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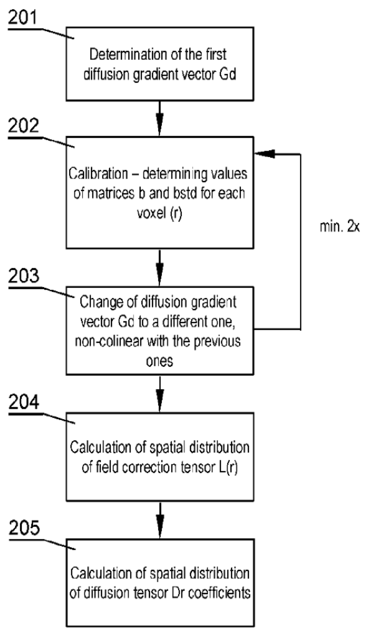

Fig. 2

(57) Abstract: A method for imaging in nuclear magnetic resonance (NMR) experiment that uses magnetic field gradients greater than the gradients used for imaging, including calculating the diffusion tensor coefficients based on a spatial distribution of the matrix b(r) obtained by calibration. Further, the method includes performing a calibration for at least three different non-collinear diffusion gradient vectors G_d, by establishing for each of the vectors G_d a value of the spatial matrix b and of the theoretical matrix b_{std} for each voxel having a spatial coordinate (r) within the imaging space; determining the spatial distribution of the components of the field correction tensor L(r) on the basis of at least three sets of specified equations, each set of said equations for each vector G; calculating a spatial distribution of the coefficients of the diffusion tensor (D_r) taking into account said spatial distribution of the components of the field correction tensor L(r).

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A CORRECTION METHOD FOR DIFFUSION TENSOR MAGNETIC RESONANCE IMAGING

TECHNICAL FIELD

The present invention relates to nuclear magnetic resonance (NMR) techniques, in particular to improve imaging in magnetic resonance imaging (MRI) experiments using diffusion as a natural contrast.

BACKGROUND

Magnetic Resonance Imaging (MRI) method, based on the phenomenon of Nuclear Magnetic Resonance (NMR) is a technique widely used and intensively developed in biomedical applications, materials engineering, petrophysics, etc.

One of essential problems limiting the progress of MRI techniques is the problem of non-uniformity of magnetic field gradients. They cause appearance of artifacts in the results of MRI experiments, i.e. visible deformations of images and/or inhomogeneous distributions of diffusion tensor coefficients which are invisible to the naked eye, but are a source of significant systematic errors.

In particular, this problem plays importance when relatively large magnetic field gradient pulses are used, such as for example in experiments involving so-called diffusion gradients, for example Diffusion-Weighted Imaging / Diffusion Tensor Imaging: DWI/DTI or similar.

Moreover, the MRI theory is based on the assumption that magnetic field gradients can change in time but must be constant in space. The following publications: Lauterbur, Paul C. "Image formation by induced local interactions: examples employing nuclear magnetic resonance." nature 242.5394 (1973): 190-191 and Mansfield, Peter, and Peter K. Grannell "NMR 'diffraction' in solids?" Journal of Physics C: solid state physics 6.22 (1973): L422 introduce a mathematical formalism describing the dependence of the NMR signal on the position of spins in space through the Fourier transform. This was an unquestionable milestone in the development of NMR tomography, however, it was also a limitation, because in reality the spatial distribution of magnetic field gradients can be observed. Said spatial distribution is caused by the MRI equipment, i.e. MRI sequences and gradient coils. The source of the inhomogeneity of the magnetic field gradients may also be the examined object, in particular an object containing elements of different magnetic susceptibility. These sources cause independent systematic errors in the spatial distribution of the gradient field and distort the real magnetic resonance image to a greater or lesser extent. Nonlinearities in magnetic field gradients cause two types of errors: spatial distortions of MR images and a reduction in accuracy in determining the diffusion coefficients or the diffusion tensor coefficients. Consequently, this leads to inaccurate determination of parameters (such as Fractional Anisotropy (FA)) or incorrect neural fiber tracking. Some solutions are available to correct the spatial distortion of MR images, but they are not widely used in practice. However, the problem of reduced accuracy in determining the diffusion coefficients or the diffusion tensor resulting from spatial inhomogeneities in the distribution of magnetic field gradients has not been successfully solved so far.

There are known some solutions for spatial correction of a gradient field.

The publication: Bammer, Roland, et al. "Analysis and generalized correction of the effect of spatial gradient field distortions in diffusion-weighted imaging." Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine 50.3 (2003): 560-569, suggests to correct the spatial gradient field distribution based on gradient coils inhomogeneity data provided by a device manufacturer.

There are known methods using anisotropic phantoms as sources of diffusion tensor norms, as described in the publications: Krzyżak, Artur Tadeusz, and Zbigniew Olejniczak. "Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix." Magnetic Resonance Imaging 33.3 (2015): 286-295; Kłodowski, Krzysztof, and Artur Tadeusz Krzyżak. "Innovative anisotropic phantoms for calibration of diffusion tensor imaging sequences." Magnetic resonance imaging 34.4 (2016): 404-409; Borkowski, Karol, and Artur Tadeusz Krzyżak. "Analysis and correction of errors in DTI-based tractography due to diffusion gradient inhomogeneity." Journal of Magnetic Resonance 296 (2018): 5-11.

The solutions mentioned above are based on a spatial distribution of magnetic field gradients, but at the same time they use a Stejskal-Tanner (S-T) equation, which assumes that gradients are constant in space, which in fact is a contradiction.

The aforementioned contradiction was theoretically proven by deriving a generalized S-T equation, which is valid for magnetic field gradients that are non-homogeneous in space, wherein the classical equation is a special solution - as discussed in the publication: Borkowski, Karol, and Artur Tadeusz Krzyżak. "The generalized Stejskal-Tanner equation for non-uniform magnetic field gradients." Journal of Magnetic Resonance 296 (2018): 23-28. This publication also explains and expands the meaning of a so-called coil tensor that has been intuitively introduced in the abovementioned publication of Bammer et al. In the most general sense, it is a Jacobian transition between a curvilinear system in which the real spatial distribution of the G gradient is constant, and a laboratory system in which it is non-uniform in space. Knowing the coil tensor allows i.a. to determine the real distribution of matrix b as well as the real distribution of the diffusion tensor.

Moreover, other solutions related to the correction of the spatial distribution of magnetic field gradients are described in the publications: Tan, Ek T., et al. "Improved correction for gradient nonlinearity effects in diffusion-weighted imaging." Journal of Magnetic Resonance Imaging 38.2 (2013): 448-453; Malyarenko, Dariya I., and Thomas L. Chenevert. "Practical estimate of gradient nonlinearity for implementation of apparent diffusion coefficient bias correction." Journal of Magnetic Resonance Imaging 40.6 (2014): 1487-1495; Malyarenko, Dariya I., Brian D. Ross, and Thomas L. Chenevert. "Analysis and correction of gradient nonlinearity bias in apparent diffusion coefficient measurements." Magnetic resonance in medicine 71.3 (2014): 1312-1323; Hansen, Colin B., et al. "Empirical field mapping for gradient nonlinearity correction of multi-site diffusion weighted MRI." Magnetic Resonance Imaging 76 (2021): 69-78. However, these solutions are imprecise and/or correct only some part of the distortions.

