(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
17 November 2016 (17.11.2016)

WIPO | PCT

(10) International Publication Number
WO 2016/180983 Al

(51) International Patent Classification:
G01R 33/48 (2006.01) *G01R 33/565* (2006.01) *G01R 33/561* (2006.01)

(21) International Application Number: PCT/EP20 16/060920

(22) International Filing Date: 13 May 2016 (13.05.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
15 167590.7 13 May 2015 (13.05.2015) EP

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available):* AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available):* ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) Title: MULTI-ECHO MRI WITH CORRECTION OF CONCOMITANT GRADIENT-INDUCED PHASE ERRORS

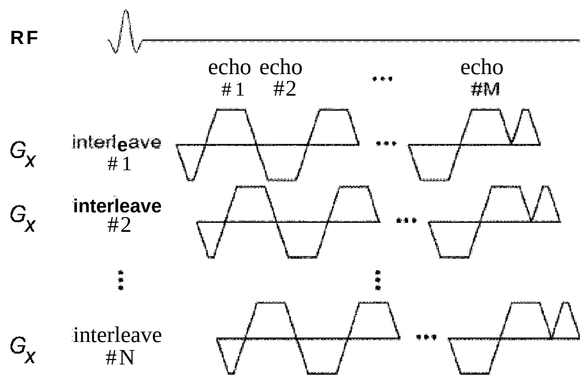

Fig. 2

(57) Abstract: The invention relates to a method of MR imaging of an object placed in an examination volume of a MR device (1). It is an object of the invention to provide a multi echo imaging technique that avoids artifacts and/or errors due the concomitant gradient- induced phase error effect. The method of the invention comprises the steps of: a) generating echo signals at different echo times by subjecting the object to a multi-echo imaging sequence of at least one RF pulse and switched magnetic field gradients; b) acquiring the echo signals; c) correcting the acquired echo signals for concomitant gradient-induced phase errors, which comprises: reconstructing a complex MR image for each echo time from the echo signals generated at this echo time; computing the accumulated concomitant gradient-induced phase error for each echo time and for each image position from the gradient waveforms of the imaging sequence; and - applying a phase correction to each voxel of each of the MR images according to the computed accumulated concomitant gradient-induced phase error for the respective echo time and image position. Moreover, the invention relates to a MR device (1) and to a computer program to be run on a MR device (1).

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MULTI-ECHO MRI WITH CORRECTION OF CONCOMITANT GRADIENT-INDUCED PHASE ERRORS

FIELD OF THE INVENTION

The invention relates to the field of magnetic resonance (MR) imaging. It concerns a method of MR imaging of a portion of a body placed in the examination volume of a MR device. The invention also relates to a MR device and to a computer program to be run on a MR device.

BACKGROUND OF THE INVENTION

Image-forming MR methods which utilize the interaction between magnetic fields and nuclear spins in order to form two-dimensional or three-dimensional images are widely used nowadays, notably in the field of medical diagnostics, because for the imaging of soft tissue they are superior to other imaging methods in many respects, do not require ionizing radiation and are usually not invasive.

According to the MR method in general, the body of the patient to be examined is arranged in a strong, uniform magnetic field B_0 whose direction at the same time defines an axis (normally the z-axis) of the co-ordinate system on which the measurement is based. The magnetic field B_0 produces different energy levels for the individual nuclear spins in dependence on the magnetic field strength which can be excited (spin resonance) by application of an electromagnetic alternating field (RF field) of defined frequency (so-called Larmor frequency, or MR frequency). From a macroscopic point of view the distribution of the individual nuclear spins produces an overall magnetization which can be deflected out of the state of equilibrium by application of an electromagnetic pulse of appropriate frequency (RF pulse), so that the magnetization performs a precessional motion about the z-axis. The precessional motion describes a surface of a cone whose angle of aperture is referred to as flip angle. The magnitude of the flip angle is dependent on the strength and the duration of the applied electromagnetic pulse. In the case of a so-called 90° pulse, the spins are deflected from the z axis to the transverse plane (flip angle 90°).

After termination of the RF pulse, the magnetization relaxes back to the original state of equilibrium, in which the magnetization in the z direction is built up again with a first time constant T_1 (spin lattice or longitudinal relaxation time), and the magnetization in the direction perpendicular to the z direction relaxes with a second time constant T_2 (spin-spin or transverse relaxation time). The variation of the magnetization can be detected by means of receiving RF coils which are arranged and oriented within an examination volume of the MR device in such a manner that the variation of the magnetization is measured in the direction perpendicular to the z-axis. The decay of the transverse magnetization is accompanied, after application of, for example, a 90° pulse, by a transition of the nuclear spins (induced by local magnetic field inhomogeneities) from an ordered state with the same phase to a state in which all phase angles are uniformly distributed (dephasing). The dephasing can be compensated by means of a refocusing pulse (for example a 180° pulse). This produces an echo signal (spin echo) in the receiving coils.

