Methods and systems for determining a particle distribution by means of electron paramagnetic resonance data

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**SAMENVATTING**

Methods and systems for determining a particle distribution A system (100) for determining a reconstruction of a particle distribution in an object based on electron magnetic resonance (EPR) measurement data of the object comprising the distribution of particles is described. The system (100) comprises a data obtaining means (110) for obtaining electron paramagnetic resonance measurement data of the object under study. The system also comprises a processor (120) for processing the obtained data by applying a numerical model for solving a numerical inverse problem of deriving from the electron paramagnetic resonance measurement data a reconstruction of the particle distribution. The system furthermore comprises an output means (130) for outputting data based on the derived reconstruction of the particle distribution.

**BESCHRIJVING** (OCR-tekst kan fouten bevatten)

**METHODS AND SYSTEMS FOR DETERMINING A PARTICLE DISTRIBUTION BY MEANS OF ELECTRON PARAMAGNETIC RESONANCE DATA**

Field of the invention

The invention relates to the field of electron magnetic resonance. More specifically, the present invention relates to methods and systems for reconstructing particle distribution data in an object based on electron paramagnetic resonance measurement data and computer related aspects based thereon, as well as to an electron magnetic resonance system comprising such a reconstruction system.

Background of the invention

Magnetic nanoparticles are increasingly applied for diagnostic and therapeutic purposes. They show a set of interesting physical properties including controllable sizes ranging from ten to several hundred nanometers, a high saturation magnetization and superparamagnetic behaviour. Their small size enables them to penetrate the endothelial walls that form the interface between circulating blood or lymph and the rest of the vessel wall and even to cross cell membranes. By custom functionalisation of the particles' surfaces, they can selectively bind to a defined biological entity (like cells or degraded extracellular matrix molecules) and deliver drugs or therapeutic DNA for targeted therapy.

By applying a controlled external magnetic field it is possible to perform different actions on the magnetic particles such as applying a mechanic force on the nanoparticles to guide them to a specific location and retaining them there for drug release (magnetic drug targeting, magnetic gene transfection); specifically heating the magnetic nanoparticles (magnetic hyperthermia); changing the local magnetic field in the particle's environment (MRI contrast agents, magnetic cell labelling); generating a specific magnetic signal that can be read from the outside (magnetic nanoparticle imaging); etc. All applications will benefit from a quantitative knowledge of the magnetic nanoparticle distribution to increase suitability, patient safety and efficacy. A non-invasive quantitative technique for magnetic nanoparticle imaging is at present not established, although several proposals have been made in literature. A first suggestion is Magnetic Particle Imaging (MPI) which is able to image the magnetic nanoparticles at very high speed, but is unable to quantitatively determine the concentration of the magnetic nanoparticles. The technique was suggested by Gleich and Weizenecker in Nature 435 (2005) pp 1214-1217. The principle of MPI is based on the nonlinearity of the particles' magnetization curve. When subject to an oscillating

**CLAIMS** (OCR-tekst kan fouten bevatten)

A system (100) for determining a reconstruction of a particle distribution in an object based on electron magnetic resonance (EPR) measurement data of the object comprising the distribution of particles, the system (100) comprising

- a data obtaining means (110) for obtaining electron paramagnetic resonance measurement data of the object under study,

- a processor (120) for processing the obtained data by applying a numerical model for solving a numerical inverse problem of deriving from the electron paramagnetic resonance measurement data a reconstruction of the particle distribution,

- an output means (130) for outputting data based on the derived reconstruction of the particle distribution.

A system (100) according to claim 1, wherein the processing means (120) is adapted for deriving a reconstruction of the particle concentration profile.

A system (100) according to any of the previous claims, wherein the processing means (120) comprises a quality determining means (122) for determining a measure of the quality of the reconstructed particle distribution.

A system (100) according to claim 3, wherein the system (100) furthermore comprises a controlling means (140) for controlling the processing of the obtained data, as function of a determined measure of quality of the reconstructed particle distribution.

A system (100) according to claim 4, herein the controlling means (140) comprises a parameter selection means (150) for selecting a parameter of the numerical model.

A system (100) according to claim 5, wherein the parameter selection means (150) is adapted for altering a set of eigenvalues of the numerical model.

A system (100) according to any of claims 3 to 6, wherein the system (100) comprises a feedback loop comprising the quality determining means (122) and wherein the feedback loop is adapted for controlling the system so as to obtain further electron magnetic resonance measurement data of the object.
magnetic field, the spectrum of the responding magnetization contains not only the base frequency but also higher harmonics that are exploited for imaging.