There are known methods of precisely determining the spatial distribution of magnetic field gradients. One of them is a method called BSD-DTI, described in the publication: Borkowski, Karol, and Artur Tadeusz Krzyżak. "The generalized Stejskal-Tanner equation for non-uniform magnetic field gradients." Journal of Magnetic Resonance 296 (2018): 23-28 and in the PCT application WO2009145648A1 and other publications of its family. Another method is called an sBSD-DTI method and is described in the PCT application WO2017017163A1. These methods are highly precise, but very time-consuming, as in practice there is a need to calibrate any parameters of the MRI sequence.

SUMMARY OF THE INVENTION

The present invention relates to MRI experiments that can be performed based on the NMR phenomenon of hydrogen nuclei 1H (protons), as well as other elements such as isotopes of carbon 13C, fluorine 19F, sodium 23Na or phosphorus 31P. Hydrogen 1H has a very high abundance and is ubiquitous, for example in biological organisms or as a component of hydrocarbons. Imaging of other elements provides complementary information with respect to imaging of 1H nuclei and is becoming more and more popular. They can additionally provide complementary diagnostic information. The present disclosure therefore addresses all elements with imaging potential through the use of the NMR phenomenon.

The present invention is applicable to imaging techniques such as Diffusion-Weighted Imaging / Diffusion Tensor Imaging (DWI/DTI), Diffusion Kurtosis Imaging, multi-tensor diffusion-MRI, and others that use relatively large magnetic field gradients pulses, i.e. greater than the gradients used for imaging. In particular, it is applicable to those techniques for which b matrices are used for calculating the diffusion tensor coefficients.

The present invention accelerates the precise determination of the spatial distribution of magnetic field gradients by using a so-called field correction tensor L(r) as introduced in the present invention. As compared to the coil tensor discussed in the publication: Bammer, Roland, et al. "Analysis and generalized correction of the effect of spatial gradient field distortions in diffusion-weighted imaging." Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine 50.3 (2003): 560-569, the field correction tensor takes into account the influence of all real sources of magnetic field gradients compared to the gradient coil gradient distribution provided by the tomograph manufacturer. The field correction tensor L(r) is determined using known spatial distributions of matrices b, which can be obtained e.g. by using anisotropic and isotropic phantoms according to the known methods such as BSD-DTI or sBSD-DTI.

The inventors of the present invention have found that known equations in the following form with diffusion tensors D_{std} (diffusion tensor coefficients calculated from the classical Stejskal-Tanner equation based on the formula 1d) and D_r (spatial distribution of diffusion tensor coefficients)

$$D_r = L^T(r)D_{std}L(r) \qquad (1a)$$

or also in the form with matrices b_{std} and b(r),

$$b(r) = L(r)b_{std}L^T(r) \qquad (1b)$$

in the general case, they do not have unequivocal solutions for L(r) variable.

The solution according to the present invention provides an experimental method which allows to unequivocally determine the components of the field correction tensor .

The field correction tensor is characteristic for the array of gradient coils in the tomograph and for a particular MRI sequence, in particular containing diffusion gradients. It should be noted that the real distribution of magnetic field diffusion gradients may depend on the MRI sequence and its parameters (such as a rising time and an amplitude of the diffusion gradient pulse, as well as a diffusion time, i.e. the time interval between the pulses of the diffusion gradient), and has a spatial and anisotropic relationship.

The inventors of the present invention have provided the possibility of unambiguously determining the value of the field correction tensor L for known dyadic matrices b(r) and b_{std} in the following manner.

The following considerations extend over the theoretical foundations described in the publication: Borkowski, Karol, and Artur Tadeusz Krzyżak. "The generalized Stejskal-Tanner equation for non-uniform magnetic field gradients." Journal of Magnetic Resonance 296 (2018): 23-28. Said publication shows that it is possible to generalize the Stejskal-Tanner equation to a form:

$$\ln\left(\frac{A(2\tau)}{A(0)}\right) = -\int_0^{2\tau} k^T(t)L^T(r)DL(r)k(t)\,dt \ . \qquad (1c)$$

By introducing the tensor (matrix) b, the tensor form of the equation can be obtained:

$$\ln\left(\frac{A(2\tau)}{A(0)}\right) = -\underbrace{L(r)b_{std}L^T(r)}_{=b(r)} : D_r = -b(r) : D_r = -b_{std} : D_{std}.$$

$$\text{wherein } b(r) \stackrel{\text{def}}{=} L(r)\underbrace{\int_0^{2\tau} k(t)k^T(t)dt}_{=b_{std}} L^T(r) = L(r)b_{std}L^T(r) \ . \qquad (1d)$$

$$D_{std} \stackrel{\text{def}}{=} L^T(\mathrm{r})D_r L(r).$$

Two different diffusion tensors appear in the formulas (1c), (1d): D_r is the real diffusion tensor of the examined sample, while D_{std} is the diffusion tensor reconstructed on the basis of the received signal and on the basis of the formula $\ln\left(\frac{A(2\tau)}{A(0)}\right) = -b_{std} : D_{std}$ (so-called theoretical diffusion tensor).

Similarly, two b matrices are distinguished: a theoretical matrix (i.e. a matrix that is constant in the imaging space for a particular direction of a diffusion gradient vector, and typically provided by the tomograph manufacturer) $b_{std} \stackrel{\text{def}}{=} \int_0^{2\tau} k(t)k^T(t)dt$ and the "real" matrix (i.e. a real spatial distribution corresponding to the real, non-uniform distribution of magnetic field gradients)

$b(r) \overset{\text{def}}{\equiv} L(r) b_{std} L^T(r)$. If a series of at least six measurements of a sample with a known diffusion tensor D is made and having the tensor D_{std} determined, then - as will be shown below - the field correction tensor L for correcting the field distortion can be determined using equations (1d).

The inventors of the present invention have noticed that in the general case the b_{std} matrix need not be a dyadic matrix (orthogonal projection).

