(12) UK Patent Application (19) GB (11) 2 304 419 (13) A

(43) Date of A Publication 19.03.1997

(21) Application No 9615571.8

(22) Date of Filing 24.07.1996

(30) Priority Data
(31) 08516539 (32) 18.08.1995 (33) US

(71) Applicant(s)
Toshiba America MRI Inc

(Incorporated in USA - California)

2441 Michelle Drive, Tustin, California 92681-2068, United States of America

(72) Inventor(s)
Weiguo Zhang
David M Kramer
David M Goldhaber

(74) Agent and/or Address for Service
F J Cleveland & Co
40-43 Chancery Lane, LONDON, WC2A 1JQ, United Kingdom

(51) INT CL[6]
G01R 33/54

(52) UK CL (Edition O)
G1N NG54A

(56) Documents Cited
JP 040079938 A1 JP 020063434 A1

(58) Field of Search
UK CL (Edition O) G1N NG54A
INT CL[6] G01R 33/54
Online:WPI,INSPEC,JAPIO

(54) Method and apparatus for providing separate fat and water MRI images in a single acquisition scan

(57) A method of obtaining three MRI images in a single scan for use in constructing separate water and fat images by appropriate equations is disclosed. The three images are obtained by sandwiching a spin echo (So) by two field echoes ($S_{-\pi}$, S_{π}). The method can also be used for multiple-echo and multiple-slice scans.