In order to realize spatial resolution in the body, constant magnetic field gradients extending along the three main axes are superposed on the uniform magnetic field B_0, leading to a linear spatial dependency of the spin resonance frequency. The signal picked up in the receiving coils then contains components of different frequencies which can be associated with different locations in the body. The signal data obtained via the receiving coils correspond to the spatial frequency domain and are called k-space data. The k-space data usually include multiple lines acquired with different phase encoding. Each line is digitized by collecting a number of samples. A set of k-space data is converted to an MR image by means of Fourier transformation.

So-called gradient echoes can be generated by using pairs of switched magnetic field gradients of opposed polarity. In this case, there is no refocusing 180° pulse. The signal data are acquired during a gradient echo which is generated by dephasing the transverse magnetization with a gradient magnetic field before it is re-phased by a gradient magnetic field of opposite polarity to generate the echo.

The so-called concomitant gradients (sometimes also referred to as 'accompanying gradients' or 'Maxwell field gradients') refer to the gradients of the magnetic field that are perpendicular to the direction of the static magnetic field. They are generated concurrently with the applied magnetic field gradients as a consequence of Maxwell's equations. The concomitant field gradients induce a phase in the excited transverse nuclear magnetization varying both in space and time, known as the concomitant field phase. As known from US 6,229,309 Bl, the concomitant field phase should be corrected or compensated to avoid a number of artifacts in the reconstructed MR images including blurring, shading and geometric distortion.

In MR imaging, it is often desired to obtain information about the relative contribution of different chemical species, such as water and fat, to the overall signal, either to suppress the contribution of some of them or to separately or jointly analyze the contribution of all of them. These contributions can be calculated if information from two or more corresponding echoes, acquired at different echo times, is combined. This may be considered as chemical shift encoding, in which an additional dimension, the chemical shift dimension, is defined and encoded by acquiring two or more echoes at different echo times. In particular when applied to the separation of the contributions of water and fat to the overall signal, these types of experiments are often referred to as Dixon-type of measurements. In general such a separation is possible because there is a known precessional frequency difference of hydrogen in fat and water.

In the known Dixon-type water/fat imaging methods, multiple MR images are acquired at different echo times, wherein each echo signal is conventionally collected in a separate sequence repetition. This increases the minimum scan times by a factor corresponding to the number of different echo time values. In more recent implementations, all echo signals are acquired in a single sequence repetition, i.e. after a single excitation, by using appropriate multi gradient echo imaging sequences, thereby significantly reducing the required scan times. So-called 'unipolar' imaging sequences may be applied to acquire all echo signals using the same magnetic field gradient polarity during signal acquisition. This mostly (but not always) ensures phase consistency among the echo signals. Alternatively, so-called 'bipolar' imaging sequences may be applied in which the echo signals are collected during both positive and negative magnetic field gradient polarities. This has several advantages. On the one hand, the so-called 'fly-back' magnetic field gradients between the echo signal acquisitions can be dispensed with which improves the signal-to-noise ratio (SNR) efficiency and the minimum echo spacing (echo time increment) can be reduced, whereby the spectral bandwidth in which water/fat can be unambiguously determined is increased.

The complex echo signals acquired in multi echo scans can be used not only for water/fat separation but also for separation of other chemical species as well as in a number of other quantitative imaging applications, e.g. to extract T_2* relaxation properties or to measure temperature. The extraction of quantitative parameters typically relies on the analysis of the complex multi-echo gradient echo data based on a signal model.

It is known that any relevant phase errors occurring with multi gradient echo imaging sequences must be taken into account in such applications, because such phase errors disturb the phase consistency between the individual echo signals and thus have an adverse effect on the result of the data analysis.

Various strategies have been proposed to minimize the effect of phase errors in multi echo acquisitions. Among them is the approach of performing a correction of the acquired echo signals based on additional calibration measurements acquiring data with opposite frequency encoding gradient polarities. However, performing an additional calibration measurement to estimate and correct the phase errors requires extra scan time, especially since the phase errors are spatially varying. Moreover, the commonly applied calibration measurements generally do not address concomitant field phase effects because (among other reasons) these effects do not depend on magnetic field gradient polarities.

