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(54) Title: A METHOD FOR CALIBRATING A DIFFUSION IMAGING SEQUENCE DURING A DIFFUSION MRI EXPERIMENT

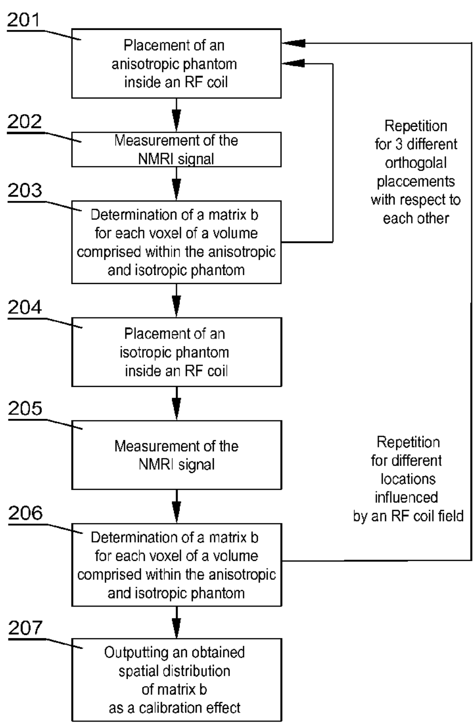

Fig. 2

(57) Abstract: A method for calibrating a diffusion imaging sequence during a DMRI (Diffusion Magnetic Resonance Imaging) experiment performed in an MR (Magnetic Resonance) tomograph, wherein the experiment comprises calculating diffusion coefficients and/or diffusion tensor coefficients on the basis of a spatial distribution of a b matrix, the method for calibrating comprising the following steps: within the field of influence of an RF (Radio Frequency) coil in an examined space of the MR tomograph: providing (201) an anisotropic diffusion phantom (101) with known values of diffusion tensor, the anisotropic diffusion phantom (101) having diffusion limited therein in at least one direction along a first axis of the principal axes of the anisotropic diffusion phantom (101); placing the anisotropic diffusion phantom (101) sequentially in a selected location within the examined space in three different positioning arrangements orthogonal with respect to each other; and placing an isotropic diffusion phantom (102) having a known diffusion tensor in said selected location; for each positioning arrangement of the anisotropic diffusion phantom (101) and the isotropic diffusion phantom (102), measuring (202, 205) MR signals; determining (203, 206) the values of the b matrix, based on the measured MR signals, for each voxel of a volume comprised inside both the volume of the anisotropic diffusion phantom (101) and the volume of the isotropic diffusion phantom (102); and providing (207) the determined spatial distribution of the b matrix as a calibration result for the DMRI sequence for the particular MR tomograph.

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A METHOD FOR CALIBRATING A DIFFUSION IMAGING SEQUENCE DURING A DIFFUSION MRI EXPERIMENT

DESCRIPTION

TECHNICAL FIELD

The present disclosure relates to a method for calibrating a diffusion imaging sequence during a DMRI experiment in an MR tomograph, in particular in a DWI, a DTI or an FMRI-DTI experiment.

BACKGROUND ART

Magnetic Resonance Imaging (MRI) is a non-invasive method of imaging the inside of objects. It is applicable in biology, geology or medicine, wherein it is one of the basic tomography techniques.

Tomography is a diagnostic method that allows obtaining an image of a cross-section of a body or a part thereof. A particular type of MRI is Diffusion Magnetic Resonance Imaging (Diffusion MRI, DMRI). It allows mapping the process of diffusion of molecules, in particular water, in porous systems such as rock cores or biological tissues. Molecular diffusion represents interactions with obstacles, such as macromolecules, fibers, membranes or the like. A distribution of diffusion of water particles allows the examination of microscopic information on architecture of the examined objects. It also allows a quantitative, non-invasive determination of substances comprising water or hydrocarbons. Diffusion Weighted Imaging (DWI), Diffusion Tensor Imaging (DTI) or Diffusion Functional MRI-DTI (FMRI-DTI) are particular types of the DMRI.

One of the methods for calibration of an MR tomograph in DWI, DTI or FMRI-DTI experiments is based on a use of anisotropic diffusion phantoms, and determining a spatial distribution of a diffusion tensor for a particular sequence of a nuclear magnetic resonance (NMR) imaging, as described in a US patent

US8643369 or the paper „Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix. Magnetic Resonance” (Krzyzak AT, Olejniczak Z, BSD-DTI, Imaging 2015; 33:286-295).

It is known from the prior art that values of the b matrix required for calculating a diffusion tensor are determined analytically, for each diffusion sequence of an MR imaging and separately for each tomograph, in an approximate manner due to complicated equations needed for their calculation. It is also known to use a single value of the b matrix to calculate the diffusion tensor, for a particular vector of a gradient of magnetic field diffusion, assumed for the whole volume of the examined object.

One drawback of the known systems for calculating the diffusion tensor is related to recalculation errors arising from the use of approximate values of the b matrix, as well as an assumption of lack of spatial distribution of the b matrix. This results in difficulties in an appropriate, precise and quantitative determination of water diffusion changes of an examined object with the use of an MR tomograph as well as lack of repeatability of the obtained results. For different MR tomographs there are different MR sequences, which in turn results in different results that are difficult to compare. These results are subject to errors due to a lack of possibility of appropriate determination of the values of the b matrix.

One solution of this problem has been described in the US patent US8643369, which is called a ”B-matrix Spatial Distribution in DTI” (BSD-DTI), as presented in the paper „Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix. Magnetic Resonance” (Krzyzak AT, Olejniczak Z, BSD-DTI, Imaging 2015; 33:286-295). The BSD-DTI method eliminates the aforementioned drawbacks, thereby allowing a precise measurement of diffusion coefficients as well as the diffusion tensor with a use of any imaging sequence, in particular in DWI, DTI and FMRI-DTI experiments.

BSD-DTI is based on the fact that in order to calibrate a particular sequence of an MR tomograph with an anisotropic diffusion phantom, the anisotropic diffusion phantom is placed in an area influenced by the field of an RF coil in an examination space of an MR tomograph, after which in order to calculate a spatial distribution of a diffusion coefficient (for DWI experiments) or a diffusion tensor (for DTI experiments), there is determined a required number of b matrices based on an anisotropic diffusion pattern, which is, except for the b_0 matrix, not less than one b matrix for DWI and not less than six b matrices in case of DTI, determined for each voxel and for each required direction of a diffusion gradient vector.

The values of the b matrix for a particular diffusion gradient vector are determined by calculating a system of equations comprising not less than six equations for different values of the diffusion tensor D. For a particular direction of the diffusion gradient vector, different values of the diffusion tensor are preferably obtained by a rotation of the anisotropic diffusion phantom in the examined area of the MR tomograph, which constitutes a diffusion pattern, for which a diffusion tensor has known values in the principal axes. Rotations are executed, with the diffusion pattern, by different Euler's angles such that for the matrix whose columns correspond to the components of the diffusion tensor D, the matrix determinant D_M, after subsequent rotations of the diffusion pattern by defined Euler's angles, is different from zero.