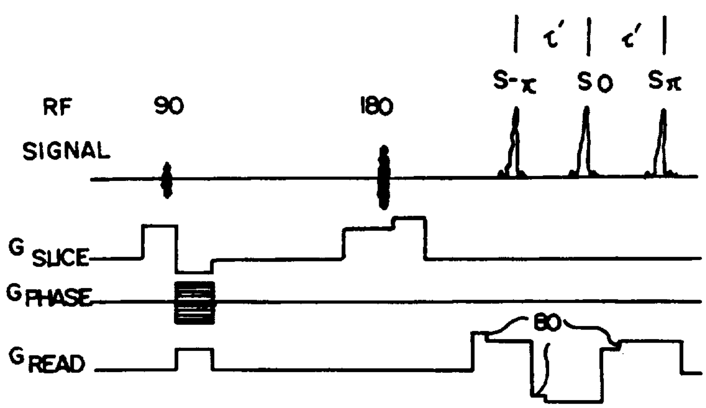

FIG. 8

GB 2 304 419 A

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

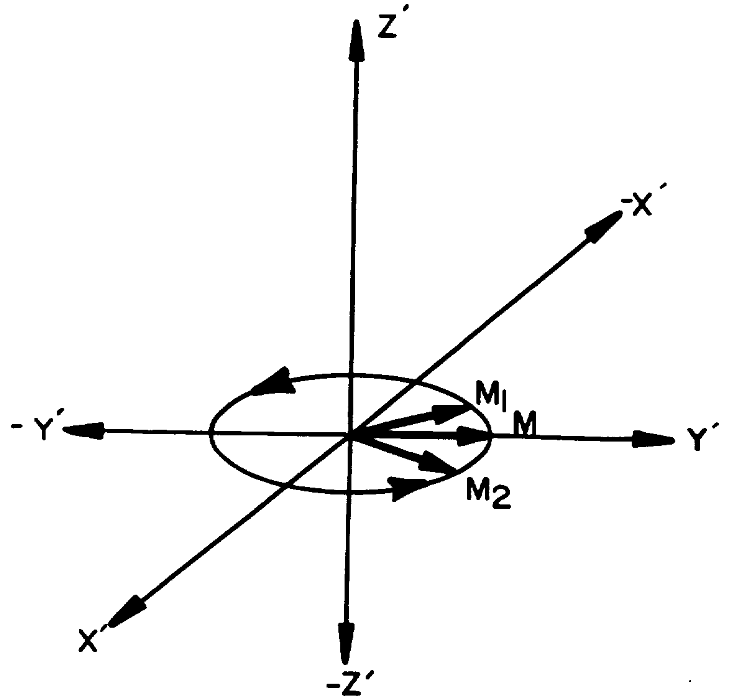

FIG. 1

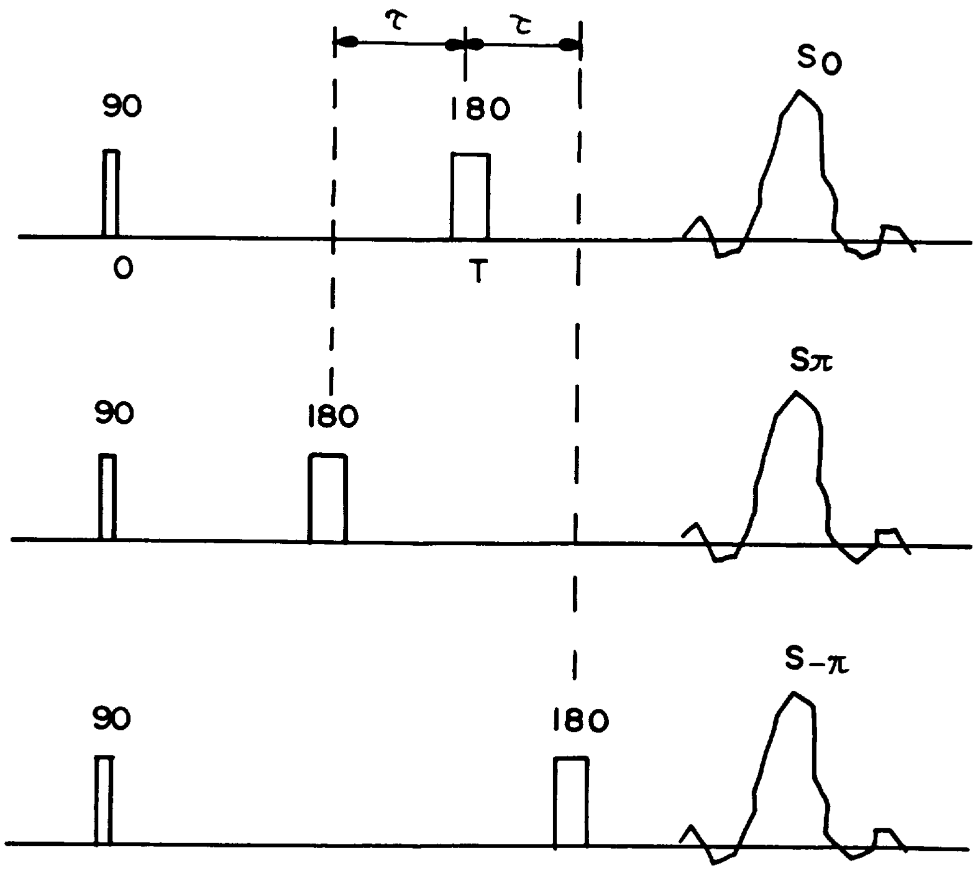

FIG. 2

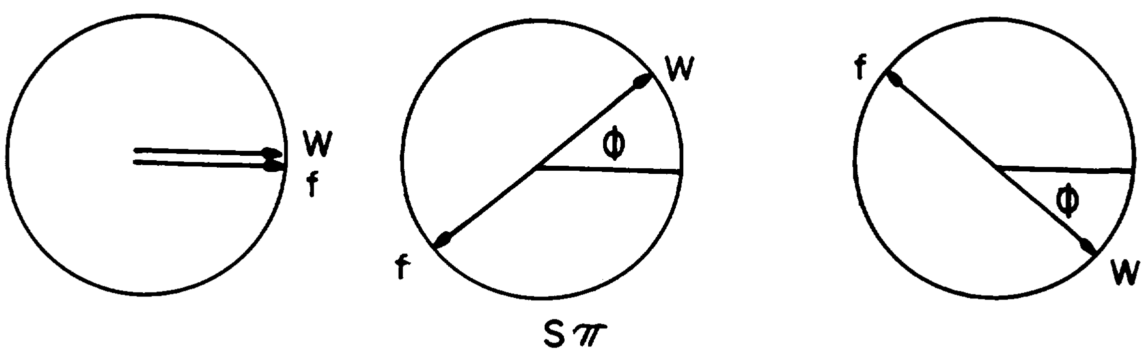

FIG. 3

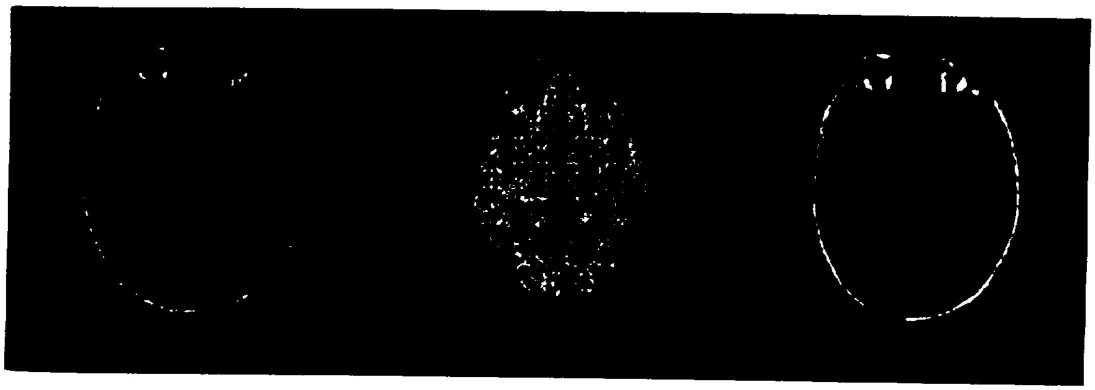

FIG. 4

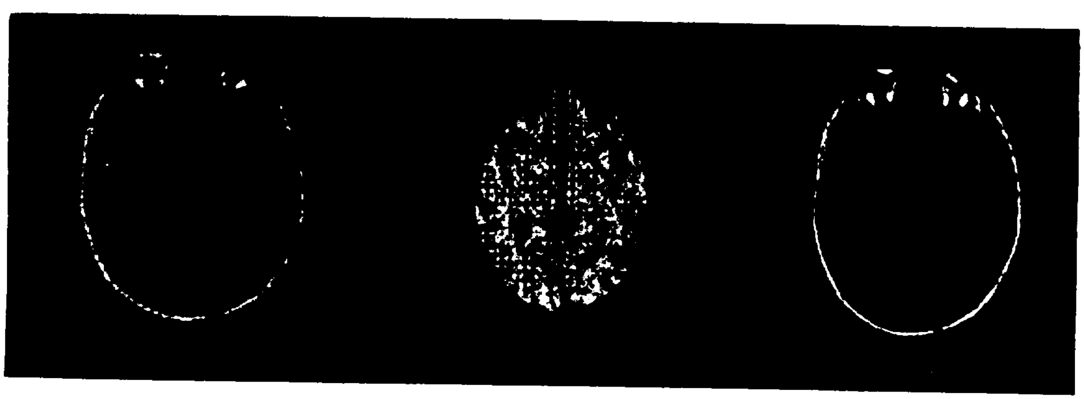

FIG. 5

FIG. 6

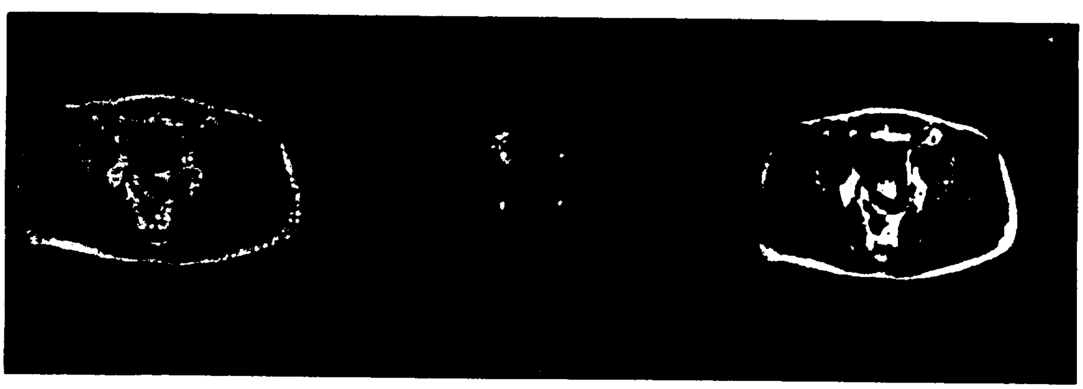

FIG. 7

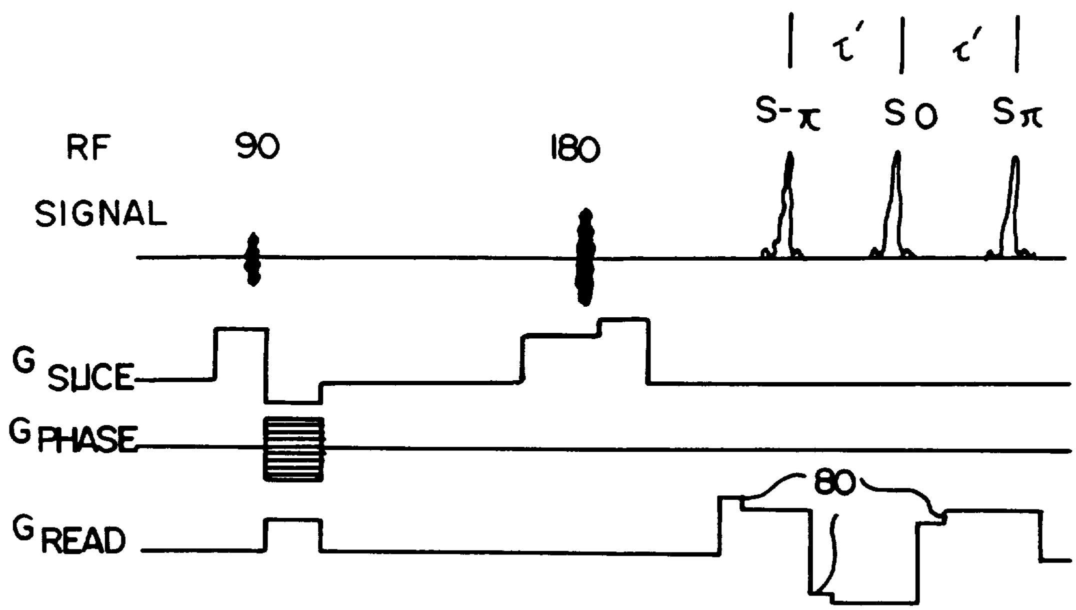

FIG. 8

2304419

METHOD AND APPARATUS FOR PROVIDING SEPARATE FAT AND WATER MRI IMAGES IN A SINGLE ACQUISITION SCAN

FIELD OF THE INVENTION

This invention relates to a method for obtaining MRI images that can be used to separate MRI images of water and fat, particularly when field inhomogeneities are present.

BACKGROUND OF THE INVENTION

MRI systems use the resonance effects that RF transmissions have on certain atomic nuclei such as those in hydrogen. Certain of these nuclei are first magnetically aligned by a strong static magnetic field B_0 created by magnetic poles on opposite sides of the MRI imaging volume. The static field B_0 is altered by gradient magnetic fields created in the X, Y, and Z directions of the imaging volume. Selected nuclei, which spin in alignment with the B_0 field, are then resonated by an RF transmission, causing them to tip from the direction of the magnetic field B_0. Thus, for example, in Figure 1, certain nuclei (designated by magnetic moment M_0) are aligned on the "Z'" axis by the static B_0 field and then rotate to the X'-Y' plane as a result of an RF transmission signal imposed on them. The nuclei then precess in the X'-Y' plane as shown in Figure 1 which is a reference frame rotating at the nominal resonance frequency around the Z' axis.