It can be assumed that the gradient $G(t)$ is a sequence of gradients composed of m component gradients (diffusion, imaging, induced by eddy currents, background etc.) G_i $i = 1,2,\dots,m$. For the purpose of the calculations below, it is not necessary to make any assumptions concerning gradients G_i, it will be needed only later. For convenience, a polar notation can be used, i.e. $G_i(t) = A_i(t)\tilde{G}_i(t)$ wherein $A_i(t)$ is the gradient amplitude G_i, and $\tilde{G}_i(t)$ is its direction vector, i.e. $\|\tilde{G}_i(t)\| = 1$, wherein t stands for time. With such assumptions:

$$G(t) = G_1(t) + \cdots + G_m(t) \text{ and}$$
$$F(t) = \int_0^t \left(\sum_{i=1}^m G_i(\alpha) \right) d\alpha = \sum_{i=1}^m \underbrace{\int_0^t A_i(\alpha)\tilde{G}_i(\alpha) d\alpha}_{F_i}.$$

If, assuming that $\forall i = 1,\dots,m \;\; \tilde{G}_i(t) \equiv const.$ then:

$$F(t) = \sum_{i=1}^m \underbrace{\tilde{G}_i \int_0^t A_i(\alpha) d\alpha}_{F_i}.$$

Finally

$$k(t) = F(t) - 2H(t-\tau)f = \sum_{i=1}^m \underbrace{(F_i(t) - 2H(t-\tau)f_i)}_{k_i}.$$

$$wherein\, f \overset{\text{def}}{\equiv} F(\tau) = \sum_{i=1}^m \underbrace{F_i(\tau)}_{f_i}.$$

$wherein$:

$$H(t) \overset{\text{def}}{\equiv} \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \text{ Heaviside's function};$$

a τ is a half period of the pulse sequence .

Similarly, *b-tensor* is determined as:

$$b_{std} = \int_0^{2\tau} k(t)k^T(t)dt = \int_0^{2\tau} \left(\sum_{i=1}^{m} k_i(t)\right)\left(\sum_{j=1}^{m} k_j(t)\right)^T dt =$$

$$= \int_0^{2\tau} \sum_{i,j=1}^{m,m} k_i(t)k_j^T(t)dt = \sum_{i,j=1}^{m,m} \underbrace{\int_0^{2\tau} k_i(t)k_j^T(t)dt}_{b_{ij}} = \sum_{i,j=1}^{m,m} b_{ij}$$

$$b_{ij} \stackrel{\text{def}}{=} \int_0^{2\tau} k_i(t)k_j^T(t)dt = \int_0^{2\tau} (F_i(t) - 2H(t-\tau)f_i)\big(F_j(t) - 2H(t-\tau)f_j\big)^T dt$$

All components of b_{ij} are dyadic:

$$\frac{b_{ij}}{\|G_i\|\|G_j\|} = \frac{G_i G_j^T}{\|G_i\|^2\|G_j\|^2} ,$$

However, the sum of dyadic matrices need not be dyadic, so b_{std} need not be a dyadic matrix.

Substituting to the equation (1b)

$$b_{std}(r) = \sum_{i,j=1}^{m,m} b_{ij} = \sum_{i,j=1}^{m,m} \frac{G_i G_j^T}{\|G_i\|\|G_j\|}$$

the following equation is obtained:

$$b(r) = \sum_{i,j=1}^{m,m} \frac{(L(r)G_i)\big(L(r)G_j\big)^T}{\|G_i\|\|G_j\|} \tag{2a}$$

The above matrix equation can be solved assuming that all gradients G_i are known and that the matrix $L(r)$ is an unknown matrix. To simplify further transformations, it can be assumed that $L = [l_{x*} \quad l_{y*} \quad l_{z*}]^T$ – wherein l_{x*}, l_{y*} and l_{z*} stand for the next rows of matrix L. With such notations, the equation (a) takes the form:

$$b(r) = \begin{bmatrix} b_{rxx} & b_{rxy} & b_{rxz} \\ b_{ryx} & b_{ryy} & b_{ryz} \\ b_{rzx} & b_{rzy} & b_{rzz} \end{bmatrix}$$

$$= \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|} \left(\begin{bmatrix} l_{x*} \\ l_{y*} \\ l_{z*} \end{bmatrix} \begin{bmatrix} G_{ix} \\ G_{iy} \\ G_{iz} \end{bmatrix} \right) \left(\begin{bmatrix} l_{x*} \\ l_{y*} \\ l_{z*} \end{bmatrix} \begin{bmatrix} G_{jx} \\ G_{jy} \\ G_{jz} \end{bmatrix} \right)^T =$$

$$= \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|} \begin{bmatrix} l_{x*}G_i \\ l_{y*}G_i \\ l_{z*}G_i \end{bmatrix} \begin{bmatrix} l_{x*}G_j \\ l_{y*}G_j \\ l_{z*}G_j \end{bmatrix}^T \qquad (2b)$$

$$= \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|} \begin{bmatrix} l_{x*}G_i \\ l_{y*}G_i \\ l_{z*}G_i \end{bmatrix} [l_{x*}G_j \, l_{y*}G_j l_{z*}G_j] =$$

$$= \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|} \begin{bmatrix} (l_{x*}G_i)(l_{x*}G_j) & (l_{x*}G_i)(l_{y*}G_j) & (l_{x*}G_i)(l_{z*}G_j) \\ (l_{y*}G_i)(l_{x*}G_j) & (l_{y*}G_i)(l_{y*}G_j) & (l_{y*}G_i)(l_{z*}G_j) \\ (l_{z*}G_i)(l_{x*}G_j) & (l_{z*}G_i)(l_{y*}G_j) & (l_{z*}G_i)(l_{z*}G_j) \end{bmatrix}$$

Comparing the elements of the matrix (2a), a classical system of second degree equations is obtained:

$$\begin{cases} \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|}(l_{x*}G_i)(l_{x*}G_j) & = & b_{rxx} \\ \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|}(l_{x*}G_i)(l_{y*}G_j) & = & b_{rxy} \\ \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|}(l_{x*}G_i)(l_{z*}G_j) & = & b_{rxz} \\ \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|}(l_{y*}G_i)(l_{y*}G_j) & = & b_{ryy} \\ \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|}(l_{y*}G_i)(l_{z*}G_j) & = & b_{ryz} \\ \sum_{i,j=1}^{m,m} \frac{1}{\|G_i\|\|G_j\|}(l_{z*}G_i)(l_{z*}G_j) & = & b_{rzz} \end{cases} \quad (2c)$$

Using the identity:

$$(a_1 + \cdots + a_m)(b_1 + \cdots + b_m) = \left(\sum_{i,j=1}^{m,m} a_i \cdot b_j \right).$$

After transforming (2c), the following can be obtained:

$$\begin{cases} \left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{x*}G_i)\right)^2 & = & b_{rxx} \\ \left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{x*}G_i)\right)\left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{y*}G_i)\right) & = & b_{rxy} \\ \left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{x*}G_i)\right)\left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{z*}G_i)\right) & = & b_{rxz} \\ \left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{y*}G_i)\right)^2 & = & b_{ryy} \\ \left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{y*}G_i)\right)\left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{z*}G_i)\right) & = & b_{ryz} \\ \left(\sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{z*}G_i)\right)^2 & = & b_{rzz} \end{cases} \quad (2d)$$