Multi echo imaging can be performed either by acquiring all echoes in a single repetition of the basic imaging sequence (single interleaf) or by acquiring the echoes in multiple repetitions (time-interleaved). Time-interleaved multi echo imaging can remove the constraints of single-interleaf multi echo imaging in the selection of the desired echo time increment. Given that the frequency encoding gradient waveforms of a time-interleaved multi (gradient) echo sequence are simply time-shifted between interleaves, the concomitant gradient-induced phase error would be identical for the same echo of different interleaves in most cases. In the presence of only water signal, the total measured phase ϕ_{ij} for the echo j of interleaf i would be equal to:

$$\boldsymbol{\phi_{ij}} = \phi_0 + 2\pi \boldsymbol{f_B TE_{ij}} + \boldsymbol{\phi_{c,j}}$$

f_B is the off-resonance frequency due to local B_0 inhomogeneity, TE_{ij} is the echo time of the j^{th} echo of the i^{th} interleave, and ϕ_{c_j} is the concomitant field phase effect that depends only on the echo index j .

In the presence of only signal contribution from water and in the absence of concomitant gradient-induced phase errors, the measured phase ϕ_{ij} depends only linearly on the echo time TE_{ij}. However, this does no longer apply in the presence of concomitant gradient-induced phase errors.

In the presence of species with different chemical shifts (such as water and fat protons), the concomitant gradient-induced phase error further complicates the dependence of the total measured phase of each acquired echo signal from the echo and interleaf index numbers. Post-processing algorithms that rely on correctly measured phase behavior can thus become unstable and not properly working if the concomitant field effect is not compensated, especially if the underlying signal model is non-linear. One example is the problem of separating water and fat from complex echo signals. The concomitant gradient-induced phase error effect can induce significant bias on the estimated water and fat signals and on the extracted fat fraction values.

The relevance of a correction of concomitant field phase effects in time-interleaved multi echo imaging has not been appreciated previously for several reasons. First, in applications such as water/fat separation, it only becomes relevant if several echoes are acquired in each of several repetitions. If all echoes are acquired in a single repetition, the concomitant field phase effects simply appear as an offset to f_B, which is usually irrelevant. If only one echo is acquired in each of several repetitions, the concomitant field phase effects simply appear as an offset to the initial phase ϕ_0, which again is usually irrelevant. Second, again in applications such as water/fat separation, methods relying on magnitude echo signals have been developed to cope with phase errors of unknown origin. However, they are commonly inferior to methods relying on complex echo signals in terms of signal-to-noise and robustness.

The Handbook by M.A. Bernstein et al. on MRI pulse sequences discusses correction for concomitant field effects in RARE pulse sequences.

SUMMARY OF THE INVENTION

The invention is based on the insight that time-interleaved multi echo imaging is particularly sensitive to concomitant field phase effects and that, for this reason, any method based on the processing of the complex echo signal data from a time-interleaved multi (gradient) echo scan generally requires appropriate correction schemes for the concomitant field phase effects.

It is thus readily appreciated that there is a need for an improved MR imaging technique. It is an object of the invention to provide a multi echo imaging technique that avoids artifacts and/or errors due the concomitant gradient-induced phase error effect.

In accordance with the invention, a method of MR imaging of an object placed in an examination volume of a MR device is disclosed. The method comprises the steps of:

a) generating echo signals at different echo times by subjecting the object to a multi-echo imaging sequence of at least one RF pulse and switched magnetic field gradients;

b) acquiring the echo signals;

c) correcting the acquired echo signals for concomitant gradient-induced phase errors, which comprises:

- reconstructing a complex MR image for each echo time from the echo signals generated at this echo time;

- computing the accumulated concomitant gradient-induced phase error for each echo time and for each image position from the gradient waveforms of the imaging sequence; and

- applying a phase correction to each voxel of each of the MR images according to the computed accumulated concomitant gradient-induced phase error for the respective echo time and image position.

Within the meaning of the invention, the multi-echo imaging sequence uses a series of echoes acquired as a train following after a single RF excitation pulse. Separate MR images are produced from each echo of the train with different spectral encoding due to the different echo times. A complete signal data set in terms of spatial phase and frequency encodings is acquired at each echo time by corresponding repetitions of the basic imaging sequence. Preferably, the multi-echo imaging sequence is a gradient echo sequence of which each repetition comprises:

- one (slice/slab-selective) RF pulse for excitation of magnetic resonance (over a slice/slab within the examination volume),
- phase encoding switched magnetic field gradients, and
- a plurality of switched magnetic field gradients for refocusing magnetic resonance and for frequency-encoding of each echo signal.