An alternative is to use magnetorelaxometry measurements as proposed by Flynn and Bryant in Physics in Medicine and Biology 50 (2005) 1273-1293. Magnetic nanoparticles can be activated using an external magnetic field where the single domains of the superparamagnetic nanoparticles are aligned with the local magnetic field. When switching off the external magnetic field, magnetic relaxation occurs following two different relaxation processes (Brown and Neel). The magnetic field originating from the particles in the different positions can be measured using sensitive magnetic field sensors such as superconducting quantum interference devices (SQUIDS).

Electron paramagnetic resonance (EPR) and pulsed EPR detection as described by Teughels and Vaes in International patent application WO2010/037800 developed by Teughels and Vaes is able to sense the concentration of particles. Quantification of the concentration in a single voxel has been reported by Gamarra in International journal of Nanomedicine 5 (2010) pp 203-211. There is still room for an accurate spatial reconstruction of magnetic nanoparticles starting from EPR measurements.

Summary of the invention

It is an object of embodiments of the present invention to provide efficient methods and systems for spatially reconstructing magnetic nanoparticles using Electron Paramagnetic Resonance (EPR) effect measurements.

It is an advantage of embodiments according to the present invention that methods and systems are provided that allow determining the values of concentration of magnetic nanoparticles in different points in space starting from measurements in a single point in space. It is an advantage of embodiment according to the present invention that systems and methods are provided that are based on solving an inverse problem whereby a model interprets in a correct way the concentration distribution, resulting in more accurate particle distribution data obtained.

The object is obtained by systems and methods according to embodiments of the present invention.

The present invention relates to a system for determining a reconstruction of a particle distribution in an object based on electron paramagnetic resonance (EPR) measurement data of the object comprising the distribution of particles, the system comprising a data obtaining means for obtaining electron paramagnetic resonance measurement data of the object under study, a processor for processing the obtained data by applying a numerical model for solving a numerical inverse problem of deriving from the electron paramagnetic resonance measurement data a reconstruction of the particle distribution, an output means for outputting the derived reconstruction of the particle distribution, and a feedback loop for controlling the data obtaining means so as to obtain further EPR measurement data.

A system (100) according to claim 7, the data obtaining means comprises an EPR measurement system (200) for measuring EPR measurement data, wherein the feedback loop is adapted for controlling the EPR measurement system (200) for obtaining further measurement data with an altered measurement condition for the object.

A method (300) for determining a reconstruction of a particle distribution in an object based on electron paramagnetic resonance (EPR) measurement data of the object comprising the distribution of particles, the method (300) comprising

- obtaining (310) electron paramagnetic resonance measurement data of the object under study,
- processing (320) the obtained data by applying a numerical model for solving a numerical inverse problem of deriving from the electron paramagnetic resonance measurement data a reconstruction of the particle distribution, and
- outputting (330) data based on the derived reconstruction of the particle distribution.

13. A method according to claim 12, wherein said processing comprises deriving a reconstruction of the particle concentration profile.

14. A method according to any of claims 12 or 13, the processing comprising determining a measure of the quality of the reconstructed particle distribution.

15. A method according to any of claims 12 to 14, the method comprising controlling the processing of the obtained data, as function of the determined measure of quality of the reconstructed particle distribution.

16. A method according to claim 15, wherein said controlling comprises selecting a parameter of the numerical model.

17. A method according to claim 16, wherein selecting comprises altering a set of eigenvectors of the numerical problem solved using the numerical model, depending on the determined measure of quality of the reconstructed particle distribution.

18. A method according to any of claims 14 to 17, wherein the method comprises obtaining further electron paramagnetic resonance measurement data of the object, based on the determined measure of quality of the reconstructed particle distribution.

19. A method according to claim 18, wherein the method comprises obtaining further measurement data for an altered measurement condition for the object.

20. A method according to any of claims 18 or 19, wherein the method comprises controlling the data obtaining means so as to obtain further EPR measurement data.

21. A method according to claim 20, wherein the method comprises

can be fine-tuned to obtain a predetermined quality so that a minimum quality requirement can be obtained.

The controlling means may comprise a parameter selection means for selecting a parameter of the numerical model. It is an advantage of embodiments according to the present invention that fine-tuning can include adjusting the numerical modeling, thus allowing an internal optimization loop for determining the best reconstruction. The parameter selection means may be adapted for altering a set of eigenvalues of the numerical problem solved using the numerical model, depending on the determined measure of quality of the reconstructed particle distribution. It is an advantage of embodiments according to the present invention that systems allow to implement, e.g. in an automated and/or automatic way although not restricted thereto, improved measurement conditions allowing to obtain an improved reconstruction of the particle distribution. The feedback loop may be adapted for controlling the data obtaining means so as to obtain further EPR measurement data. It is an advantage of embodiments of the present invention that fine-tuning can include adjusting the required measurement input, when the predetermined, e.g. desired, reconstruction quality is not obtained.