With the accuracy to a sign, each solution of the system of equations (2d) must be also the solution of the following system of linear equations – but not vice-versa:

$$\begin{cases} \sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{x*}G_i) & = & \sqrt{b_{rxx}} \\ \sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{y*}G_i) & = & sgn\,(b_{rxy})\sqrt{b_{ryy}} \\ \sum_{i=1}^{m} \frac{1}{\|G_i\|}(l_{z*}G_i) & = & sgn\,(b_{rxz})\sqrt{b_{rzz}} \end{cases} \quad (3)$$

In a detailed notation, the equation (3) takes the following form:

$$\begin{cases} l_{xx}\left(\sum_{i=1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{xy}\left(\sum_{i=1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{xz}\left(\sum_{i=1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = & \pm\sqrt{b_{rxx}} \\ l_{yx}\left(\sum_{i=1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{yy}\left(\sum_{i=1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{yz}\left(\sum_{i=1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = & sgn\left(b_{rxy}\right)\sqrt{b_{ryy}} \\ l_{zx}\left(\sum_{i=1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{zy}\left(\sum_{i=1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{zz}\left(\sum_{i=1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = & sgn\left(b_{rxz}\right)\sqrt{b_{rzz}} \end{cases}$$

If it is assumed that the unknowns are l_{ij} – the coefficients of the field correction tensor L, then the system (3) is a system of three linear equations with nine unknowns. Such a system can at most be an indefinite system with an infinite number of solutions, but if measurements are made for at least three sequences of gradients, the result will be the (combined) system of nine linear equations of the form:

$$\begin{bmatrix} G_{1x} & G_{1y} & G_{1z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{1x} & G_{1y} & G_{1z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G_{1x} & G_{1y} & G_{1z} \\ G_{2x} & G_{2y} & G_{2z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{2x} & G_{2y} & G_{2z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G_{2x} & G_{2y} & G_{2z} \\ G_{3x} & G_{3y} & G_{3z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{3x} & G_{3y} & G_{3z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G_{3x} & G_{3y} & G_{3z} \end{bmatrix} \cdot \begin{bmatrix} l_{xx} \\ l_{xy} \\ l_{xz} \\ l_{yx} \\ l_{yy} \\ l_{yz} \\ l_{zx} \\ l_{zy} \\ l_{zz} \end{bmatrix} = \begin{bmatrix} +\sqrt{b_{r1xx}} \\ sgn\left(b_{r1xy}\right)\sqrt{b_{ryy}} \\ sgn\left(b_{r1xz}\right)\sqrt{b_{rzz}} \\ +\sqrt{b_{r2xx}} \\ sgn\left(b_{r2xy}\right)\sqrt{b_{r2yy}} \\ sgn\left(b_{r2xz}\right)\sqrt{b_{r2zz}} \\ +\sqrt{b_{r3xx}} \\ sgn\left(b_{r3xy}\right)\sqrt{b_{r3yy}} \\ sgn\left(b_{r3xz}\right)\sqrt{b_{r3zz}} \end{bmatrix} \quad (4)$$

wherein $G1, G2$ and $G3$ are three sequences of the gradients. With the appropriate selection of the gradients G1, G2 and G3 the system (4) is a determinate system.

In fact:

$$\det\begin{bmatrix} G1_x & G1_y & G1_z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G1_x & G1_y & G1_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G1_x & G1_y & G1_z \\ G2_x & G2_y & G2_z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G2_x & G2_y & G2_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G2_x & G2_y & G2_z \\ G3_x & G3_y & G3_z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G3_x & G3_y & G3_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G3_x & G3_y & G3_z \end{bmatrix}$$

$$= \det\begin{bmatrix} G1_x & G1_y & G1_z & 0 & 0 & 0 & 0 & 0 & 0 \\ G2_x & G2_y & G2_z & 0 & 0 & 0 & 0 & 0 & 0 \\ G3_x & G3_y & G3_z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G1_x & G1_y & G1_z & 0 & 0 & 0 \\ 0 & 0 & 0 & G2_x & G2_y & G2_z & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{3x} & G_{3y} & G_{3z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G1_x & G1_y & G1_z \\ 0 & 0 & 0 & 0 & 0 & 0 & G2_x & G2_y & G2_z \\ 0 & 0 & 0 & 0 & 0 & 0 & G3_x & G3_y & G3_z \end{bmatrix} =$$

$$= \left(\det\begin{bmatrix} G_{1x} & G_{1y} & G_{1z} \\ G_{2x} & G_{2y} & G_{2z} \\ G_{3x} & G_{3y} & G_{3z} \end{bmatrix}\right)^3 = \left(\det\begin{bmatrix} \sum_{i=1}^{m}\frac{G1_{ix}}{\|G1_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G1_{iy}}{\|G1_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G1_{iz}}{\|G1_\mathrm{i}\|} \\ \sum_{i=1}^{m}\frac{G2_{ix}}{\|G2_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G2_{iy}}{\|G2_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G2_{iz}}{\|G2_\mathrm{i}\|} \\ \sum_{i=1}^{m}\frac{G3_{ix}}{\|G3_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G3_{iy}}{\|G3_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G3_{ix}}{\|G3_\mathrm{i}\|} \end{bmatrix}\right)^3$$

$$= \left(\det\begin{bmatrix} \sum_{i=1}^{m}\frac{G1_{ix}}{\|G1_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G1_{iy}}{\|G1_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G1_{iz}}{\|G1_\mathrm{i}\|} \\ \sum_{i=1}^{m}\frac{G2_{ix}}{\|G2_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G2_{iy}}{\|G2_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G2_{iz}}{\|G2_\mathrm{i}\|} \\ \sum_{i=1}^{m}\frac{G3_{ix}}{\|G3_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G3_{iy}}{\|G3_\mathrm{i}\|} & \sum_{i=1}^{m}\frac{G3_{ix}}{\|G3_\mathrm{i}\|} \end{bmatrix}\right)^3 \neq 0.$$

