, March 2-7, 1997.

[C80]. A. Krzyżak. MR Microscopy of Water Diffusion Tensor in Injured Spinal Cord. XXXIX Polish Seminar on Magnetic Resonance and its Application, Kraków 1996.

[C81]. P. Sagnowski, A. Jasiński, A. Krzyżak, M. Baj. MR Microscopy of Water Diffusion Tensor in Rat Spinal Cord Model Injury, Second Meeting of the Polish Medical Magnetic Resonance Society, Kraków 1996.

[C82]. P. Sagnowski, A. Jasiński, A. Krzyżak, M.Baj. Water Diffusion Tensor in MRI, Mathematics and Diagnostics, Second Meeting of the Polish Medical Magnetic Resonance Society, Kraków 1996.

[C83]. A. Jasiński,A. Krzyżak. MR Microscopy of Water Diffusion Anisotropy in a Rat Spinal Cord, The Second Annual Meeting of the British Chapter of the International Society of Magnetic Resonance in Medicine, Londyn 1996, p.64.

[C84]. P. Kulinowski, K. Szybiński, Z. Sułek, A. Jasiński. „Oprogramowanie kontrolera gradientów do eksperymentu MRI” Materiały XXVIII Ogólnopolskiego Seminarium Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków 4-5 grudnia 1995, Raport IFJ 1717/PL, 347(1996).

[C85]. A. Jasiński, A. Krzyżak, J. Kuśmiderski, D. Adamek, M. Baj, S. Kwieciński, J. Kozub, T. Skórka, P. Sagnowski. "MR Imaging of Water Diffusion Tensor in Rat Spinal Cord" IV NMR School, Zakopane 1996.

[C86]. A. Jasiński, J. Kuśmiderski. "Tensor dyfuzji - nowy mechanizm kontrastu w obrazowaniu MR" II Zjazd Polskiego Medycznego Towarzystwa Magnetycznego Rezonansu, Kraków 1996.

[C87]. P. Sagnowski, A. Jasiński, A. Krzyżak, D. Adamek, M. Baj, J. Kuśmiderski "Mikroskopia MR tensora dyfuzji wody na modelu zwierzęcym urazu rdzenia kręgowego" II Zjazd Polskiego Medycznego Towarzystwa Magnetycznego Rezonansu, Kraków 1996.

[C88]. P. Sagnowski, A. Krzyżak, A. Jasiński, J. Kuśmiderski "Tensor dyfuzji wody w MR: matematyka a diagnostyka” II Zjazd Polskiego Medycznego Towarzystwa Magnetycznego Rezonansu, Kraków 1996.

[C89]. A. Jasiński, A. Krzyżak, J. Kuśmiderski „Mikroskopia MR tensora dyfuzji wody w uszkodzonym rdzeniu kręgowym” Materiały XXIX Ogólnopolskiego Seminarium Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków 2-3 grudnia 1996.

[C90]. D. Adamek, P. Sagnowski, M. Baj, A. Krzyżak, A. Jasiński, J. Kuśmiderski „Interpretacja zmian w obrazach MR dyfuzji wody w rdzeniu kręgowym szczura po urazie mechanicznym” Materiały XXIX Ogólnopolskiego Seminarium Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków 2-3 grudnia 1996.

[C91]. S. Kwieciński, A. Jasiński, L. Przywara, B. Tomanek, A. Krzyżak, P. Kulinowski and K. Szybiński. MR Microscopy of the Plant Dactylis glomerata, Annual Report IFJ 1995 VIII-4.

[C92]. A. Krzyżak, A.Jasiński, J.Kuśmiderski, D. Adamek, M. Baj and P. Sagnowski, MR Microscopy of Water Diffusion Anisotropy in a Rat Injured Spinal Cord, Annual Report IFJ 1996.

[C93]. A. Jasiński, Z. Sułek, B. Tomanek, T. Skórka, A. Krzyżak, P. Kulinowski and J. Muszyńska. MR Microscopy Study of Honey Bee Queen and Drone in vivo, 3 rd Interrnational Conference on Magnetic Resonance. Wurzburg 1995.

[C94]. A. Jasiński, A. Krzyżak, M. Baj, S. Kwieciński, J .Kozub, T. Skórka, P. Sagnowski. MR Imaging of Water Diffusion Tensor in Rat Spinal Cord, IV NMR School, Zakopane 1995.

[C95]. S. Kwieciński, B. Tomanek, A. Jasiński, A. Krzyżak, P. Kulinowski, T. Skórka, Z. Sułek, K. Szybiński, MR Microscopy of the Plant Dactylis Glomerata, Interrnational Conference on Magnetic Resonance. Wurzburg 1995.

[C96]. A. Krzyżak, A. Jasiński, Z. Sułek, F. Hennel, B. Tomanek, P. Kulinowski, T. Skórka, S.Kwieciński, PC-based MRS and MRI Software, Proc. 10th Congress of the Polish Society of Medical Physics, Kraków, Poland,1995.

[C97]. A. Jasiński, Z. Sułek, B. Tomanek, T. Skórka, A. Krzyżak, P. Kulinowski and J. Muszyńska. MR Microscopy of Honey Bee of all Casts, Proc. 12th Conference of the International Society of Magnetic Resonance, ISMAR 95, Sydney, July 1995.