The feedback loop may be adapted for controlling the data obtaining means so as to obtain further EPR measurement data of the object sampled at different or additional relative positions of a magnetic field of the EPR system with respect to the object, sampled using different or additional gradient magnetic fields applied to the object, or sampled using a different spatial sampling point distribution over the sample. Different parameters determining the EPR measurement data collection can be tuned for obtaining optimal reconstruction quality.

The present invention relates to a system for obtaining electron paramagnetic resonance data of an object, the system comprising a system for determining a reconstruction of a particle distribution in an object as described above.

The present invention relates to a method for determining a reconstruction of a particle distribution in an object based on electron paramagnetic resonance (EPR) measurement data of the object comprising the distribution of particles, the method comprising obtaining electron paramagnetic resonance measurement data of the object under study, processing the obtained data by applying a numerical model for solving a numerical inverse problem of deriving from the electron paramagnetic resonance measurement data a reconstruction of the particle distribution, and outputting data based on the derived reconstruction of the particle distribution.

Said processing may comprise deriving a reconstruction of the particle concentration profile.

The processing may comprise determining a measure of the quality of the reconstructed particle distribution.

The method may comprise controlling the processing of the obtained data, as function of the determined measure of quality of the reconstructed particle distribution. Said controlling may comprise selecting a parameter of the numerical model.

Selecting may comprise altering a set of eigenvalues of the numerical problem solved using the numerical model, depending on the determined measure of quality of the reconstructed particle distribution.

The method may comprise obtaining further electron paramagnetic resonance measurement data of the object, based on the determined measure of quality of the reconstructed particle distribution.

The method may comprise obtaining further measurement data for an altered measurement condition for the object.

The method may comprise controlling the data obtaining means so as to obtain further EPR measurement data.

The method may comprise obtaining further EPR measurement data of the object sampled at different or additional relative positions of a magnetic field of the EPR system with respect to the object, sampled using different or additional gradient magnetic fields applied to the object, or sampled using a different spatial sampling point distribution over the sample.

The present invention relates to an image or volumetric image obtained using a system as described above or using a method as described above.
The present invention also relates to a computer program product for, if implemented on a processing unit, performing the method as described above.

The present invention also relates to a data carrier comprising a computer program product as described above or the transmission thereof over a network.

Particular and preferred aspects of the invention are set out in the accompanying independent and dependent claims. Features from the dependent claims may be combined with features of the independent claims and with features of other dependent claims as appropriate and not merely as explicitly set out in the claims.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiment(s) described hereinafter. Brief description of the drawings

FIG. 1 shows a schematic representation of an exemplary system according to an embodiment of the present invention.

FIG. 2 illustrates an electron paramagnetic resonance measurement system comprising a distribution reconstruction means as described in FIG. 1.

FIG. 3 illustrates a schematic overview of steps in an exemplary method for reconstructing a particle distribution in an object, according to an embodiment of the present invention.

FIG. 4 illustrates an example of an inverse modeling step as can be applied in a method for reconstructing a particle distribution in an object according to an embodiment of the present invention.

FIG. 5 illustrates assumed concentrations in a volume, as used in simulations illustrating features according to embodiments of the present invention.

FIG. 6 illustrates calibration functions for different concentration values and Field strengths as used in simulations illustrating features according to embodiments of the present invention.

FIG. 7 illustrates examples of a set of different applied gradient fields in one direction, as used for simulations illustrating features according to embodiments of the present invention.

FIG. 8 illustrates a linear net effect is obtained using the calibration functions as shown in FIG. 6.

FIG. 9 illustrates the net effect measurements for certain concentrations using the conditions described in FIG. 5 to FIG. 8.

FIG. 10 illustrates a reconstructed concentration profile, illustrating features of method embodiments according to the present invention.

FIG. 11 illustrates an experimental setup whereby for the example shown movement of the sample was performed along the positive XY-axis, as used in the example illustrating features of embodiments of the present invention.

FIG. 12 illustrates measured response functions for the situation shown in FIG. 11. FIG. 13 illustrates the natural response function, as used in an example illustrating features of embodiments of the present invention.

FIG. 14A to FIG. 14D illustrates a comparison of the performed measurements and the simulated measurements, illustrating features of embodiments of the present invention.