In real implementations, the parameters of some of the gradients present in the sequence of gradients G_i are unknown. To effectively solve the system (4), the unknown parameters have to be removed from it. Assuming that the gradient parameters $G_i \ \ i = 1, \ldots, k < m$ are unknown, usually these will be imaging gradients and others, e.g. background gradients, without diffusion gradients. If a separate measurement is made using only unknown gradients $G_i \ \ i = 1, \ldots, k < m$, the following system can be obtained:

$$
\begin{aligned}
b_0 &= \begin{bmatrix} b_{0xx} & b_{0xy} & b_{0xz} \\ b_{0yx} & b_{0yy} & b_{0yz} \\ b_{0zx} & b_{0zy} & b_{0zz} \end{bmatrix} \\
&= \sum_{i,j=1}^{k,k} \frac{1}{\|G_i\|\|G_j\|} \left(\begin{bmatrix} l_{x*} \\ l_{y*} \\ l_{z*} \end{bmatrix} \begin{bmatrix} G_{ix} \\ G_{iy} \\ G_{iz} \end{bmatrix} \right) \left(\begin{bmatrix} l_{x*} \\ l_{y*} \\ l_{z*} \end{bmatrix} \begin{bmatrix} G_{jx} \\ G_{jy} \\ G_{jz} \end{bmatrix} \right)^T = \\
&= \sum_{i,j=1}^{k,k} \frac{1}{\|G_i\|\|G_j\|} \begin{bmatrix} l_{x*}G_i \\ l_{y*}G_i \\ l_{z*}G_i \end{bmatrix} \begin{bmatrix} l_{x*}G_j \\ l_{y*}G_j \\ l_{z*}G_j \end{bmatrix}^T \\
&= \sum_{i,j=1}^{k,k} \frac{1}{\|G_i\|\|G_j\|} \begin{bmatrix} l_{x*}G_i \\ l_{y*}G_i \\ l_{z*}G_i \end{bmatrix} [l_{x*}G_j \; l_{y*}G_j l_{z*}G_j] = \\
&= \sum_{i,j=1}^{k,k} \frac{1}{\|G_i\|\|G_j\|} \begin{bmatrix} (l_{x*}G_i)(l_{x*}G_j) & (l_{x*}G_i)(l_{y*}G_j) & (l_{x*}G_i)(l_{z*}G_j) \\ (l_{y*}G_i)(l_{x*}G_j) & (l_{y*}G_i)(l_{y*}G_j) & (l_{y*}G_i)(l_{z*}G_j) \\ (l_{z*}G_i)(l_{x*}G_j) & (l_{z*}G_i)(l_{y*}G_j) & (l_{z*}G_i)(l_{z*}G_j) \end{bmatrix}
\end{aligned}
\tag{5}
$$

which is analogous to the system (2b), but corresponding only to the sequence of the unknown gradients. After appropriate transformations, the same as for the system (3), for b_0, (for example for the matrix corresponding to the imaging and background gradients) the following system is obtained:

$$\begin{cases} l_{xx}\left(\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}\right)+l_{xy}\left(\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}\right)+l_{xz}\left(\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}\right) & = \pm\sqrt{b_{0xx}} \\ l_{yx}\left(\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}\right)+l_{yy}\left(\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}\right)+l_{yz}\left(\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}\right) & = sgn\left(b_{0xy}\right)\sqrt{b_{0yy}} \\ l_{zx}\left(\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}\right)+l_{zy}\left(\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}\right)+l_{zz}\left(\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}\right) & = sgn\left(b_{0xz}\right)\sqrt{b_{0zz}} \end{cases}.$$

Getting back to the system (4):

$$\begin{cases} l_{xx}\left(\sum_{i=1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{xy}\left(\sum_{i=1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{xz}\left(\sum_{i=1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = \pm\sqrt{b_{rxx}} \\ l_{yx}\left(\sum_{i=1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{yy}\left(\sum_{i=1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{yz}\left(\sum_{i=1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = sgn\left(b_{rxy}\right)\sqrt{b_{ryy}} \\ l_{zx}\left(\sum_{i=1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{zy}\left(\sum_{i=1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{zz}\left(\sum_{i=1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = sgn\left(b_{rxz}\right)\sqrt{b_{rzz}} \end{cases}$$

$$\begin{cases} l_{xx}\left(\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{xy}\left(\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{xz}\left(\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = \\ l_{yx}\left(\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{yy}\left(\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{yz}\left(\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = \\ l_{zx}\left(\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{zy}\left(\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{zz}\left(\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}+\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|}\right) & = \end{cases}$$

$$\begin{cases} \underbrace{l_{xx}\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}+l_{xy}\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}+l_{xz}\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}}_{\pm\sqrt{b_{0xx}}}+l_{xx}\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}+l_{xy}\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}+l_{xz}\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|} \\ \underbrace{l_{yx}\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}+l_{yy}\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}+l_{yz}\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}}_{sgn\left(b_{0xy}\right)\sqrt{b_{0yy}}}+l_{yx}\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}+l_{yy}\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}+l_{yz}\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|} \\ \underbrace{l_{zx}\sum_{i=1}^{k}\frac{G_{ix}}{\|G_i\|}+l_{zy}\sum_{i=1}^{k}\frac{G_{iy}}{\|G_i\|}+l_{zz}\sum_{i=1}^{k}\frac{G_{iz}}{\|G_i\|}}_{sgn\left(b_{0xz}\right)\sqrt{b_{0zz}}}+l_{zx}\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}+l_{zy}\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}+l_{zz}\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|} \end{cases}$$

Finally, a system of equations (6) is obtained:

$$\begin{cases} l_{xx}\left(\sum_{i=k+1}^{m}\frac{G_{ix}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)+l_{xy}\left(\sum_{i=k+1}^{m}\frac{G_{iy}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)+l_{xz}\left(\sum_{i=k+1}^{m}\frac{G_{iz}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)=\pm\sqrt{b_{rxx}}\mp\sqrt{b_{0xx}} \\ l_{yx}\left(\sum_{i=k+1}^{m}\frac{G_{ix}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)+l_{yy}\left(\sum_{i=k+1}^{m}\frac{G_{iy}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)+l_{yz}\left(\sum_{i=k+1}^{m}\frac{G_{iz}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)=sgn\left(b_{rxy}\right)\sqrt{b_{ryy}}-sgn\left(b_{0xy}\right)\sqrt{b_{0yy}} \\ l_{zx}\left(\sum_{i=k+1}^{m}\frac{G_{ix}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)+l_{zy}\left(\sum_{i=k+1}^{m}\frac{G_{iy}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)+l_{zz}\left(\sum_{i=k+1}^{m}\frac{G_{iz}}{\|\boldsymbol{G}_{\mathrm{i}}\|}\right)=sgn\left(b_{rxz}\right)\sqrt{b_{rzz}}-sgn\left(b_{0xz}\right)\sqrt{b_{0zz}} \end{cases}$$

wherein:

l_{xx}, l_{xy}, l_{xz}, l_{yx}, l_{yy}, l_{yz}, l_{zx}, l_{zy}, l_{zz} are components of the field correction tensor L;

m is the number of different sources of magnetic field gradients ;

G_{ix}, G_{iy}, G_{iz} are the x, y, z components of the i-th gradient vector ;

$\|$ G_i $\|$ is the amplitude of a particular gradient vector;

b_{rxx}, b_{rxy}, b_{ryy}, b_{rxz}, b_{rzz} are components of the b_r matrix;

b_{0xx}, b_{0xy}, b_{0yy}, b_{0xz}, b_{0z} are components of the b_0 matrix;

sgn() is the signum function.