The technique of the invention calculates the concomitant gradient-induced phase error based on the sequence parameters (i.e. the time-dependent waveforms of the switched magnetic field gradients). The signal can then be directly corrected using the calculated phase terms. This pure post-processing routine will robustly correct the concomitant gradient-induced phase error, as the effect is removed directly from the measured signal and does not need to be further considered, e.g., in a signal model employed to extract the parameters of interest from the acquired multi echo data.

The present invention concerns the correction for phase errors due to concomitant fields in a time-interleaved multi-echo magnetic resonance imaging sequence. It is an insight of the present invention that if several (gradient) echoes are acquired in several (different) repetitions, the concomitant field effects become more complicated than just appearing as a frequency offset. Further, in water-fat separation, an insight of the invention is that methods relying on complex-valued echoes have a better signal-to-noise ratio and robustness, but are more sensitive to concomitant field errors. In other words, it is an insight of the present invention that water-fat separation based on time-interleaved multi-echo gradient -echo sequences and employing complex-valued magnetic resonance images do need correction for concomitant field effects. Whenever rigorously measured phase behavior is required in multi-echo imaging, the approach of the invention compensates the confounding effect of concomitant gradients. This particularly applies in the case of Dixon water/fat separation in which signal contributions of at least two different chemical species to each (complex) voxel are separated on the basis of the phase-corrected MR images.

During the signal separation step according to the invention, a spectral model for the different chemical species may be employed. Such model may approximate the fat spectrum by a single, dominant peak. However, this simple model may fail to provide an efficient fat suppression. This is because hydrogen atoms in fat are known to comprise multiple spectral peaks. It is also possible in accordance with the invention that the spectrum of one of the chemical species is modeled, for example, by a multi-peak spectral model, while another chemical species (for example water protons) may simply be modeled by a single-peak spectrum. The signal model mathematically describes the acquired echo signals as a function of the respective echo time. The signal model may include the (a-priori known) spectrum of each of the chemical species as well as the (unknown) spatial variation of the main magnetic field B_0 in the examination volume, the (unknown) effective transverse relaxation rate, and/or the (unknown) eddy current-induced phase errors. In the step of separating the contributions of the at least two chemical species values of all unknown parameters of the signal model are sought that best fit the acquired echo signals. In other words, the phase errors are modeled along with the contributions of the different chemical species, just like the main magnetic field inhomogeneity and/or the effective transverse relaxation rate. Under the provision that echo signals are acquired at a sufficient number of different echo time values, the true values of all parameters of the applied signal model are established and thus fully taken into account in the process of separating the signal contributions of the different chemical species. Since the concomitant gradient-induced phase errors have been robustly removed directly from the measured echo signals they do not need to be further considered in the signal model for separating the contributions of the at least two chemical species. This enables the unambiguous determination of the contributions of the different chemical species and thus makes it possible, for example, to quantitatively determine a fat fraction in a diagnostic examination at high accuracy.

It has to be noted that the term 'chemical species' has to be broadly interpreted in the context of the invention as any kind of chemical substance or any kind of nuclei having

MR properties. In a simple example, the MR signals of two chemical species are acquired, wherein the chemical species are protons in the 'chemical compositions' water and fat. In a more sophisticated example, a multi-peak spectral model actually describes nuclei in a set of different chemical compositions which occur in known relative amounts.

In a preferred embodiment of the invention, the accumulated concomitant gradient-induced phase error is computed for each echo time and for each image position x,y,z as

$$\phi_C(x,y,z) = \gamma \int B_C(x,y,z,t)dt,$$

Wherein

$$B_C(x,y,z,t) = \frac{1}{2B_0}\left(G_x^2 z^2 + G_y^2 z^2 + G_z^2 \frac{x^2+y^2}{4} - G_x G_z xz - G_y G_z yz\right).$$

G_x, G_y, G_z are the time-dependent gradient waveforms in the three orthogonal spatial directions x,y,z respectively. Each voxel of each of the MR images is then corrected using the phase term ϕ_C and the spatial information.

As mentioned above, the method of the invention is advantageously applied in the context of time-interleaved multi-echo imaging, wherein the echo signals are generated at different echo times in two or more repetitions of the gradient echo sequence. This means, in other words, that the set of echo times at which echo signals are acquired during one repetition of the basic imaging sequence differs from the set of echo times at which echo signals are acquired during another repetition of the imaging sequence. Preferably, the echo times of one repetition are temporally shifted ('interleaved') with respect to the echo times of another repetition of the imaging sequence, for example for the purpose of increasing the bandwidth of the spectral encoding.