FIG. 15 illustrates the eigenvalue distribution for a measurement resolution of 1 mm and a reconstruction resolution of 1 mm, as used in an example illustrating features of embodiments of the present invention.

FIG. 16 illustrates the influence of noise on the reconstruction quality for the case of 5 retained eigenvalues, illustrating features of embodiments of the present invention. FIG. 17 illustrates responses of a real measurement, simulated measurement without noise and a simulated measurement with noise, illustrating features of embodiments of the present invention.

FIG. 18 illustrates the inclusion of measurements that also consider the insertion and removal of the concentration with respect to the magnetic field, illustrating features of embodiments of the present invention.

FIG. 19 illustrates the effect of the inclusion of measurements according to FIG. 14 on the eigenvalue distribution.

FIG. 20 illustrates the effect of the response function used on the reconstructed concentration profile, illustrating features of embodiments of the present invention. The drawings are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes.

Any reference signs in the claims shall not be construed as limiting the scope.

In the different drawings, the same reference signs refer to the same or analogous elements.

Detailed description of illustrative embodiments

The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes. The dimensions and the relative dimensions do not correspond to actual reductions to practice of the invention.
manner. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the
embodiments of the invention described herein are capable of operation in other sequences than described or illustrated
herein.

Moreover, the terms top, under and the like in the description and the claims are used for descriptive purposes and not
necessarily for describing relative positions. It is to be understood that the terms so used are interchangeable under
appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other
orientations than described or illustrated herein.

It is to be noticed that the term "comprising", used in the claims, should not be interpreted as being restricted to the means
listed thereafter; it does not exclude other elements or steps. It is thus to be interpreted as specifying the presence of the
stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or
more other features, integers, steps or components, or groups thereof. Thus, the scope of the expression "a device
comprising means A and B" should not be limited to devices consisting only of components A and B. It means that with
respect to the present invention, the only relevant components of the device are A and B.

Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure
or characteristic described in connection with the embodiment is included in at least one embodiment of the present
invention. Thus, appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this
specification are not necessarily all referring to the same embodiment, but may. Furthermore, the particular features,
structures or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the
art from this disclosure, in one or more embodiments.

Similarly it should be appreciated that in the description of exemplary embodiments of the invention, various features of
the invention are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of
streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method
of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features
than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all
features of a single foregoing disclosed embodiment. Thus, the claims following the detailed description are hereby
expressly incorporated into this detailed description, with each claim standing on its own as a separate embodiment of this
invention.

Furthermore, while some embodiments described herein include some but not other features included in other
embodiments, combinations of features of different embodiments are meant to be within the scope of the invention, and
form different embodiments, as would be understood by those in the art. For example, in the following claims, any of the
claimed embodiments can be used in any combination.

In the description provided herein, numerous specific details are set forth.

However, it is understood that embodiments of the invention may be practiced without these specific details. In other
instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an
understanding of this description.

In embodiments of the present invention, methods and system are provided for gathering information about an object
under test that includes particles presenting paramagnetic properties. These particles may be introduced in any suitable
way such as for example by administering, by mixing, by pouring, etc. More particularly, the information gathered is based
on or related to the distribution of the particles representing paramagnetic properties in the object. Particles comprising
paramagnetic properties may be nano-particles, typically referring to particles having a critical dimension, e.g. diameter, in
the range of 1 nm to 1000 nm. The nano-particles or magnetic nano-particles may be single domain particles. The
particles may be magnetic particles with a broad line width, reference may be made to a line width of 3MHz or larger, e.g.
in a range from 3MHz to 400MHz. Reference may be made to particles having a line width, e.g. a full width at half
maximum FWHM, larger than 5%, e.g. larger than 10%, e.g. larger than 20% of the central line frequency. It is to be
noticed that embodiments of the present invention can be advantageously applied to spin systems with a broad line width,
although embodiments of the present invention are not limited thereto and can be applied to spin systems with any line
width, i.e. including spin systems with narrow line width.

Where in embodiments according to the present invention reference is made to an object under study, such an object may
be a non-living object or a living object. In some embodiments - the present invention not being limited thereto - the object
may be a body of a living creature, such as for example an animal or human body. The object under study according to
embodiments of the present invention are paramagnetic objects. Embodiments of the present invention can also be used
for in-vitro testing, e.g. for the quantification of cells linked with the paramagnetic objects). Embodiments of the invention
allow to reconstruct the distribution of the paramagnetic objects with a high sensitivity and accuracy. Examples of
applications include 3D imaging. Objects under study may be paramagnetic objects as of nature or may be made at least
partially paramagnetic by adding, e.g. through administering, paramagnetic particles, such as paramagnetic nanoparticles,
to the object. The administering step may be performed prior to application of the method according to embodiments of
the present invention for detecting electron paramagnetic resonance of the object under study.