The RF signal will, of course, tip more than one species of the target isotope in a particular area. Immediately after the RF transmission signal tips them, the spinning nuclei will all be in-phase; that is, the rotating magnetic moments all cross the "Y'" axis all at the same time. After the RF transmission signal ends, the nuclei begin to freely precess around the Z' axis. As they do, the phase of the rotating nuclei will differ as a result of such parameters as the physical or chemical environment that the nuclei are located in. Nuclei in fat, for example, precess at a different rate than do nuclei in water. In an imaging pulse sequence there are magnetic field gradients which dephase the moments due to their local resonance frequency varying in space.

Also, once the spins are disturbed from their equilibrium, processes known as relaxation cause the component of magnetic moment in the X'-Y' plane to decay and the Z'-component to recover to its equilibrium magnitude, M_0. These processes are usually characterized by exponentials whose time constants are called T_2 and T_1, respectively. When magnetic resonance signals are observed through flux oscillation in a plane coexistent with they X'-Y' plane, both of these processes decrease the signal strength.

As a result, if the components of the magnetic moments in the X'-Y' plane of Figure 1 begin aligned on the Y'-axis, over time they will begin to spread out and disperse to fill the full rotational area. The moment M_2, for example, which initially crossed the Y'-axis at the same time as M, gradually moves during the relaxation period to the position shown in Figure 1 as it spins faster than M_0. M_1, by contrast, spins slower than both M and M_2, and thus begins to lag them during the dephasing period. The strength of the signal in the Y-direction thus decays as the magnetic moments disperse (i.e., lose phase coherence) in the X'-Y' plane.

Information about the hydrogen nuclei can be obtained, in part, by measuring the decay times. In addition, before the nuclei become completely dephased another RF signal (usually a 180° signal) can tip the magnetic moments to a 180° (-Y') position. This inverts the spinning magnetic moments M, M_1 and M_2 so the fastest moment M_2 lags M, which in turn lags the slowest moment M_1. Eventually, the faster moment M_2 will catch and pass the slowest moment M_1 during which, a so-called "spin-echo" can be detected from the changes in magnetic moment. The whole procedure must be completed before T_1 or T_2 relaxation destroy the X'-Y' component of the magnetic moment.

Echoes can also be formed by application of a field gradient and it's subsequent reversal, provided that it is done before T_1 or T_2 relaxation destroy $M_{X'Y'}$. This is commonly called a field echo or race-track echo.

The above are just two background examples of how the nuclei can be tipped, relaxed, brought in- or out-of-phase, etc. from which information about the nuclei can be obtained.

The differences in the phase relationships between the nuclei in one tissue versus another can be used as information to separate MRI images of fate components of tissue from fluids or water-based tissue (for these purposes, "water-based tissue" and "fluids" are used interchangeably).

Although MR images of both water and fat may contain the same or different diagnostic information, they often interfere with each other's interpretation when overlapped in an MRI image. At high fields strengths, the separation of water and fat images or suppression of fat signals can be achieved using selective excitation or non-excitation approaches. However, at mid- or low fields, approaches based on chemical shift selectivity become impractical, if not impossible. At all field strengths, the difficulties of water/fat separation are further exacerbated when there are large magnetic field inhomogeneities.

This difficulty in separating fat and water images in a practical MR imaging application is particularly true for mid- and low-field systems where the frequency separation between the water and fat signals is much reduced in comparison to that at high fields. Recently, several techniques were introduced for separation of water and fat images in the presence of large field inhomogeneities. Some of these techniques use multiple spin-echoes, thus requiring the use of multiple RF refocusing pulses. They are therefore sensitive to B_1 inhomogeneities and also preclude multiple-echo experiments. On the other hand, the three-point Dixon method uses a single spin-echo sequence, but requires a minimum of three scans.

The Three-Point Dixon method has promising features for mid- or low field applications. It relies on the acquisition of three images for water/fat separation, an in-phase image and two out-phase images. Unfortunately, it requires three scans to do so.