The method of the invention described thus far can be carried out by means of a MR device including at least one main magnet coil for generating a uniform, steady magnetic field B_0 within an examination volume, a number of gradient coils for generating switched magnetic field gradients in different spatial directions within the examination volume, at least one RF coil for generating RF pulses within the examination volume and/or for receiving MR signals from a body of a patient positioned in the examination volume, a control unit for controlling the temporal succession of RF pulses and switched magnetic field gradients, and a reconstruction unit for reconstructing MR images from the received MR signals. The method of the invention can be implemented by a corresponding programming of the reconstruction unit and/or the control unit of the MR device.

The method of the invention can be advantageously carried out on most MR devices in clinical use at present. To this end it is merely necessary to utilize a computer program by which the MR device is controlled such that it performs the above-explained method steps of the invention. The computer program may be present either on a data carrier or be present in a data network so as to be downloaded for installation in the control unit of the MR device.

BRIEF DESCRIPTION OF THE DRAWINGS

The enclosed drawings disclose preferred embodiments of the present invention. It should be understood, however, that the drawings are designed for the purpose of illustration only and not as a definition of the limits of the invention. In the drawings:

Figure 1 shows a MR device for carrying out the method of the invention;

Figure 2 schematically illustrates a multi-echo imaging sequence in accordance with the invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

With reference to Figure 1, a MR device 1 is shown. The device comprises superconducting or resistive main magnet coils 2 such that a substantially uniform, temporally constant main magnetic field B_0 is created along a z-axis through an examination volume. The device further comprises a set of shimming coils 2', wherein the current flow through the individual shimming coils of the set 2' is controllable for the purpose of minimizing B_0 deviations within the examination volume.

A magnetic resonance generation and manipulation system applies a series of RF pulses and switched magnetic field gradients to invert or excite nuclear magnetic spins, induce magnetic resonance, refocus magnetic resonance, manipulate magnetic resonance, spatially and otherwise encode the magnetic resonance, saturate spins, and the like to perform MR imaging.

More specifically, a gradient pulse amplifier 3 applies current pulses to selected ones of whole-body gradient coils 4, 5 and 6 along x, y and z-axes of the examination volume. A digital RF frequency transmitter 7 transmits RF pulses or pulse packets, via a send-/receive switch 8, to a body RF coil 9 to transmit RF pulses into the examination volume. A typical MR imaging sequence is composed of a packet of RF pulse segments of short duration which, together with any applied magnetic field gradients, achieve a selected manipulation of nuclear magnetic resonance. The RF pulses are used to saturate, excite resonance, invert magnetization, refocus resonance, or manipulate resonance and select a portion of a body 10 positioned in the examination volume. The MR signals are also picked up by the body RF coil 9.

For generation of MR images of limited regions of the body 10, e.g. by means of parallel imaging, a set of local array RF coils 11, 12, 13 are placed contiguous to the region selected for imaging. The array coils 11, 12, 13 can be used to receive MR signals induced by body-coil RF transmissions.

The resultant MR signals are picked up by the body RF coil 9 and/or by the array RF coils 11, 12, 13 and demodulated by a receiver 14 preferably including a pre-amplifier (not shown). The receiver 14 is connected to the RF coils 9, 11, 12 and 13 via send-/receive switch 8.

A host computer 15 controls the shimming coils 2' as well as the gradient pulse amplifier 3 and the transmitter 7 to generate any of a plurality of MR imaging sequences, such as echo planar imaging (EPI), echo volume imaging, gradient and spin echo imaging, fast spin echo imaging, and the like. For the selected sequence, the receiver 14 receives a single or a plurality of MR data lines in rapid succession following each RF excitation pulse. A data acquisition system 16 performs analog-to-digital conversion of the received signals and converts each MR data line to a digital format suitable for further processing. In modern MR devices the data acquisition system 16 is a separate computer which is specialized in acquisition of raw image data.

Ultimately, the digital raw image data are reconstructed into an image representation by a reconstruction processor 17 which applies a Fourier transform or other appropriate reconstruction algorithms, such as SENSE or SMASH. The MR image may represent a planar slice through the patient, an array of parallel planar slices, a three-dimensional volume, or the like. The image is then stored in an image memory where it may be accessed for converting slices, projections, or other portions of the image representation into appropriate format for visualization, for example via a video monitor 18 which provides a man-readable display of the resultant MR image.

In an embodiment of the invention, echo signals are generated at different echo times by means of a multi gradient echo imaging sequence. Depending on the respective echo time, the contributions of water and fat spins to the echo signals are more out of phase or more in phase. A plurality of echo signals is generated and acquired with appropriate phase encoding in a common fashion in order to be able to reconstruct a complete MR image of the desired field-of-view.