In a first aspect, the present invention relates to a system for reconstructing or determining a reconstruction of a particle
distribution in an object. Such determining is based on electron paramagnetic resonance (EPR) measurement data of the
object comprising the distribution of particles. Embodiments according to the present invention can be used for all types of
electron paramagnetic resonance (EPR) detection, such as for example for detecting paramagnetic particles with broad


According to one aspect of the present invention, the invention also relates to an EPR system comprising a reconstruction embodiment comprises in a first step obtaining 310 electron paramagnetic resonance measurement data of the object under study. Such a data obtaining means may be an input port via which previously recorded electron paramagnetic resonance measurement data is received. Alternatively, such a data obtaining means may include an electron paramagnetic resonance system for recording the measurement data. The measurement data as such may be data recorded through any suitable measurement technique. One example are the measurement techniques as described in the international patent applications WO 2010/037800 and/or in international patent application WO 2010/037801, or in particular techniques as described e.g. in international patent application PCT/EP2012/055042 or in GB patent application GB1104758.6.

The system furthermore comprises a processing means 120. As described above, such a processing means typically may be adapted for processing the obtained data by applying a numerical model for solving a numerical inverse problem of deriving from the electron paramagnetic resonance measurement data a reconstruction of the particle distribution. One example of an implementation of such a numerical model will be described later. Nevertheless, embodiments are not limited thereto. In general the numerical modeling technique comprises input parameter values and output values. In the present examples, the input typically is the particle distribution, while the output of the system are the simulated signals in the sensors. The numerical inverse problem comprises using this numerical modeling so to determine the parameter values that correspond with the measured signals. According to one embodiment, the processing means comprises a quality determining means 122, allowing to determine a measure of the quality of the reconstructed particle distribution. Quality may e.g. express the way the reconstruction coincides or approaches the measurements.

In some embodiments, the reconstruction system 100 also comprises a controlling means for controlling the processing of the obtained data as function of the determined measure of quality of the reconstruction. Such a controlling may be adapted for controlling the processor, e.g. by adjusting the numerical modeling. One way of adjusting the numerical modeling may be by selecting different numerical modeling parameters and the processor therefore may be equipped with a parameter selecting means. Selection of different numerical modeling parameters may be performed based on predetermined algorithms, a neural network, look up tables, according to predetermined rules, etc. One example of adjusting may be selecting the number or the specific set of eigenvalues used in the problem to be solved. For example, when the quality is insufficient, the number of eigenvalues used may be increased or decreased to deal therewith. Other examples of rules that can be implemented may make use of the condition where the difference between measured and simulated signals is smaller than a certain tolerance or if the difference between the particle distribution in a certain iteration compared to the previous one is smaller than a certain tolerance. The difference can in one example be expressed as a least-squares difference (L2-norm), another norm, correlation coefficients, etc.

In another embodiment, the system comprises a feedback loop, and controlling the system as function of the quality does not only affect the reconstruction process as such, but also the measurement data used. In other words, the control system may be adapted for controlling the processor so as to obtain further electron paramagnetic resonance measurement data of the object. Such further electron paramagnetic resonance measurement data may for example comprise measurement data recorded with an altered measurement condition for the object. Such measurement data may be for example data sampled at different or additional relative positions of a magnetic field of the EPR system with respect to the object, sampled using different or additional gradient magnetic fields applied to the object, or sampled using a different spatial sampling point distribution over the sample.

According to one aspect of the present invention, the invention also relates to an EPR system comprising a reconstruction system as described above. The EPR system as such may for example be a system as described in any of the international patent applications WO 2010/037800 and/or in international patent application WO 2010/037801, or in particular techniques as described e.g. in international patent application PCT/EP2012/055042 or in GB patent application GB1104758.6.