There is a need to further improve the methods for calibration of imaging sequences in a DMRI-type experiment in order to simplify procedures and decrease time required for the calibration.

SUMMARY

The method presented herein is an alternative to the aforementioned BSD-DTI method. It considerably reduces (even 2x) the time required for calibration, as well as simplifies calibration procedures.

There is disclosed a method for calibrating a diffusion imaging sequence during a DMRI (Diffusion Magnetic Resonance Imaging) experiment performed in an MR (Magnetic Resonance) tomograph, wherein the experiment comprises calculating diffusion coefficients and/or diffusion tensor coefficients on the basis of a spatial distribution of a b matrix, the method for calibrating comprising the following steps: within the field of influence of an RF (Radio Frequency) coil in an examined space of the MR tomograph: providing an anisotropic diffusion phantom with known values of diffusion tensor, the anisotropic diffusion phantom having diffusion limited therein in at least one direction along a first axis of the principal axes of the anisotropic diffusion phantom; placing the anisotropic diffusion phantom sequentially in a selected location within the examined space in three different positioning arrangements orthogonal with respect to each other; placing an isotropic diffusion phantom having a known diffusion tensor in said selected location; for each positioning arrangement of the anisotropic diffusion phantom and the isotropic diffusion phantom, measuring MR signals; determining the values of the b matrix, based on the measured MR signals, for each voxel of a volume comprised inside both the volume of the anisotropic diffusion phantom and the volume of the isotropic diffusion phantom; providing the determined spatial distribution of the b matrix as a calibration result for the DMRI sequence for the particular MR tomograph.

The method may comprise determining the spatial distribution of the b matrix for different parameters, of the diffusion sequence, selected from a group comprising: values of diffusion gradients, diffusion times, directions of a diffusion gradient vector, amplitude of a diffusion gradient vector.

The method may comprise repeating the calibration in subsequent steps, while assuming, as starting values of the calibration, the spatial distribution of the b matrix provided in a preceding step.

The method may comprise verifying the spatial distribution of the b matrix by using it to calculate a diffusion tensor for the reference anisotropic phantom and the reference isotropic phantom having known values of the diffusion tensor.

In case a standard deviation for a spatial distribution of the diffusion tensor for the reference phantoms exceeds a preferred value, the method may comprise repeating the calibration of the diffusion imaging sequence to further correct the spatial distribution of the b matrix.

The method may comprise positioning the anisotropic diffusion phantom sequentially in three different orthogonal positioning arrangements with the principal axes of the phantom being in parallel to the principal axes of the laboratory framework.

The method may comprise determining, for each voxel, three diagonal elements (bxx, byy, bzz) of the b matrix as well as their effective value (beff) calculated as a sum of the three diagonal elements (bxx, byy, bzz), from diffusion imaging experiments executed for three positioning arrangements of the anisotropic diffusion phantom being a reference of the anisotropic diffusion tensor.

The method may comprise determining, for each voxel, an effective value of the matrix (beff_iso) from a diffusion imaging experiment performed for the isotropic diffusion phantom being a reference of the isotropic diffusion tensor.

The method may comprise normalizing the diagonal values (bxx, byy, bzz) as well as the effective value of the b matrix (beff) obtained from the diffusion imaging experiment performed for the anisotropic diffusion phantom, to an effective value of the matrix (beff_iso) from the diffusion imaging experiment performed for the isotropic diffusion phantom being a reference of the isotropic diffusion tensor.

The method may comprise determining the non-diagonal values of the b matrix as products of the radices of the diagonal elements.

The method may comprise, for each voxel, using the values of the b matrix calculated for that voxel to determine diffusion coefficients in DWI (Diffusion Weighted Imaging) experiments.

The method may comprise, for each voxel, using the values of the b matrix calculated for this voxel to determine components of a diffusion tensor in DTI (Diffusion Tensor Imaging) experiments.

There is also disclosed a method for performing an experiment in an MR (Magnetic Resonance) tomograph, comprising calculating diffusion coefficients and/or diffusion tensor coefficients on the basis of the spatial distribution of the b matrix obtained as a result of the calibration according to the method described above.

The method may comprise using the spatial distribution of the b matrix obtained as a result of the calibration for any object in the DMRI-type experiment.

The method may comprise performing calibration before every change of parameters of the imaging sequence, in particular before a change of values and directions of diffusion gradient vectors.

There is also disclosed an MR (Magnetic Resonance) tomograph comprising a configuration controller configured to perform all the steps of the method as described above.

BRIEF DESCRIPTION OF DRAWINGS

The method is presented by means of example embodiment in a drawing, wherein:

Figs. 1A-1C present three examples of positioning arrangements of an anisotropic plate phantom, that are orthogonal with respect to each other within an RF coil;

Fig. 1D presents an example of a positioning arrangement of an isotropic phantom inside an RF coil;

Fig. 2 presents a flowchart of a method described herein;

Figs. 3A-3B presents distributions of primary values of a diffusion tensor;

Fig. 3C presents a differential distribution of a b_{eff} matrix obtained by using the sBSD-DTI; and

Fig. 4 presents a system described herein.

DETAILED DESCRIPTION

The method as described below will be referred to as sBSD-DTI (simplified B-matrix Spatial Distribution in DTI) and sBSD-DWI (simplified B-matrix Spatial Distribution in DWI) for DTI and DWI experiments respectively.

The following abbreviations are used for:

- MR - Magnetic Resonance;
- NMR - Nuclear Magnetic Resonance;
- DTI - Diffusion Tensor Imaging;
- DWI - Diffusion Weighted Imaging;
- FMRI-DTI - Functional Magnetic Resonance Imaging - Diffusion Tensor Imaging;
- BSD-DTI – B-matrix Spatial Distribution in DTI.

According to the sBSD method as presented herein, a spatial distribution of the b matrix is precisely determined from DMRI measurements, of an anisotropic phantom, in three different positioning arrangements that are orthogonal with respect to each other, as well as from measurements of an isotropic phantom. Subsequently, the spatial distribution of the b matrix, obtained in this manner, becomes a calibrating element for a particular imaging sequence (DWI, DTI, FMRI-DTI).

Figs. 1A-1C present three examples of positioning arrangements of an anisotropic, plate phantom 101, that are orthogonal with respect to each other within an RF coil 111. Fig. 1D presents an example of a positioning arrangement of an isotropic phantom 102 inside the RF coil 111. Preferably, the principal axes of the phantom x, y, z should be parallel to the principal axes X, Y, Z of the laboratory framework.

The phantoms are placed such that a volume comprised inside the anisotropic diffusion phantom 101 and the isotropic diffusion phantom 102 covers an area, in which the target objects are to be subsequently examined. Therefore, there a single set of large phantoms can be used, the volume of which covers the whole space in which the target objects are to be examined. Alternatively, a set of smaller phantoms can be used and the smaller phantoms can be placed subsequently in different locations of the RF coil 111 in order to cover the whole space in which the target objects are to be examined.

The values of the b matrix for any particular element of the space inside the RF coil 111 should be the same. If the distribution turns out to be non-uniform, it indicates an undesired distribution of magnetic field gradients, which may be taken into account in the target experiments and the DMRI may be corrected for any examined object.