As shown in Fig. 2, an arbitrary time-interleaved multi-echo gradient echo imaging can be performed according to the invention to acquire multiple echoes at different echo times. The depicted sequence will employ N interleaves acquiring M echoes per interleaf and will therefore acquire $N*M$ echo signals in total. The echo signals can be acquired using mono-polar or bi-polar frequency encoding gradients. For simplicity, Fig. 2 shows only the frequency-encoding magnetic field gradient G_x.

As a next step, complex single echo MR images are reconstructed from the echo signals, wherein each single echo MR image is attributed to one echo time.
The accumulated concomitant gradient-induced phase error is then computed for each echo time and for each image position x,y,z as

$$\phi_C(x,y,z) = \gamma \int B_c(x,y,z,t)dt\ ,$$

wherein the integral is computed over the time interval from the radiation of the RF excitation pulse to the respective echo time (γ being the gyromagnetic ratio), wherein the low-order concomitant magnetic field relation

$$B_c(x,y,z,t) = \frac{1}{2B_0}\left(G_x^2 z^2 + G_y^2 z^2 + G_z^2 \frac{x^2+y^2}{4} - G_x G_z xz - G_y G_z yz\right)$$

is used. G_x, G_y, G_z are the time-dependent gradient waveforms in the three orthogonal spatial directions x,y,z respectively. Each voxel of each of the MR images is then corrected using the phase term ϕ_C and the spatial information (the coordinates x,y,z of the respective voxel). This means that each complex voxel value at position x,y,z of the MR image for the respective echo time is multiplied by $e^{-i\phi_C(x,y,z)}$.

Finally, for example, a water image is computed in a conventional fashion from the phase-corrected complex single echo images, wherein the echo time-dependent phase evolution of the phase-corrected voxels is attributed to the frequency difference between water and fat hydrogen atoms and residual main magnetic field inhomogeneity. Since the method of the invention will robustly remove the concomitant gradient-induced phase error directly from the measured echo signals it does not need to be further considered in the step of water/fat separation.

The invention has been described above in the context of water/fat separation using time-interleaved multi-echo gradient echo imaging, but it may also be relevant in other phase-sensitive applications requiring multiple repetitions to cover the spectral or spatial domain ('multi-shot'), e.g. in echo planar spectroscopic imaging (EPSI).

CLAIMS:

1. Method of MR imaging of an object (10) placed in an examination volume of a MR device (1), the method comprising the steps of:

a) generating echo signals at different echo times by subjecting the object to a multi-echo imaging sequence of at least one RF pulse and switched magnetic field gradients; wherein the multi-echo imaging sequence is a gradient echo sequence of which each repetition comprises:

- one RF pulse for excitation of magnetic resonance, and
- a plurality of switched magnetic field gradients for refocusing magnetic resonance and for frequency-encoding of each echo signal and

wherein the multi-echo imaging sequence is a time-interleaved multi-echo imaging sequence, wherein the echo signals are generated at different echo times in two or more repetitions of the gradient echo sequence,

b) acquiring the echo signals;

c) correcting the acquired echo signals for concomitant gradient-induced phase errors, which comprises:

- reconstructing a complex MR image for each echo time from the echo signals generated at this echo time;
- computing the accumulated concomitant gradient-induced phase error for each echo time and for each image position from the gradient waveforms of the imaging sequence; and
- applying a phase correction to each voxel of each of the MR images according to the computed accumulated concomitant gradient-induced phase error for the respective echo time and image position.

2. Method of claim 1, wherein signal contributions of at least two different chemical species to each voxel are separated on the basis of the phase-corrected MR images.

3. Method of claim 2, wherein a spectral model for the different chemical species is employed in the step of separating the contributions of the different chemical species.

4. Method of claim 3, wherein the spectral model attributes a phase error to each echo signal.

5. Method of claim 4, wherein all unknown parameters of the signal model including the contributions of the at least two chemical species, the spatial variation of the main magnetic field, the effective transverse relaxation rate, and/or eddy current-induced phase errors are derived in the step of separating the contributions of the different chemical species.

6. Method of any one of claims 1-5, wherein the accumulated concomitant gradient-induced phase error is computed for each image position x,y,z as

$$\phi_C(x,y,z) = \gamma \int B_C(x,y,z,t)dt$$

for each echo time based on

$$B_C(x,y,z,t) = \frac{1}{2B_0}\left(G_x^2 z^2 + G_y^2 z^2 + G_z^2 \frac{x^2+y^2}{4} - G_x G_z xz - G_y G_z yz\right),$$

with G_x, G_y, G_z being the time-dependent gradient waveforms in the three orthogonal spatial directions x,y,z respectively.