In another aspect, embodiments of the present invention relate to a method for reconstructing or determining a reconstruction of a particle distribution in an object based on electron paramagnetic resonance (EPR) measurement data of the object. The reconstructed distribution may be or provide a concentration profile of the particles in the object. The particle distribution envisaged thereby is a distribution of particles comprising paramagnetic properties, as described above. Different steps of a method according to an embodiment of the present invention are further illustrated with reference to FIG. 3. In one embodiment of the present invention not being limited thereby. The method according to an embodiment comprises in a first step obtaining 310 electron paramagnetic resonance measurement data of the object under study. Such obtaining data may comprise merely receiving the data via an input port. Alternatively, obtaining the data may include performing the electron paramagnetic resonance measurements and receiving the data thereof in the reconstruction system. The method also comprises processing 320 the obtained data by applying a numerical model for solving a numerical inverse problem of deriving from the electron paramagnetic resonance measurement data a reconstruction of the particle distribution.

whereby based on the measurement data obtained a concentration is derived. A theoretical description of how such
inverse model can be solved will be described later. Furthermore, besides performing the inverse reconstruction, typically
also a so-called forward model is applied, whereby starting from a determined concentration, the estimated measurement
results are derived. Such forward calculation, which needs to include information regarding the measurement conditions,
can for the present case relate to deriving concentrations based on performed EPR measurements.

The method furthermore comprises outputting 330 data based on the derived reconstruction of the particle distribution.
The method may be implemented such that it operates automated and/or automatic. It may be implemented in a processor
and may be based on predetermined algorithms, using predetermined rules and/or look up tables, make use of a neural
network for its processing, ....

It is an advantage of at least some embodiments of the present invention that the quality of the reconstruction can be
monitored. In some embodiments, the quality (or a measure/metric expressing the quality) of the reconstruction is not only
monitored, but it is also tuned to reach a predetermined value, so that an accurate interpretation of the results obtained
can be envisaged. When the required or envisaged quality is not obtained by the reconstruction, different actions are
possible.

In some embodiments, an internal feedback loop is installed and the quality can be improved or optimized by altering the
processing of the obtained data. The latter may include using a certain numerical model, altering the numerical model
used, e.g. by altering a set of eigenvalues of the numerical problem solved using the numerical model, etc. In some
embodiments, if the envisaged quality is not obtained, further electron paramagnetic resonance measurement data of the
object are obtained or used. The method then may comprise obtaining further measurement data for an altered
measurement condition for the object. Obtaining such further EPR measurement data thereby may for example comprise
obtaining further EPR measurement data of the object sampled at different or additional relative positions of a magnetic
field of the EPR system with respect to the object, sampled using different or additional gradient magnetic fields applied to
the object, or sampled using a different spatial sampling point distribution over the sample.

Other features and optional steps may correspond with the functionality of components described with reference to
systems for reconstructing particle distribution based on electron paramagnetic resonance measurements, as described.

In one aspect, embodiments of the present invention also relate to computer-implemented methods for performing at least
part of the methods as described above or to corresponding computing program products. Such methods may be
implemented in a computing system, such as for example a general purpose computer. The computing system may
comprise an input means for receiving data. The system may be or comprise a data processor for processing data, e.g.
the electron paramagnetic resonance data of the single domain particles. The computing system may include a processor,
a memory system including for example ROM or RAM, an output system such as for example a CD-rom or DVD drive or
means for outputting information over a network. Conventional computer components such as for example a keyboard,
display, pointing device, input and output ports, etc also may be included. Data transport may be provided based on data
busses. The memory of the computing system may comprise a set of instructions, which, when implemented on the
computing system, result in implementation of part or all of the standard steps of the methods as set out above and
optionally of the optional steps as set out above. Therefore, a computing system including instructions for implementing
part or all of a method as described above is not part of the prior art. Further aspect of embodiments of the present
invention encompass computer program products embodied in a carrier medium carrying machine readable code for
execution on a computing device, the computer program products as such as well as the data carrier such as dvd or cd-
rom or memory device. Aspects of embodiments furthermore encompass the transmitting of a computer program product
over a network, such as for example a local network or a wide area network, as well as the transmission signals

While the above detailed description has shown, described, and pointed out novel features of the invention as applied to
various embodiments, it will be understood that various omissions, substitutions, and changes in the form and details of
the device or process illustrated may be made by those skilled in the technology without departing from the spirit of the
invention.

As indicated, without wishing to be bounded by theory, the fact that the numerical inverse problem can be solved using a
numerical model can be seen based on the theoretical considerations given below.

The gathering of information regarding the magnetic nanoparticles and its translation into a numerical problem typically
includes the following:

(i) Measurement associated to single voxels with fixed concentration in different points in space.
(ii) Use of a 'system matrix' A that links the magnetic nanoparticles concentration in a certain point in space to the
measurement. A is based on (i).
(iii) It is possible to build the matrix A, e.g. by moving the sample or by exciting the internal state of the sample through the
use of gradients.
(iv) Synthesis of concentrations in different points in space using vector C, and synthesis of different measurements in
vector V. Typically, the following relationship can be derived:

\[ V_m = A \, C \]

wherein \( V_m \) denotes the modeled responses. (v) Starting from the measured responses \( V_{meas} \), the intention is then to
C*=A' V_recon