The anisotropic diffusion phantom 101, used for calibration of any MR imaging sequence according to the presented method, may have arbitrary shape. It can be any phantom exhibiting a diffusion anisotropy for hydrogen comprised in H_2O and adapted to a particular RF coil.

The phantom has a structure that allows limiting the diffusion in at least one direction along at least one axis of the principal axes (x, y, z of Fig. 1A-1C) related to the anisotropic diffusion phantom 101, for a particular temperature, a particular range of diffusion times Δ,δ, in a particular MR imaging sequence. For example, it may be a capillary or a plate phantom. A free diffusion of water particles, which occurs for example across the capillaries or perpendicularly to the plane of thin glass plates, is stopped by an opposite wall of a capillary or by a plane of a neighboring thin glass plate, thereby exhibiting a limit of the diffusion process.

By regulating a diameter of the capillaries or a thickness of the layer of H_2O, hydrogel or any other substance comprising hydrogen nuclei between thin glass plates, a magnitude of the limit of diffusion for particular times of diffusion Δ can be determined, taking into account that the free diffusion is defined with the Einstein-Smoluchowski equation:

$$(r-r_o)(r-r_o) = 6Dt \qquad (1)$$

wherein:

r is a vector of location of a diffusing particle after time t;

r_o is an vector of an initial location.

The equation defines a relationship between an average square of a distance and a diffusion coefficient D.

The anisotropic diffusion phantom 101 may be defined in the laboratory framework by a symmetric diffusion tensor D as:

$$\begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix}$$

which after diagonalization in the principal axes system has a form of:

$$\begin{pmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{pmatrix}$$

wherein:

D_{ij} are components of the symmetric diffusion tensor in the laboratory framework;

D_1, D_2, D_3 are the diffusion coefficients of the tensor determined in the principal axes system, preferably in conformity with the phantom principal axes.

In the present method, a calibration of any diffusion imaging sequence in MR experiments is executed in order to precisely measure a diffusion coefficient and/or a diffusion tensor of any object.

The measurement of the diffusion tensor in DWI, DTI and FMRI-DTI experiments is effected by using the known equation defined in 1965 by Stejskall and Tanner:

$$\ln \frac{A(b)}{A(0)} = -\sum_{i=1}^{3} \sum_{j=1}^{3} b_{ij} D_{ij} \quad (2)$$

wherein

A(b) is an echo signal (an intensity of the MR image) for a particular value b measured for each voxel;

A(0) is the intensity of the MR image for b=0;

b_{ij} is an element of a symmetric b matrix;

D_{ij} is an element of a symmetric diffusion tensor D.

From the equation (2) it follows that for the DTI experiments, in order to calculate a diffusion tensor for water, wherein a symmetric tensor is a 3x3 matrix, there should be executed not less than seven MR experiments, for which the MR sequences will comprise six different, non-colinear directions of diffusion gradients and one (the seventh) without diffusion gradients. Therefore, for the simplest DTI experiment, for each diffusion gradient vector, there is a need to determine not less than six symmetric b matrices, each of which comprises six different components.

Assuming a typical assumption used in commerce that the b matrix is represented by the following expression:

$$b = bg \qquad (3)$$

wherein b is a constant coefficient for any DWI measurement in a direction defined by a single diffusion gradient vector $G_n^T = (g_x, g_y, g_z)$ and the g matrix is the following product: $G_n G_n^T$, therefore:

$$g = \begin{pmatrix} g_x^2 & g_x g_y & g_x g_z \\ g_y g_x & g_y^2 & g_y g_z \\ g_z g_x & g_z g_y & g_z^2 \end{pmatrix} \qquad (4)$$

This approach assumes a lack of influence of imaging gradients and their interaction with diffusion gradients. Further, it reduces a number of variables, required to determine the b matrix, from 6 to 3.

A diffusion phantom shall be constructed and adapted to the examined space, i.e. a particular RF coil, depending on the shape and parameters of that space. There are known various types of RF coils, such as volumetric coils, surface coils, birdcage coils, saddle coils. The coils can be also classified depending on their use, for example diagnostic coils for head, spinal cord, shoulder, trunk, limb, knee joint, elbow joint etc.

In order to perform a calibration of any MR imaging sequence, with an anisotropic 101 and an isotropic diffusion phantom 102, reference diffusion phantoms are placed in step 201 in an examined space of an MR tomograph. The anisotropic phantom 101 is positioned in three different orthogonal positioning arrangements with respect to each other inside the RF coil (as presented in Figs. 1A-1C). The number of positioning arrangements depends on a required precision of the experiment. The higher the number of measurements, the more precise the distribution of the b matrix and the calibration of a particular diffusion imaging sequence.

In each positioning arrangement of the phantoms, the MR signals are measured in step 202 for each space element (voxel), to determine the elements of the b matrix for these positioning arrangements using equations (2), (3) and (4).

In particular, for each voxel, for the three positioning arrangements of the anisotropic phantom 101 being a reference of an anisotropic diffusion tensor, there are determined in step 203 the three diagonal elements (bxx, byy, bzz) of the b matrix, as well as their effective value (beff) calculated as a sum of the three diagonal elements (bxx, byy, bzz). Further, for each voxel there is determined an effective value of the matrix (beff_iso) in step 206 from the experiment of diffusion imaging executed for the isotropic diffusion phantom 102 in steps 204, 205, being a reference of an isotropic diffusion tensor.

Subsequently, the diagonal values (bxx, byy, bzz), as well as the effective value of the b matrix (beff) from the experiment of diffusion imaging, executed for the anisotropic diffusion phantom 101, is normalized to an effective value of the matrix (beff_iso) from the experiment of diffusion imaging executed for the isotropic diffusion phantom.

The effective value of the matrix (beff_iso) from the experiment executed for the isotropic diffusion phantom 102 may be determined with a higher precision than the respective diagonal values (bxx, byy, bzz) from the experiment executed for the anisotropic diffusion phantom 101. Therefore, the normalization of values (bxx, byy, bzz, beff) to the (beff_iso) value increases the precision of calculations.

The non-diagonal values of the b matrix are determined as products of radices of the diagonal elements and single diffusion gradient vectors using the following formula:

$$b_{ij} = \sqrt{b_{ii}}\sqrt{b_{jj}}\,\frac{|g_i|}{g_i}\frac{|g_j|}{g_j}$$

wherein i, j = x, y, z.

The obtained spatial distributions of the b matrix are output in step 207 as a calibration result for a sequence of a DMRI-type of a particular tomograph, so that they may be subsequently used to execute DWI, DTI, FMRI-DTI experiments. In case there is a need to further improve the precision, the calibration process may be executed again using the already determined distribution of the b matrix, thus the calibration may be repeated in further iteration steps.