7. MR device for carrying out the method of any one of claims 1-6, which MR device (1) includes at least one main magnet coil (2) for generating a uniform, steady main magnetic field B_0 within an examination volume, a number of gradient coils (4, 5, 6) for generating switched magnetic field gradients in different spatial directions within the examination volume, at least one RF coil (9) for generating RF pulses within the examination volume and/or for receiving MR signals from an object positioned in the examination volume, a control unit (15) for controlling the temporal succession of RF pulses and switched magnetic field gradients, and a reconstruction unit (17) for reconstructing MR images from the received MR signals, wherein the MR device (1) is arranged to perform the following steps:

a) generating echo signals at different echo times by subjecting the object to a multi-echo imaging sequence of at least one RF pulse and switched magnetic field gradients; wherein the multi-echo imaging sequence is a gradient echo sequence of which each repetition comprises:

- one RF pulse for excitation of magnetic resonance, and

- a plurality of switched magnetic field gradients for refocusing magnetic resonance and for frequency-encoding of each echo signal and

wherein the multi-echo imaging sequence is a time-interleaved multi-echo imaging sequence, wherein the echo signals are generated at different echo times in two or more repetitions of the gradient echo sequence,

b) acquiring the echo signals;

c) correcting the acquired echo signals for concomitant gradient-induced phase errors, which comprises:

- reconstructing a complex MR image for each echo time from the echo signals generated at this echo time;

- computing the accumulated concomitant gradient-induced phase error for each echo time and for each image position from the gradient waveforms of the imaging sequence; and

- applying a phase correction to each voxel of each of the MR images according to the computed accumulated concomitant gradient-induced phase error for the respective echo time and image position.

8. Computer program to be run on a MR device, which computer program comprises instructions for:

a) generating echo signals at different echo times by performing a multi-echo imaging sequence of at least one RF pulse and switched magnetic field gradients;

wherein the multi-echo imaging sequence is a gradient echo sequence of which each repetition comprises:

- one RF pulse for excitation of magnetic resonance, and

- a plurality of switched magnetic field gradients for refocusing magnetic resonance and for frequency-encoding of each echo signal and

wherein the multi-echo imaging sequence is a time-interleaved multi-echo imaging sequence, wherein the echo signals are generated at different echo times in two or more repetitions of the gradient echo sequence,

b) acquiring the echo signals;

c) correcting the acquired echo signals for concomitant gradient-induced phase errors, which comprises:

- reconstructing a complex MR image for each echo time from the echo signals generated at this echo time;

- computing the accumulated concomitant gradient-induced phase error for each echo time and for each image position from the gradient waveforms of the imaging sequence; and

- applying a phase correction to each voxel of each of the MR images according to the computed accumulated concomitant gradient-induced phase error for the respective echo time and image position.