(vi) The reconstruction (iv) is possible by performing an inversion based on the singular value decomposition (SVD) of the matrix A: A=USV^T. The reconstructed concentrations in each voxel are given by

\[ C^* = \sum_{k=1}^{N} \frac{V_{recon}}{S_k} S_k \]

with singular values S_k (from matrix A) and U_k, k the eigenvectors in the matrices U,V. As is illustrated in embodiments of the present invention the accuracy of the reconstruction can be further optimized by a good, improved or optimal choice of the parameter r in the above formula and a good, improved or optimal system matrix choice A. It is to be noted that there exist a number of different methods for obtaining C*.

In application of embodiments according to the present invention, gradient fields can be used for 'spatially encoding' the volume using a magnetic field H(r) that is spatially dependent (r = (x,y,z)). Using the applied magnetic field B(r) = \mu_0 H(r), the volume under study has a magnetization M(r). In the most general way, the measured signal S can be expressed as (superposition):

\[ S \cdot \int F(B(r), n, C(r)) dV \]

v

where F is basically determined by the 2\textsuperscript{nd}Effect(\theta'), measurement angle and the concentration, n is the sensitive axis of the sensor. In the case of homogeneous activation and 1-voxel quantification, one has

\[ S \cdot \int F(B_{hom}, C_{hom}) dV = V \cdot F(B_{hom}, C_{hom}) \]

v

with V the volume of the sample, B_{hom}, hom defined for the single voxel. It is proximated that the function F will also hold when using multiple voxels.

When discretizing the volume, (1) becomes:

\[ N \sum_{n=1}^{N} S \cdot \int F(L_n, C_n) dV \]

\[ (3) \]

k=1 with L_k the value of f(r)\cdot w within that voxel and AV^h the volume of each voxel (can be chosen the same for each voxel using regular grid). In at least some embodiments, the aim is to reconstruct C_k by using fields, i.e. L_k different from each other, and multiple measurements.

By using multiple activations (i=1,...,N, with total activations N_a), it is possible to generate different L_k because of the spatially (and directional) varying magnetic fields. Different possibilities exist to generate spatially varying magnetic fields.

A first possibility is to use a gradient coil configuration, i.e. instead of using Helmholtz coils, coils can be placed as Maxwell coils.

Each signal is then represented by

\[ N \sum_{n=1}^{N} S \cdot \int F(L_n, C_n) dV \]

\[ (4) \]

Starting from the 5, measurements one aims to reconstruct G. By way of illustration, embodiments of the present invention not being limited thereto, exemplary results are shown, illustrating features and advantages as can be used in embodiments or the present invention.

In a first example, illustrating numerical results, it is assumed that there is a certain test concentration that fluctuates ID (x-direction). If there is for example a volume of 20.4x12x16.8 mm, one wants to reconstruct the particles along the 20.4 side.

FIG. 5 illustrates two test concentrations that were used in the simulations. The concentration thereby is defined here as the concentration in a volume 1x12x16.8 mm^3.

In the present example, use is also made of the following calibration function f(B,C), which is function of the applied magnetic induction B and the concentration C whereby use is made of interpolation for continuous B and C values.

For the quantitative imaging, the following set of spatially varying magnetic fields is applied. FIG. 7 illustrates an example of 10 spatially varying applied magnetic inductions that are sequentially applied by using a gradient magnetic field of -10mT to 10mT over the region of 20mm, yielding gradient of 1T/m, and where a Helmholtz homogeneous field is applied with steps of 2.2mT. These 10 sequential gradient fields are necessary so to obtain different measurements for the reconstruction of the magnetic nanoparticles.

Using a method according to an embodiment of the present invention, the inverse solver used, uses the following assumption: the calibration function is linear with respect to the concentration: f(B,C) = n(B/C). This is approximately the
relationship of the calibration function with respect to B. It is to be noticed that it is possible to deal with nonlinearities in the calibration function. When applying the 10 gradient activations of Fig. 7 for the test concentration in Fig. 5 (above) and with calibration function of Fig. 6, we obtain the following net effect measurements.

Starting from these numerical ‘measurements’, the distribution of the concentration reconstructed using the inverse solver is shown in Fig. 10. These results were obtained without incorporating the accurate magnetic induction variation (variation on the idealized magnetic induction shown in Fig. 7) so to have a more accurate forward solver. This will increase the accuracy of the inverse problem. So, theoretically, with assumptions and simple representations of magnetic fields, the present example illustrates that the methods are able to spatially reconstruct the distribution of magnetic nanoparticle concentrations in EPR.