All the coefficients (G_i, b_r, b_0) are already known. Next the procedure proceeds as in the case of the system (4). Measurements for at least three appropriately selected (i.e. for non-colinear diffusion gradient vectors G_d) sequences of gradients G_i $i = k+1, \ldots, m$ have to be made. If three sequences of gradients G are used, a system of nine linear equations (6) has to be solved, for example by the method of determinants. If more than three G gradient sequences are used, a system of 3*m equations (6) has to be solved, for example by the method of least squares.

Knowing the spatial distribution of the field correction tensor L(r), diffusion tensor coefficients can then be calculated using the formula (1a).

In conclusion, knowing b_r and b_{std} (for the gradient sequence under study, determined e.g. by BSD-DTI or sBSD-DTI), the equation (1b) in an explicit form is a system of six second-degree equations with nine unknowns. By decomposing the b_{std} matrix into the sum of dyadic matrices, we can reduce three equations from the system $b_r = Lb_{std}L^T$ to the form of linear equations. By making measurements for three sequences of gradients, we will obtain a system of nine linear equations with nine unknowns. By appropriately selecting the sequence of gradients, we will get a defined system, the solution of which is a solution to the equation $b_r = L b_{std} L^T$. It may happen that the parameters of some Gi gradients occurring in the analyzed sequence are not known. Then we perform measurements using only undefined gradients and using the additivity of linear systems, we eliminate unknown components from the system of equations.

The determination of the field correction tensor L(r) with respect to the coil tensor as suggested by Bammer takes into account the influence of all real sources of magnetic field gradients compared to the gradient distribution of the gradient coils provided by the manufacturer.

The field correction tensor L(r) is determined for a particular DWI sequence with particular diffusion gradient parameters such as amplitude, rise time and width of the diffusion gradient, and diffusion time, i.e. the time interval between diffusion gradients.

The above fact simplifies the known calibration method according to the BSD-DTI and sBSD-DTI, namely after determining the field correction tensor L(r) according to the invention, the values of the b_r matrix or the diffusion tensor D_r in the DWI experiment performed for any diffusion gradient vector, can be obtained directly by substituting the values of the tensor L(r) to the equations 1a and 1b. There is no need to perform further BSD-DTI or sBSD-DTI method calibrations. Effects of such action on the examples where the visualization of neural fiber tracts was made will be illustrated in an example on Fig. 4B.

In addition, the determination of the field correction tensor L(r) allows the calculation of the curvilinear space p(r), leading to further progress in imaging in non-uniform magnetic field gradients.

SHORT DESCRIPTION OF THE DRAWINGS

The invention is illustrated by means of an exemplary embodiment and the appended drawings, in which:

Fig. 1 shows schematically an anisotropic plate phantom inside an RF coil during determination of matrix b;

Fig. 2 shows a diagram of the method according to the invention;

Fig. 3 shows the MR image for the selected ROI of the brain, for which the neural fiber tracts were determined using the fiber tracking method;

Figs. 4A and 4B show a visualization of the neural fiber tracts for a selected ROI from Fig. 3 made on the basis of the DTI data calculated in a standard manner (4A) and using the field correction tensor L(r) (Fig. 4B).

DETAILED DESCRIPTION OF AN EMBODIMENT

The method according to the invention comprises the following steps, according to Fig. 2. In the first step 201, the first diffusion gradient vector G_d is determined. In step 202, a calibration is performed by determining for each particular vector G_d the value of the spatial matrix b and of the theoretical matrix b_{std} for each voxel with the spatial coordinate (r) within the imaging space, for example according to the BSD-DTI or sBSD-DTI technique, for example by placing an anisotropic plate phantom 101 inside the RF coil 111 as shown schematically in Fig. 1. Then, in step 203, the diffusion gradient vector G_d is changed to another one, that is not collinear with the preceding vectors for which step 202 was performed, and step 202 is repeated so as to perform step 202 for at least three different non-collinear diffusion gradients G_d. Next, in step 204 the spatial distribution of the field correction tensor L(r) components is determined based on at least three sets of equations (6), one set of equations (6) for each vector G. Next in step 205 the spatial distribution of the coefficients of the diffusion tensor (D_r) is calculated taking into account said spatial distribution of the components of the field correction tensor L(r) on the basis of the formula (1a).

Fig. 3 shows an MR image for the selected region (Region of Interest, ROI) of the brain for which the neural fiber tracts were determined by fiber tracking.

Figs 4A and 4B show a visualization of the neural fiber tracts for the selected ROI from Fig. 3 made from the DTI data calculated in a standard manner (4A) and using the field correction tensor L(r) (Fig. 4B). This allowed to obtain a visualization of the neural fiber tracts which is more consistent with reality. The experiments were performed on the 3T Siemens MAGNETOM Skyra scanner. Echo-planar imaging diffusion tensor imaging (EPI-DTI) was performed with the following parameters: TR = 2500 ms, TE = 80 ms, FOV = 160 mm, matrix size = 160 x 160, resolution = 1 x 1 x 2 mm, number of averages = 4, b value = 1000 s / mm2 and six diffusion gradient directions.

CLAIMS

1. A method for imaging in a nuclear magnetic resonance (NMR) experiment that uses magnetic field gradients greater than the gradients used for imaging, wherein the method comprises calculating the diffusion tensor coefficients based on a spatial distribution of the matrix b(r) obtained by calibration, characterized in that the method further comprises the steps of:

- performing a calibration (201-203) for at least three different non-collinear diffusion gradient vectors G_d, by establishing for each of the vectors G_d a value of the spatial matrix b and of the theoretical matrix b_{std} for each voxel having a spatial coordinate (r) within the imaging space;
- determining (204) the spatial distribution of the components of the field correction tensor L(r) on the basis of at least three sets of equations (6), each set of equations (6) for each vector G:

$$\begin{cases} l_{xx}\left(\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{xy}\left(\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{xz}\left(\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|}\right)=\pm\sqrt{b_{rxx}}\mp\sqrt{b_{0xx}} \\ l_{yx}\left(\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{yy}\left(\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{yz}\left(\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|}\right)=sgn\left(b_{rxy}\right)\sqrt{b_{ryy}}-sgn\left(b_{0xy}\right)\sqrt{b_{0yy}} \\ l_{zx}\left(\sum_{i=k+1}^{m}\frac{G_{ix}}{\|G_i\|}\right)+l_{zy}\left(\sum_{i=k+1}^{m}\frac{G_{iy}}{\|G_i\|}\right)+l_{zz}\left(\sum_{i=k+1}^{m}\frac{G_{iz}}{\|G_i\|}\right)=sgn\left(b_{rxz}\right)\sqrt{b_{rzz}}-sgn\left(b_{0xz}\right)\sqrt{b_{0zz}} \end{cases}$$

wherein:

l_{xx}, l_{xy}, l_{xz}, l_{yx}, l_{yy}, l_{yz}, l_{zx}, l_{zy}, l_{zz} are components of the field correction tensor L;

m is the number of different sources of magnetic field gradients ;

G_{ix}, G_{iy}, G_{iz} are the x, y, z components of the i-th gradient vector ;

$\| G_i \|$ is the amplitude of a particular gradient vector;

b_{rxx}, b_{rxy}, b_{ryy}, b_{rxz}, b_{rzz} are components of the b_r matrix;

b_{0xx}, b_{0xy}, b_{0yy}, b_{0xz}, b_{0z} are components of the b_0 matrix;

sgn() is the signum function; and

- calculating (205) a spatial distribution of the coefficients of the diffusion tensor (D_r) taking into account said spatial distribution of the components of the field correction tensor L(r) by using the formula:

$$D_r = L^T(r)DL(r).$$

2. The method according to claim 1, comprising determining (202) the spatial distribution of matrix b as a result of calibration performed by a BSD-DTI method.