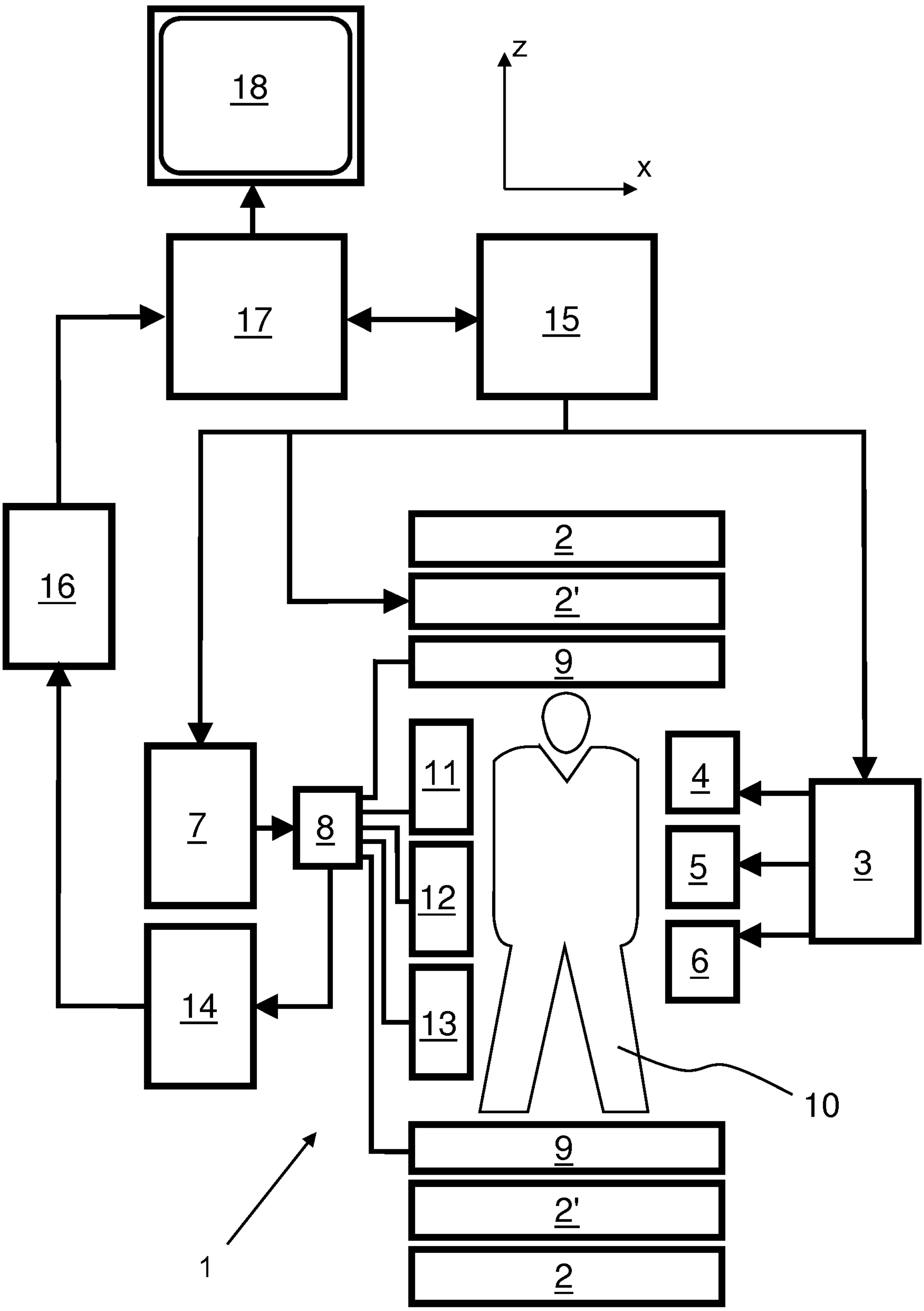

Fig. 1

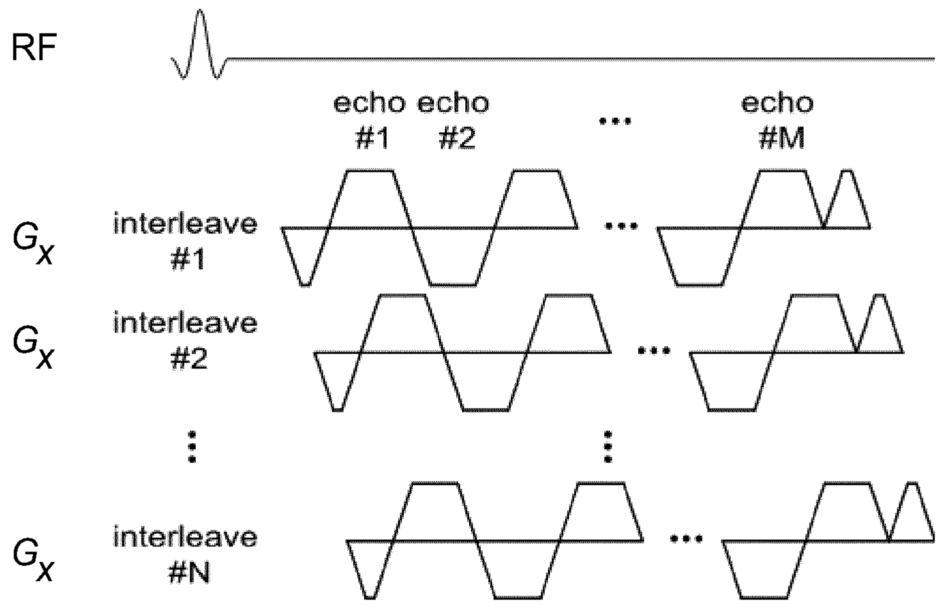
RF
echo #1
echo #2
...
echo #M
G_X
interleave #1
G_X
interleave #2
G_X
interleave #N

Fig. 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/060920

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R33/48 G01R33/561 G01R33/565
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

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X	JACOB A. BENDER ET AL: "The importance of k-space trajectory on off-resonance artifact in segmented echo-planar imaging", CONCEPTS IN MAGNETIC RESONANCE PART A, vol. 42A, no. 2, 19 March 2013 (2013-03-19), pages 23-31, XP055293339, US ISSN: 1546-6086, DOI: 10.1002/cmr.a.21255 page 25, column 1, paragraph 1 - page 27, column 2, paragraph 1; figures 1, 6 -----	1-8

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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

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"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
19 August 2016	02/09/2016

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

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

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2016/060920

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