[C98]. A. Krzyżak, A. Jasiński, S. Kwieciński, T. Skórka, J. Kozub, M. Baj. MR Imaging of Water Diffusion Anisotropy in the Patiole of Saintpaulia Ionantha, XXVIII Polish Seminar on Nuclear Magnetic Resonance and its Applications, Kraków 1995;IFJ Report 1717/PL (1996) 339.

[C99]. P. Kulinowski, A. Krzyżak, K. Szybiński, Z. Sułek, A. Jasiński. Gradient Controller Software for MRI Experiment. XXVIII Polish Seminar on Nuclear Magnetic Resonance and its Applications, Kraków 1995;IFJ Report 1717/PL (1996) 347.

[C100]. A. Jasiński, A. Krzyżak, J. Kuśmiderski, T. Skórka, S. Kwieciński, D. Adamek, M. Baj, J. Kozub. "MR Imaging of Diffusion Anisotropy in Biological Systems" Materiały XXVIII Ogólnopolskiego Seminarium Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków 4-5 grudnia 1995, Raport IFJ 1717/PL, 333(1996).

[C101]. B.Tomanek, A.Jasiński, Z.Sułek, T.Skórka, A.Krzyżak, J.Kibiński, J.Muszyńska, Nieinwazyjne badania pszczoły miodnej metodą mikrotomografii MR, XXXI Naukowa Konferencja Pszczelarska, Puławy 1994.

[C102]. B. Tomanek, A. Jasiński, Z. Sułek, J. Muszyńska, S. Kwieciński, T. Skórka, A. Krzyżak, J. Kibiński. Application of MR Microtomography to Investigation of Honey Bee and Honey Bee Queen in Vivo, 2nd NMR School, Zakopane, 30 May-4 June,1994.

[C103]. B. Tomanek, A.Jasiński, Z. Sułek, J. Muszyńska, S. Kwieciński, T. Skórka, A. Krzyżak, J. Kibiński. Magnetic Resonance Microscopy Stydy of Honey Internal Structure, Polish-German Symp., Oberusel, 19-23 September 1994, Germany.

[C104]. B. Tomanek, A. Jasiński, Z. Sułek, J. Muszyńska, S. Kwieciński, T. Skórka, A. Krzyżak, J. Kibiński. MR Microscopy of Honey Bee Morphology in Vivo. XXVII Ogólnopolski Sem. nt. MRJ i Jego Zastosowań, Kraków, 1994.

[C105]. B. Tomanek, A. Jasiński, Z. Sułek, J. Muszyńska, S. Kwieciński, T. Skórka, A. Krzyżak, J. Kibiński. MR Microscopy of Plants. XXVII Ogólnopolski Sem. nt. MRJ i Jego Zastosowań, Kraków, 1994.

[C106]. Z. Sułek, B. Tomanek, A. Jasiński, J. Muszyńska, S. Kwieciński, T. Skórka, A. Krzyżak, J. Kibiński. Modular MR Microscope. XXVII Ogólnopolski Sem. nt. MRJ i Jego Zastosowań, Kraków, 1994.

[C107]. B. Tomanek, A. Jasiński, Z. Sułek, S. Kwieciński, T. Skórka, A. Krzyżak, J. Kibiński and J. Muszyńska. Magnetic Resonance Microscopy Study of Honeybee Internal Structure XXVII Ogólnopolski Sem. nt. MRJ i Jego Zastosowań, Kraków, 1994. Annual Report IFJ 1994 VIII-5.

[C108]. A. Jasiński, Z. Sułek, B. Tomanek, F. Hennel, J. Kibiński, T. Skórka, A. Krzyżak, P. Kulinowski and J. Muszyńska. MR Microscopy Study of Honey Bee in vivo, 2nd International Conference on Magnetic Resonance Microscopy, Heidelberg 1993.

D Manuscripts of scientific publications in reviews in journals from the JCR database

[D1] K. Borkowski, A. Krzyżak, K. Kłodowski. The influence of diffusion gradient inhomogeneity on the DTI based tractography. Magnetic Resonance Imaging 2016, (IF-1.98).

[D2] A. Krzyżak, K. Kłodowski, K. Borkowski. Application of a Simplified B-Matrix Spatial Distribution method to a clinical 3.0 T MRI Scanner. Magnetic Resonance Imaging 2016, (IF-1.98).

[D3] Ł. Kaczmarek, T. Wejrzanowski, J. Skibiński, M. Maksimczuk, A. Krzyżak. High-resolution computed microtomography for characterization of diffusion tensor imaging phantom. Acta Geophysica 2015, (IF-1.068).

[D4] A. Krzyżak, I. Habina, G. Machowski. Novel approach to determination of the porosity coefficients by low field NMR. Fuel 2016, (IF-1.98).

[D5] I. Habina, N. Radzik, T. Topor, A. Krzyżak. Insight into oil and gas-shales compounds signatures in low field 1H NMR and its application in porosity evaluation. Microporous and Mesoporous Materials 2016, (IF-3.45).

[D6] A. Fheed, A. Krzyżak. Textural and diagenetic assessment of the Zechstein carbonates in the scope of Nuclear Magnetic Resonance. Journal of Petroleum 2016, (IF-1.65).