3. The method according to claim 1, comprising determining (202) the spatial distribution of matrix b as a result of calibration performed by a sBSD-DTI method.

4. The method according to any of previous claims, wherein the determination (204) of the spatial distribution of the field correction tensor L(r) is performed for various DWI sequences and diffusion sequence parameters selected from the group consisting of: diffusion gradient width values, diffusion times, amplitudes of the diffusion gradient vector.

5. The method according to any of previous claims, further comprising verifying the obtained spatial distribution of the tensor L(r) by using it to compute the diffusion tensor for model isotropic and anisotropic phantoms with known values of the diffusion tensor.

6. The method according to claim 5 wherein the obtained spatial distributions of the field correction tensor L(r) constitute the final element of the calibration of an arbitrary imaging sequence of the DMRI type experiment, which are then routinely used in the imaging of any object in the DMRI type experiment.

7. The method according to any of previous claims wherein the calibration (201-203) is performed before each change of the imaging sequence parameters, in particular before changing the value of the amplitude, width of the pulses of the diffusion gradient vectors and diffusion time.

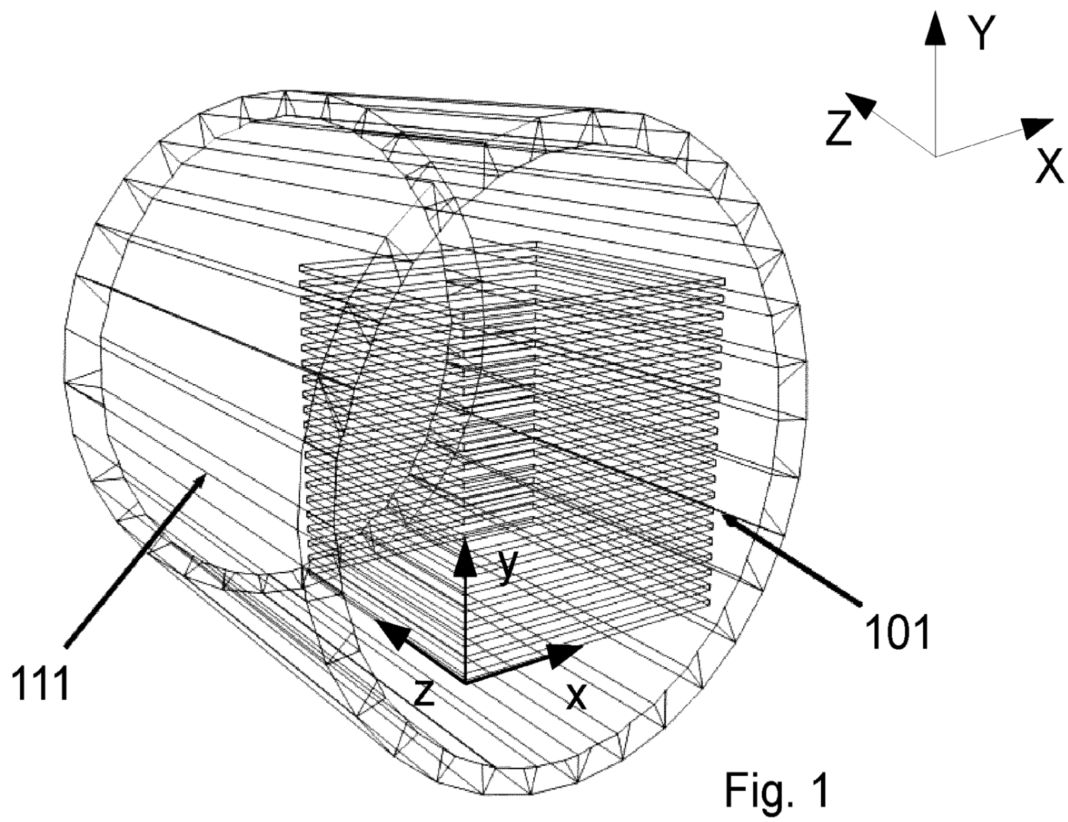

Fig. 1

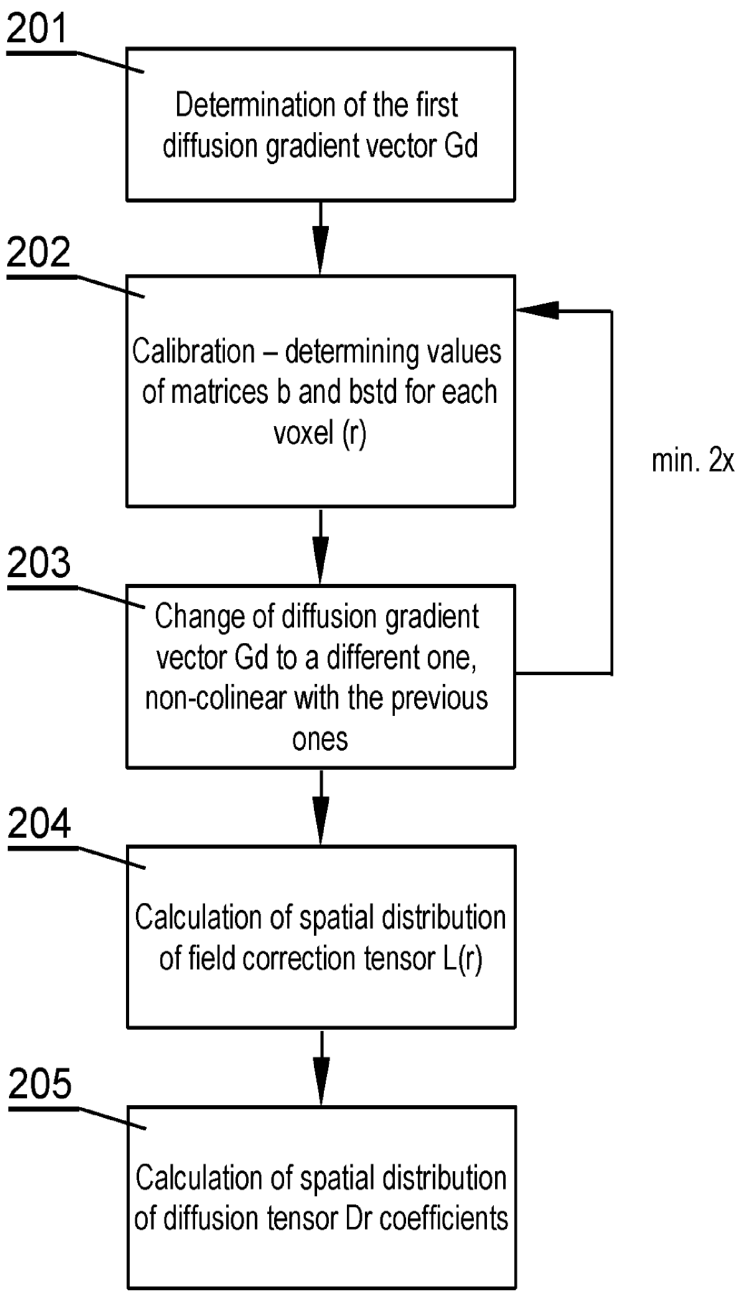
201
Determination of the first diffusion gradient vector Gd
202
Calibration – determining values of matrices b and bstd for each voxel (r)
min. 2x
203
Change of diffusion gradient vector Gd to a different one, non-colinear with the previous ones
204
Calculation of spatial distribution of field correction tensor L(r)
205
Calculation of spatial distribution of diffusion tensor Dr coefficients