Figure 2 shows the three data acquisition schemes for the three images. Slice selection is not shown for simplicity. As those in the art will understand from Figure 2, three different scans are used. In the first, a 90° pulse is followed by a 180° pulse at a time T, yielding the spin echo S_0. Then, a 90° pulse is followed by a 180° pulse a time τ earlier than the time T, yielding a spin echo S_π. Finally, another 90° pulse is followed by a 180° pulse a time τ later than the time T, yielding a spin echo $S_{-\pi}$. The Dixon Methodology is described in "Three-Point Dixon Technique for True Water Fat Decompositions with B_0 Inhomogeneity Corrected," 18 Magnetic Resonance in Medicine, 371-383 (1991), by Glover et al., "True Water and Fat MR Imaging With Use of Multiple-Echo Acquisition", 173 Radiology 249-253 (1989), by Williams et al., "Separation of True Fat and Water

Images By Correcting Magnetic Field Inhomogeneity In Situ," 159 Radiology 783-786 (1986), by Yeung et al., which are incorporated herein by reference, and are summarized in part below.

The value of τ is determined according to $\tau = 1/(4\Delta v)$ with Δv being the frequency difference between the water and fat signals. The value of τ is thus chosen so the phase between the nuclei in, respectively, fat and water are 1) in-phase, 2) out-of-phase by π, and 3) out-of-phase by $-\pi$. Figure 3 schematically shows in a rotating frame the MR signals in the three different acquisition schemes.

In the presence of field inhomogeneities, the MR signals can be described by

$$S_0 = (P_w + P_f)$$

$$S_\pi = (P_w - P_f)^{e^{i\phi}}$$

$$S_{-\pi} = (P_w - P_f)^{e^{-i\phi}}$$

where ϕ is the phase angle due to field inhomogeneities or frequency offset, and P_w and P_f are water and fat spin densities, respectively.

Thus ϕ can be determined from S_π and $S_{-\pi}$ by

$$\phi = \tfrac{1}{2}\arg\,(S_\pi \,.\, S^*_{-\pi})$$

where arg produces the phase angle of a complex number.

Water and fat images can then be reconstructed according to

$$I_{water} = S_0 + 0.5S_\pi e^{-i\phi} + 0.5S_{-\pi}e^{i\phi}$$
$$I_{fat} = S_0 - 0.5S_\pi e^{-i\phi} - 0.5S_{-\pi}e^{i\phi}$$

The central component of this method--and also the most demanding component to determine--is the phase angle ϕ. The phase angle is generally determined by phase mapping. Calculating ϕ from S_{π} and $S_{-\pi}$ involves:

1) fitting the phase derivatives to polynomial functions; and
2) phase unwrapping.

Each of these are discussed in turn below.

i. **Polynomial fitting**

The magnetic field is modeled using a polynomial function:

$$B(x,y)=\sum_{n=1}^{3}\left[a_n(x-x_o)^n+b_n(y-y_o)^n\right]+c_o$$

To find the coefficients a_n and b_n, partial spatial derivatives of the phase value ϕ are calculated and fit to the polynomial functions:

$$\frac{\partial\phi(x,y)}{\partial x}=p_3x^2+p_2x+p_1$$

$$\frac{\partial\phi(x,y)}{\partial y}=q_3y^2+q_2y+q_1$$

Fitting was performed with weighted least-square with the weighting factors determined according to

$$w(x,y)=\left|\frac{S_0(x,y)}{S_{0_{max}}}\right|$$

where $S_o(x,y)$ is the pixel value in the in-phase image and S_{0max} is the maximum of that image.