In a second example, results are illustrated using EPR measurements. First the response function and forward model is described. A one dimensional reconstruction through screening was performed, i.e. the sample is moved in the vicinity of the excitation and measurement coils. The response function vs position was measured. Measurements of Resovist 18.8 (18.8 μM), Resovist J (0.29 μM), Resovist K (0.15 μM) and Resovist L (0.07 μM) (shielded, results of 11 averaged measurements) were used to obtain the response function. The measurements were performed for the positive XY-axis with a discretization of 1 mm, as shown in FIG. 11. The response function was measured (i.e. measurements at different points in EPR) for the 4 different samples described above. The measured response functions are shown in FIG. 12. Using the response function from the previous example, a forward model was developed. First the response function was extended to a ‘natural response function’, with a discretization ΔN of 0.1 mm, using splines, as shown in FIG. 13.

The forward model used in the present example is based on the above response functions. As an example, FIG. 14A to FIG. 14D shows measurements that are sensitive to the distribution of particles. We observe correspondence between the forward model and the real measurements of the different particles. The discrepancy between forward and real measurements is here mainly because of noise and changes in the system (for example temperature).

In a following step of the description of the experiment, the screening is discussed. Using measurements it is possible to reconstruct the spatial variation of the magnetic nanoparticles. Inversion of the system matrix is performed. The results shown here are for a reconstruction resolution of 1 mm. This means that if one has two magnetic nanoparticle sources, with a certain concentration and separated by a distance of 1 mm, these sources should be reconstructed with their respective concentrations. FIG. 15 shows the distribution of the eigenvalues for the Leadfield matrix L used. These eigenvalues represent the sensitivities of the response function for a measurement resolution of 1 mm and a reconstruction resolution of 1 mm. In total there are 19 eigenvalues. The eigenvalue distribution is dependent on the reconstruction and measurement resolution.

In the following section, the handling of eigenvalues will be discussed in some more detail, including an advantageous embodiment of the present invention whereby selection of the optimal eigenvalues is based on the processing according to an embodiment of the present invention. The selection of the optimal eigenvalue distribution can be obtained by proposing an internal optimization loop that determines numerically the best eigenvalues that give the best reconstruction quality. To investigate the influence of a measurement error on the reconstruction, the correlation coefficient for different concentrations using different noise levels were compared. The obtained construction result is dependent on the number of used eigenvalues. For lower noise levels, one should use more eigenvalues. The latter can be explained by the fact that in this case most eigenvalues represent signal sources instead of noise sources.

In FIG. 16, a big decrease in reconstruction quality can be seen when increasing the noise to 10%. When more eigenvalues are retained the decrease is even steeper. After the noise level of 10% a more gradual decrease of the reconstruction quality is noticed. The noise level should be as low as possible, preferably below 5 - 10%. The reconstruction scores are the result of 50 averaged simulations.

The differences between the results of the forward model and the real measurements were also compared, allowing to investigate what the error will be in the reconstruction, when a certain difference is present between the measured and simulated measurements. FIG. 17 shows an example of a measurement, a simulated measurement without noise and a simulated measurement with noise and the corresponding reconstructions. The differences between the responses cause errors on the reconstructions.

Further, also the impact of the leadfield matrix was discussed. A first used Leadfield matrix only considered the concentration distribution inside the magnetic field (meaning that for every element of the concentration distribution there exists a corresponding response function value). Initially a low condition number was obtained for the Leadfield matrix, however due to changes of the response function (more measurements) this condition number became higher. The condition number should be as low as possible, as a condition number shows the extent to which a calculated value (in our case the reconstruction) will change, when fixed parameters are changed (our Leadfield matrix). A high condition number means a big difference in reconstruction values for only a small change of the Leadfield values. This means that a response function with a small error, will have a major effect on the reconstruction. The Leadfield matrix was therefore extended with more measurements. These measurements also consider the insertion and removal of the concentration with respect to the magnetic field, as indicated in FIG. 18. This means rows are added that contain zeros (concentration elements that are on a position where there is no response anymore). Surprisingly, the zeros did not cause a higher noise sensitivity of the Leadfield matrix (i.e. the newly added measurements did not contain mostly noise and did add more information for the reconstruction step). Extending the Leadfield Matrix resulted in a different eigenvalue distribution.

FIG. 19 shows the (normalized) eigenvalues.

Finally, also the reconstruction results are discussed in some more detail. The above experiment illustrates that, using the
concentration distribution. The accuracy depends on the used response function (that varies due to different temperature).

An overview of the obtained results for different response functions is given in FIG. 20.

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