Fig. 2

Fig. 3

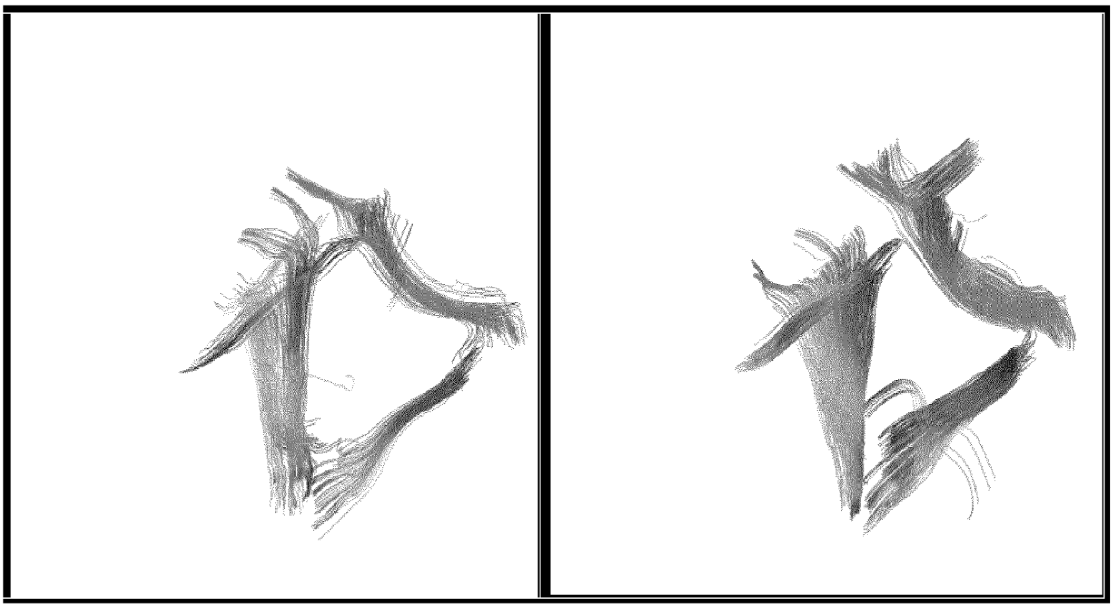

Fig. 4A Fig. 4B

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/062240

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R33/563 G01R33/58
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BORKOWSKI KAROL ET AL: "Improving precision and accuracy of DTI experiments with the simplified BSD calibration - computer simulations", 2016 FEDERATED CONFERENCE ON COMPUTER SCIENCE AND INFORMATION SYSTEMS (FEDCSIS), POLISH INFORMATION PROCESSING SOCIETY, 11 September 2016 (2016-09-11), pages 935-938, XP032994329, [retrieved on 2016-11-03] cited in the application the whole document -----	1-7

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 January 2022	24/01/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Raguin, Guy

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Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BORKOWSKI KAROL ET AL: "The generalized Stejskal-Tanner equation for non-uniform magnetic field gradients", JOURNAL OF MAGNETIC RESONANCE, ACADEMIC PRESS, ORLANDO, FL, US, vol. 296, 30 August 2018 (2018-08-30), pages 23-28, XP085530529, ISSN: 1090-7807, DOI: 10.1016/J.JMR.2018.08.010 cited in the application the whole document -----	1-7
A	KLODOWSKI KRZYSZTOF ET AL: "Innovative anisotropic phantoms for calibration of diffusion tensor imaging sequences", MAGNETIC RESONANCE IMAGING, ELSEVIER SCIENCE, TARRYTOWN, NY, US, vol. 34, no. 4, 19 December 2015 (2015-12-19), pages 404-409, XP029447456, ISSN: 0730-725X, DOI: 10.1016/J.MRI.2015.12.010 cited in the application the whole document -----	1-7
A	BORKOWSKI KAROL ET AL: "Analysis and correction of errors in DTI-based tractography due to diffusion gradient inhomogeneity", JOURNAL OF MAGNETIC RESONANCE, ACADEMIC PRESS, ORLANDO, FL, US, vol. 296, 30 August 2018 (2018-08-30), pages 5-11, XP085530528, ISSN: 1090-7807, DOI: 10.1016/J.JMR.2018.08.011 cited in the application the whole document -----	1-7
A	WO 2017/017163 A1 (AKADEMIA GORNICZO-HUTNICZA IM STANISLAWA STASZICA W KRAKOWIE [PL]) 2 February 2017 (2017-02-02) cited in the application the whole document -----	1-7

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BAMMER R. ET AL: "Analysis and generalized correction of the effect of spatial gradient field distortions in diffusion-weighted imaging", MAGNETIC RESONANCE IN MEDICINE, vol. 50, no. 3, 20 August 2003 (2003-08-20), pages 560-569, XP055871694, US ISSN: 0740-3194, DOI: 10.1002/mrm.10545 cited in the application the whole document -----	1-7

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INTERNATIONAL SEARCH REPORT	International application No. PCT/EP2021/062240

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 1-7(partially)
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims;; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 1-7(partially)

The reasons for which the application is not considered to comply with the requirements of the PCT to the extent where a complete search is not possible and the assessment of novelty and an inventive step of the claimed subject-matter is not possible are specified in the annexed written opinion accompanying the partial search results (Form PCT/ISA/237).

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guidelines C-IV, 7.2), should the problems which led to the Article 17(2) PCT declaration be overcome.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2021/062240

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2017017163 A1	02-02-2017	PL 232529 B1	28-06-2019
		WO 2017017163 A1	02-02-2017