From p_n and q_n, a_n and b_n are calculated from the equations:

$$\begin{cases} p_1 = a_1 - 2a_2x_0 + 3a_3x_0^2 \\ p_2 = 2a_2 - 6a_3x_0 \\ p_3 = 3a_3 \end{cases}$$

$$\begin{cases} q_1 = b_1 - 2b_2y_0 + 3b_3y_0^2 \\ q_2 = 2b_2 - 6b_3y_0 \\ q_3 = 3b_3 \end{cases}$$

ii. ***Binary Phase Unwrapping***

If it can be assumed that the magnetic field fitting is relatively accurate within a small error range, for example, $\pm 0.2\pi$, then unwrapping can be performed by simply comparing the measured phase ϕ with the predicted phase ϕ_p:

$$\Delta\phi = \phi_p - \phi$$

If $|\Delta\phi| > \pi$, then ϕ_f used for water and fat image reconstruction is determined by

$$\phi_f = \phi + integer\left(\frac{\Delta\phi}{2\pi}\right) x\ 2\pi .$$

where integer truncates the resulting quotient to whole number.

iii. Unwrapping by Region Growing

However, the field fitting may contain large errors (for example, $> \pi$) which will cause errors in phase unwrapping and consequently result in water/fat mutual contamination in the final images. To unwrap in a more fool-proof way, a region growing algorithm was implemented as the following:

(A) A pixel in the image was chosen as the subseed for unwrapping and the measured phase value was assigned to the final phase value used for water and fat image reconstruction.

$$\phi_f (x_o, y_o) = \phi(x_o, y_o)$$

(B) From the subseed, a 4x4 seed was built by comparing the phase values to the subseed value. If the difference is larger than a predetermined threshold, a 2π unwrapping is executed:

$$\Delta\phi = \phi - \phi(x_o, y_o)$$

$$\phi_f = \phi + sign(\Delta\phi) \ x \ 2\pi$$

(C) Continuing from the seed, a four column cross is built using a single direction prediction:

$$\phi_p = 1/4 \ \{ \phi_f^{-4} + \phi_f^{-3} + \phi_f^{-2} \ \phi_f^{-1} + 4\delta\phi^{-1} + 3\delta\phi^{-2} + 2\delta\phi^{-3} + \delta\phi^{-4} \}$$

$$\Delta\phi = \phi - \phi_p$$

where ϕ_f^{-1} (i = 1, ...4) are unwrapped phase values of the neighboring pixel, $\delta\phi^{-1}$ (i = 1,...4) are phase increments between two neighboring pixels from the polynomial fitting.

If the pixel value is smaller than the intensity threshold, ϕ_f is set to ϕ_p. Otherwise, if $|\Delta\phi| < \pi$ set ϕ_f to ϕ. If $|\Delta\phi| > \pi$ then $\phi_f = \phi + \text{integer}(\delta\phi/2\pi) \times 2\pi$.

(D) Using the cross, the four quadrants of the image are unwrapped using the same prediction approach, but in two directions. Unwrapping is executed when both directions show the same execution for unwrapping. In other situations, the average of the predicted values is used. When the pixel value is below the intensity threshold, the phase value is again set to the predicted average value.

iv. Results

Shown in Figure 4 are head images reconstructed with binary phase unwrapping. The left image of Figure 4 is a water and fat image; the middle image is water only; and the right image is fat only. The corresponding images reconstructed using the region growing algorithms are shown in Figure 5. Figures 6 and 7 show the abdominal images reconstructed in the same way as for Figure 3 and Figure 4, respectively.

As can be seen, this prior method obtains separate fat and water images but disadvantageously requires three scans to obtain them.

SUMMARY OF THE INVENTION

The present invention is a technique which acquires all the information necessary for separating water and fat images using only a single scan. During the scan, a single "sandwich" spin-echo sequence is used in which a spin echo signal is sandwiched between two field echo signals to obtain the information necessary to solve the I_{water} and I_{fat} equations.

The method is also capable of multiple-slice multiple-echo acquisition.

BRIEF DESCRIPTION OF THE DRAWINGS

The purpose and advantages gained by the present invention will be understood by careful study of the following detailed description of the presently preferred embodiment with particular reference to the accompanying drawings.