The obtained spatial distributions of the b matrix may be verified by their use in calculations of a diffusion tensor for reference phantoms. both anisotropic and isotropic, having known values of the diffusion tensor. If a standard deviation for the spatial distribution of a diffusion tensor calculated in such manner, for the reference phantoms, exceeds a required threshold, then in order to obtain more precise results the calibration of the diffusion imaging sequence is repeated, in order to further correct the spatial distribution of the b matrix. The corrected spatial distributions of the b matrix obtained this way are a final element of the calibration of any imaging sequence of a DMRI-type experiment, which are subsequently routinely used during imaging of any object in a DMRI-type experiment.

A calibration for DWI or DTI measurements is particularly important in case of experiments that require high precision, such as FMRI-DTI experiments, wherein the observed changes do not exceed a few percent. Initial experiments performed according to the method presented herein, similarly as in the BSD-DTI method, allow the improvement of precision by an order of magnitude, while significantly reducing the time of calibration, as well as simplifying the calibration procedures.

The calibration has to be repeated before every change of imaging sequence parameters, in particular before a change of values and directions of diffusion gradient vectors.

Another advantage of the presented sBSD-DTI method for calibration of any diffusion sequence, is an improved precision of measurement of a diffusion tensor.

Example

Figs. 3A-3B present distributions of primary values of a diffusion tensor for an isotropic phantom 102 obtained with a standard DTI method (Fig. 3A) and the sBSD-DTI method presented herein (Fig. 3B). The rows present 25 layers while the columns refer to primary values of the diffusion tensor. Fig. 3C presents a differential distribution of a beff matrix (C) for 25 layers (rows) and 6 directions of a diffusion gradient (columns) obtained by using the sBSD-DTI method. These experiments have been executed on a clinical scanner (GE 3T model).

The primary values for water should be uniform and as close as possible in terms of color (Fig. 3A, 3B). The diffusion tensor for water should have identical primary values. In turn, as shown in Fig. 3C, the difference of values of the beff matrix should equal 0 (corresponding to a color from the middle of the colors range). The visible distribution therefore indicates a non-uniformity of gradient fields, which should be taken into account when calculating the values of diffusion coefficients and tensors.

A calibration of a diffusion sequence SE-EPI (Spin Echo - Echo Plannar Imaging) has been performed on a clinical MR tomograph, equipped with a 3T superconductive magnet, by using the method presented herein and a cubic anisotropic phantom having a side length of 5cm formed by thin glass plates of 180um thickness, split with 20um water layers. The experiments have been executed at a temperature T = 21.5^{o}. The following steps were performed.

1. The anisotropic diffusion phantom 101 as described above was located in an MR tomograph equipped with a 3T superconductive magnet, in a the field of influence of an RF head-coil of a birdcage type having a diameter of 30 cm. The tomography measurements have been obtained using an SE-EPI sequence.

2. DTI tomography measurements using SE-EPI, in order to determine a spatial distribution of b matrix for any single direction of diffusion gradient

(DWI), were performed for 3 different positioning arrangements of the anisotropic phantom 101, orthogonal with respect to each other and for one arrangement of the isotropic phantom. In the first arrangement, the anisotropic phantom 101 was rotated with respect to the (x,y,z) axes by (0,0,0) degrees – Fig. 1A, in the second arrangement it was rotated by (90,0,0) degrees – Fig. 1B, and in the third arrangement by (0,0,90) degrees – Fig. 1C.

3. Step 2 was repeated for 6 directions of a diffusion gradient vector.

4. In this manner there were determined spatial distributions of the b matrix, which were subsequently used to measure a diffusion tensor using the sBSD-DTI method.

5. Thus, the precision was improved by 3 times with respect to diffusion tensor calculation for the isotropic phantom 102 (Fig. 3B) with respect to the standard method (Fig. 3A). The improvement is defined as a ratio of standard deviations (SD) of primary values of a diffusion tensor measured with both methods.

6. For water, the SD should be as low as possible.

Fig. 4 presents a system for performing the method described herein. The system may be realized using dedicated components or custom made FPGA or ASIC circuits. The system may comprise a data bus communicatively coupled to a memory 405. Additionally, other components of the system may be communicatively coupled to the system bus so that they may be managed by a calibration controller 401.

The memory 405 may store computer program or programs executed by the controller 401 in order to execute steps of the method described herein.

The calibration controller 401 is configured to access all relevant data previously described as required for the calibration process. These data must be stored in respective memories prior to executing the calibration.

The system comprises an imaging sequence memory 403 configured to store the measurements of NMRI (steps 202, 205). Further, the system comprises a b matrix memory 402 configured to store the b matrix. Further, the system comprises a reference parameters memory 404 configured to store the known values of diffusion tensor for the anisotropic diffusion phantom 101 and the isotropic diffusion phantom 102.

The calibration controller 201 can be configured to output signals indicating that a different positioning arrangement of a phantom or a different phantom is now expected to be placed within the area influenced by the RF coil. Similarly, the calibration controller 201 can be configured to read signals indicating that the aforementioned positioning has been applied and the calibration process may be continued.

The presented system of Fig. 4 can be embedded within or coupled with an MRI tomograph device.

At least parts of the method presented herein may be computer implemented. Accordingly, the method may be implemented by an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a “circuit”, “module” or “system”.

Furthermore, the presented method may be implemented by a computer program product embodied in any tangible medium of expression having computer usable program code embodied in the medium.

It can be easily recognized, by one skilled in the art, that the aforementioned method for calibration of a diffusion imaging in a DMRI-type experiment executed in a MR tomograph, may be performed and/or controlled by one or more computer programs. Such computer programs are typically executed by utilizing the computing resources in a computing device. Applications are stored on a non-transitory medium. An example of a non-transitory medium is a non-volatile memory, for example a flash memory while an example of a volatile memory is RAM. The computer instructions are executed by a processor. These memories are exemplary recording media for storing computer programs comprising computer-executable instructions performing all the steps of the computer-implemented method according the technical concept presented herein.

While the method and system presented herein has been presented, described, and has been defined with reference to particular preferred embodiments, such references and examples of implementation in the foregoing specification do not imply any limitation on the presented system and method. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader scope of the technical concept. The presented preferred embodiments are exemplary only, and are not exhaustive of the scope of the technical concept presented herein.

CLAIMS

1. A method for calibrating a diffusion imaging sequence during a DMRI (Diffusion Magnetic Resonance Imaging) experiment performed in an MR (Magnetic Resonance) tomograph, wherein the experiment comprises calculating diffusion coefficients and/or diffusion tensor coefficients on the basis of a spatial distribution of a b matrix, the method for calibrating comprising the following steps:

- within the field of influence of an RF (Radio Frequency) coil in an examined space of the MR tomograph:
    - providing (201) an anisotropic diffusion phantom (101) with known values of diffusion tensor, the anisotropic diffusion phantom (101) having diffusion limited therein in at least one direction along a first axis of the principal axes of the anisotropic diffusion phantom (101);
    - placing the anisotropic diffusion phantom (101) sequentially in a selected location within the examined space in three different positioning arrangements orthogonal with respect to each other; and
    - placing an isotropic diffusion phantom (102) having a known diffusion tensor in said selected location;
- for each positioning arrangement of the anisotropic diffusion phantom (101) and the isotropic diffusion phantom (102), measuring (202, 205) MR signals;
- determining (203, 206) the values of the b matrix, based on the measured MR signals, for each voxel of a volume comprised inside both the volume of the anisotropic diffusion phantom (101) and the volume of the isotropic diffusion phantom (102); and
- providing (207) the determined spatial distribution of the b matrix as a calibration result for the DMRI sequence for the particular MR tomograph.

2. The method according to claim 1, comprising determining the spatial distribution of the b matrix for different parameters, of the diffusion sequence, selected from a group comprising: values of diffusion gradients, diffusion times, directions of a diffusion gradient vector, amplitude of a diffusion gradient vector.

3. The method according to claim 1 or 2, comprising repeating the calibration in subsequent steps, while assuming, as starting values of the calibration, the spatial distribution of the b matrix provided in a preceding step.

4. The method according to any of previous claims, comprising verifying the spatial distribution of the b matrix by using it to calculate a diffusion tensor for the reference anisotropic phantom and the reference isotropic phantom having known values of the diffusion tensor.

5. The method according to claim 4, wherein in case a standard deviation for a spatial distribution of the diffusion tensor for the reference phantoms exceeds a preferred value, the method further comprises repeating the calibration of the diffusion imaging sequence to further correct the spatial distribution of the b matrix.

6. The method according to any of previous claims, comprising positioning the anisotropic diffusion phantom (101) sequentially in three different orthogonal positioning arrangements with the principal axes of the phantom being in parallel to the principal axes of the laboratory framework.

7. The method according to any of previous claims, comprising determining, for each voxel, three diagonal elements (bxx, byy, bzz) of the b matrix as well as their effective value (beff) calculated as a sum of the three diagonal elements (bxx, byy, bzz), from diffusion imaging experiments executed for three positioning arrangements of the anisotropic diffusion phantom (101) being a reference of the anisotropic diffusion tensor.

8. The method according to claim 7, comprising determining, for each voxel, an effective value of the matrix (beff_iso) from a diffusion imaging experiment performed for the isotropic diffusion phantom (102) being a reference of the isotropic diffusion tensor.

9. The method according to claim 8, comprising normalizing the diagonal values (bxx, byy, bzz) as well as the effective value of the b matrix (beff) obtained from the diffusion imaging experiment performed for the anisotropic diffusion phantom (101), to an effective value of the matrix (beff_iso) from the diffusion imaging experiment performed for the isotropic diffusion phantom (102) being a reference of the isotropic diffusion tensor.

10. The method according to claim 6, comprising determining the non-diagonal values of the b matrix as products of the radices of the diagonal elements.

11. The method according any of previous claims, comprising, for each voxel, using the values of the b matrix calculated for that voxel to determine diffusion coefficients in DWI (Diffusion Weighted Imaging) experiments.

12. The method according any of previous claims, comprising, for each voxel, using the values of the b matrix calculated for this voxel to determine components of a diffusion tensor in DTI (Diffusion Tensor Imaging) experiments.

13. A method for performing an experiment in an MR (Magnetic Resonance) tomograph, comprising calculating diffusion coefficients and/or diffusion tensor coefficients on the basis of the spatial distribution of the b matrix obtained as a result of the calibration according to the method of any of the previous claims.

14. The method according to claim 13, comprising using the spatial distribution of the b matrix obtained as a result of the calibration for any object in the DMRI-type experiment.

15. The method according to claim 13 or 14, comprising performing calibration before every change of parameters of the imaging sequence, in particular before a change of values and directions of diffusion gradient vectors.

16. An MR (Magnetic Resonance) tomograph comprising a configuration controller (401) configured to perform all the steps of the method according to any of previous claims.

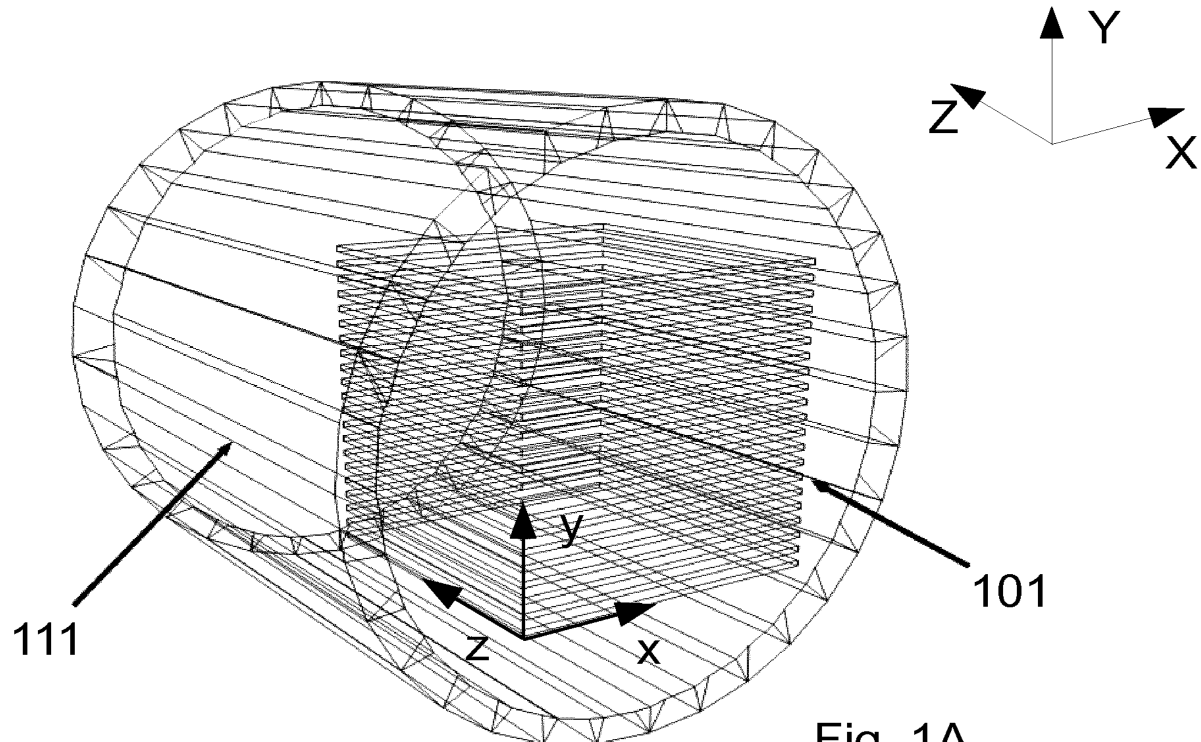

Fig. 1A

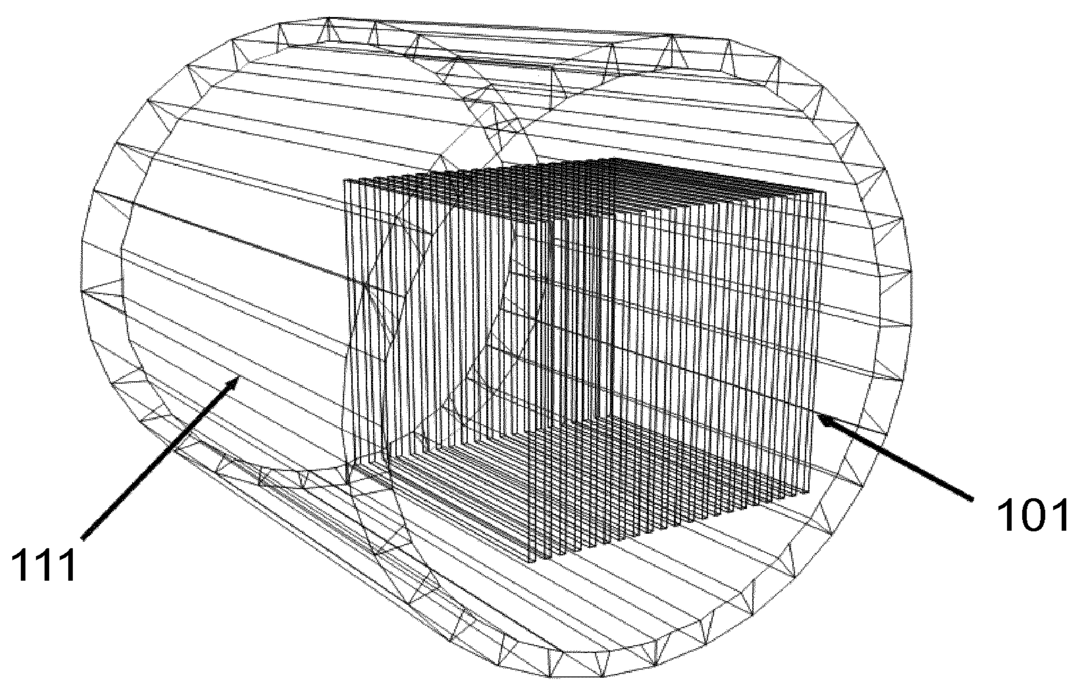

Fig. 1B

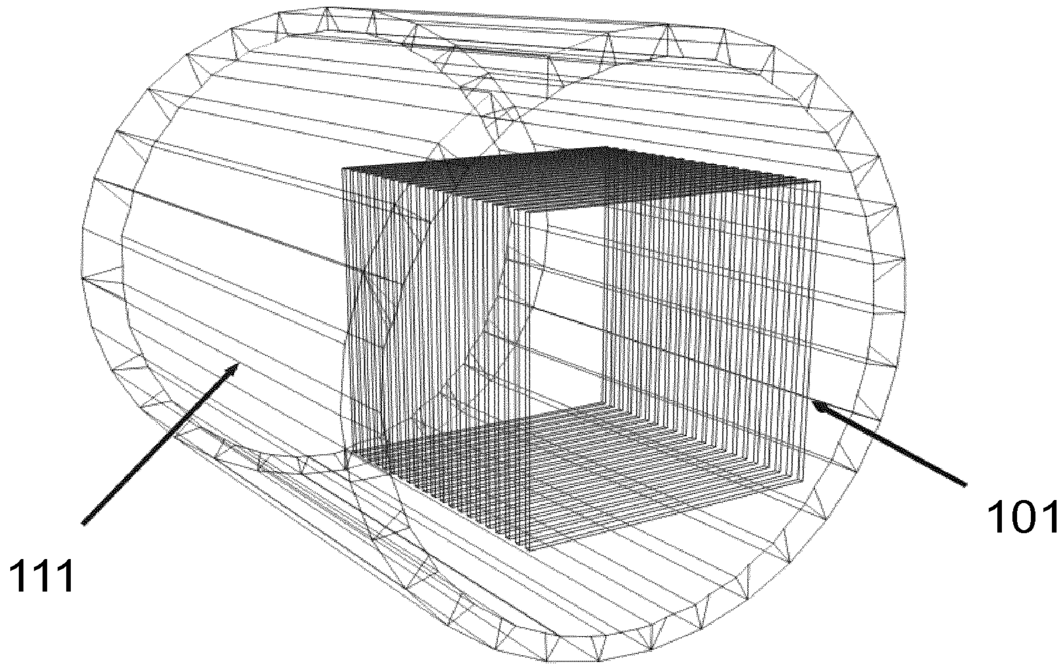

Fig. 1C

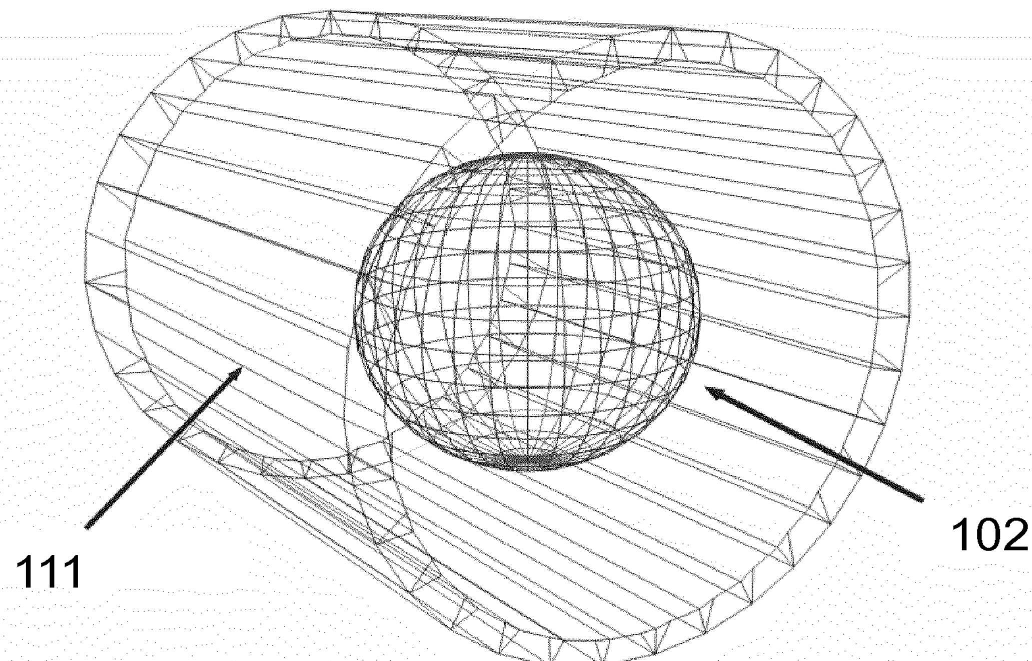

Fig. 1D

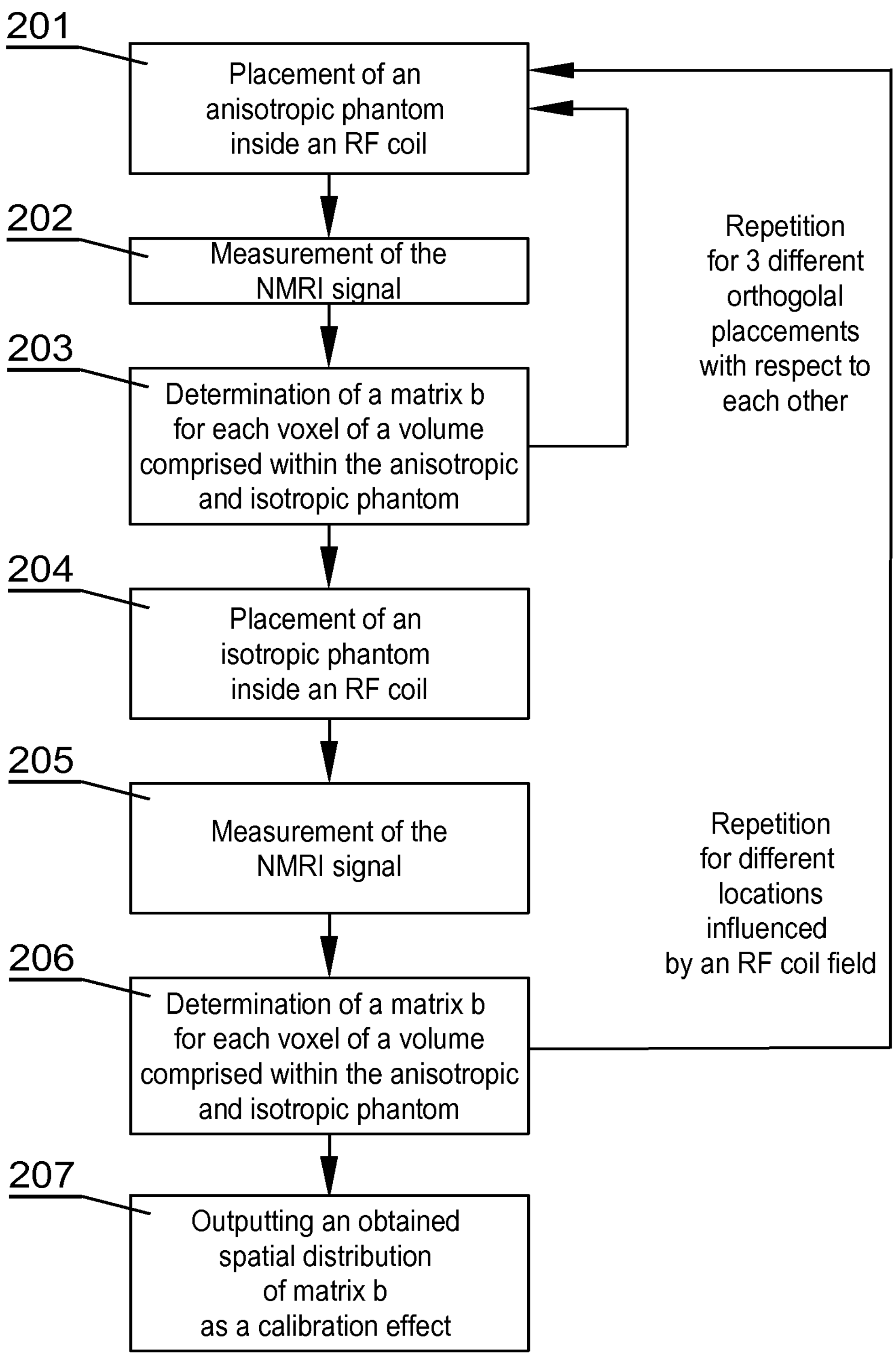
201
Placement of an anisotropic phantom inside an RF coil
202
Measurement of the NMRI signal
203
Determination of a matrix b for each voxel of a volume comprised within the anisotropic and isotropic phantom
204
Placement of an isotropic phantom inside an RF coil
205
Measurement of the NMRI signal
206
Determination of a matrix b for each voxel of a volume comprised within the anisotropic and isotropic phantom
207
Outputting an obtained spatial distribution of matrix b as a calibration effect
Repetition for 3 different orthogolal placcements with respect to each other
Repetition for different locations influenced by an RF coil field

Fig. 2

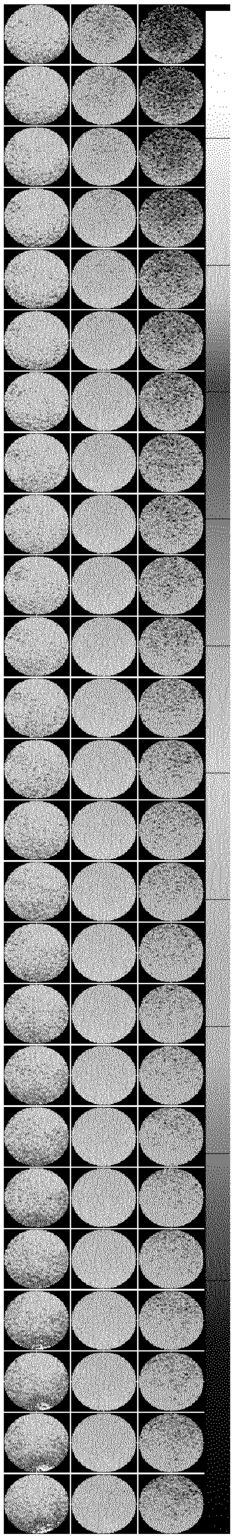

Fig. 3A

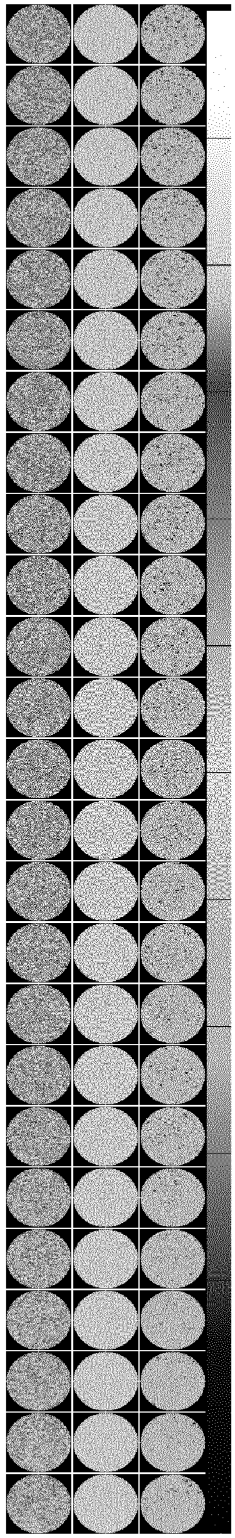

Fig. 3B

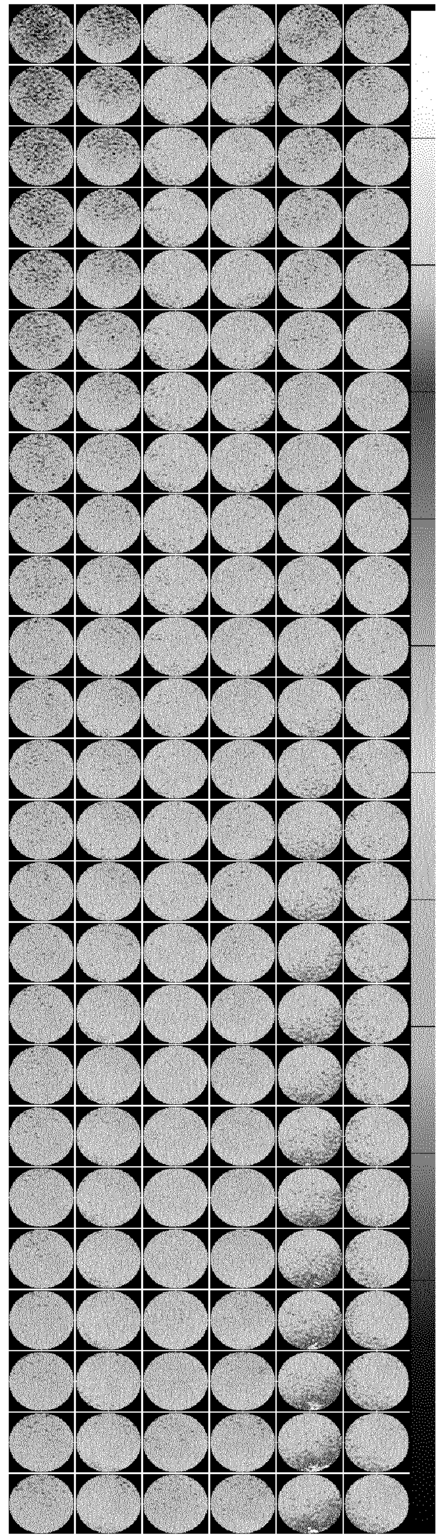

Fig. 3C

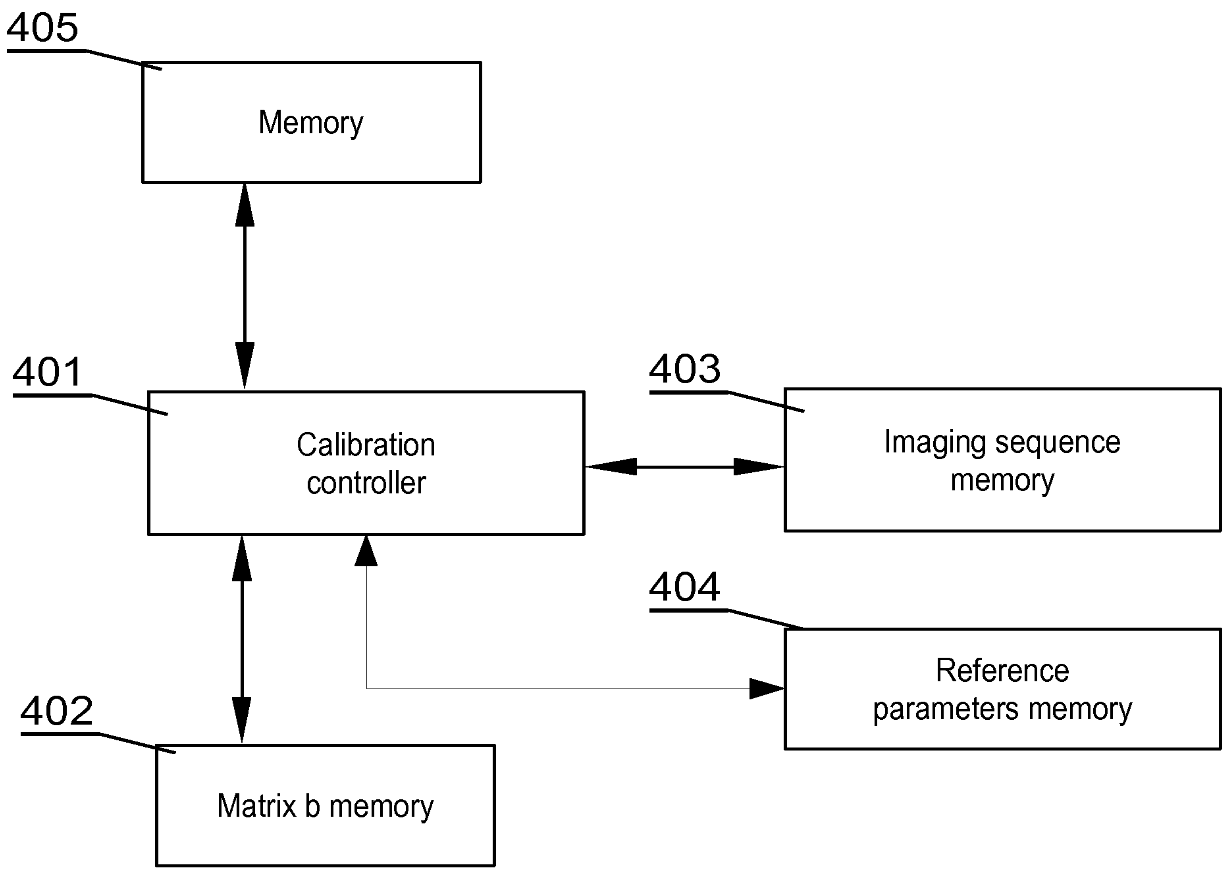
405
Memory
401
Calibration controller
403
Imaging sequence memory
404
Reference parameters memory
402
Matrix b memory

Fig. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/067964

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.
X	ARTUR TADEUSZ KRZYZAK ET AL: "Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix", MAGNETIC RESONANCE IMAGING, vol. 33, no. 3, 7 November 2014 (2014-11-07), pages 286-295, XP055298319, TARRYTOWN, NY, US ISSN: 0730-725X, DOI: 10.1016/j.mri.2014.10.007 cited in the application page 289; figures 3, 5, 6, 8; tables 3-5 -----	1-16
A	US 8 643 369 B2 (KRZYZAK ARTUR [PL]) 4 February 2014 (2014-02-04) cited in the application the whole document -----	1-16

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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
16 November 2016	25/11/2016

Name and mailing address of the ISA/	Authorized officer
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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.
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A	GOVIND NAIR ET AL: "Manifestation and post hoc correction of gradient cross-term artifacts in DTI", MAGNETIC RESONANCE IMAGING, ELSEVIER SCIENCE, TARRYTOWN, NY, US, vol. 30, no. 6, 15 February 2012 (2012-02-15), pages 764-773, XP028513127, ISSN: 0730-725X, DOI: 10.1016/J.MRI.2012.02.021 [retrieved on 2012-03-07] the whole document -----	1-16
A	MATTIELLO J ET AL: "PART II ANALYTICAL CALCULATION OF THE B MATRIX IN DIFFUSION IMAGING", DIFFUSION AND PERFUSION MAGNETIC RESONANCE IMAGING, XX, XX, 1 January 1995 (1995-01-01), pages 77-99, XP001205119, page 87 - page 89 -----	1-16
A	MATTIELLO J ET AL: "The b matrix in diffusion tensor echo-planar imaging", MAGNETIC RESONANCE IN MEDICINE, JOHN WILEY & SONS, INC, US, vol. 37, 1 January 1997 (1997-01-01), pages 292-300, XP002524441, ISSN: 0740-3194, DOI: 10.1002/MRM.1910370226 page 298 - page 299 -----	1-16
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2016/067964

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