FIGURE 1 is a schematic diagram of a rotating frame of MRI signals;

FIGURE 2 is a graphical representation in the time domain of a prior art sequencing technique;

FIGURE 3 is a schematic diagram of rotating frames of the MRI signals of Figure 2;

FIGURE 4 are MRI three-point Dixon head images processed using the binary phase unwraparound algorithm;

FIGURE 5 are MRI three-point Dixon head images processed using the region growing algorithm;

FIGURE 6 are MRI three-point Dixon abdominal images processed using the binary phase unwraparound algorithm;

FIGURE 7 are MRI three-point Dixon abdominal images processed using the region growing algorithm; and

FIGURE 8 is a graphical representation in the time domain of a sequencing method according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENT

"Sandwich" Spin-Echo Sequence for Water/Fat Imaging

The basic principle of the Dixon technique for separating water/fat images is the acquisition of separate images with in-phase or out-phase water/fat signals, respectively. To obtain these images, the present invention recognizes that at lower field, the time period needed for the spin system to evolve from in-phase to out-phase is much longer (e.g., 10.2 *ms* at 0.35 T vs. 2.4 *ms* at 1.5 T for a 3.3 ppm chemical shift difference). As a result, it is possible to acquire a complete k-space data line within this evolution period. Figure 8 depicts one of such implementation by sandwiching a spin-echo between two field-echoes.

To obtain the three images in a single scan, a slice along the axis perpendicular to the desired viewing plane is selected for imaging by activating the slice axis gradient coil (G_{slice}). Thereafter, a 90° RF transmission signal nutates the selected nuclei 90° (for example) to a position on the Y'-axis. The nuclei in the excited plane are then dephased according to position along the encode-axis by the phase-encode gradient coils (G_{phase}).

Later, at a time T following the 90° pulse, a 180° RF transmission nutates the nuclei 180°. This induces a spin echo S_0 at a time T following the 180° RF transmission. This spin echo is detected by an RF receiver coil and RF receiver. It can be used as S_0 in the Dixon equations.

Between the 90° and 180° RF transmissions, the readout or frequency-encode axis gradient coil imposes a preliminary phase gradient on the nuclei. Then, before the spin echo S_0 occurs, the readout axis gradient coil (G_{read}) is activated to produce a field echo $S_{-\pi}$ at a time τ' before the spin echo occurs. This field echo $S_{-\pi}$ is detected by an RF receiver coil and RF receiver. It can be used as $S_{-\pi}$ in the Dixon equations. In essence, since the spin echo S_0 will naturally occur at a time duration following the 180° pulse equal to the time duration between the 90° and 180° pulse, the field echo $S_{-\pi}$ can be timed to occur a time amount τ' before that expected S_0 echo.

Before the spin echo S_0 occurs, the readout axis gradient coil current is inverted. Then, after the spin echo S_0, the readout axis gradient coil current is again inverted to produce a second field echo S_π at a time τ' after the spin echo S_0. This field echo S_π is also detected and used in the Dixon equations.

The time τ' is determined in accordance with $\tau' = 1/2(\Delta\upsilon)$ as described below. The field echoes are timed to the value of τ' by bump adjustments 80 as shown at the leading edges of the G_{read} signal. The height (or depth) and width of the bump adjustment in the G_{read} signal will move the resultant $S_{-\pi}$ and S_π echoes relative to the S_0 echo so the field echoes can be timed to $+\tau'$ and $-\tau'$, respectively, from the spin echo S_0 occurrence. The bump adjustments are set based on normal calibration parameters, and will be affected by such things as the gradient power amplifier slew rate, etc.

With values for $S_{-\pi}$, S_0, and S_π in the Dixon equations, I_{water} and I_{fat} can be determined according to the methods described above in the Background of the Invention.

In particular, the value of τ' was determined according to

$$\tau' = \frac{1}{2\Delta\nu}$$

with $\Delta\upsilon$ being the frequency separation of the water and fat signals.

The MRI sequence depicted in Figure 8 was implemented on a Toshiba 0.35 T system, and both phantom and human head images were acquired. Data processing procedures involved for separating water/fat images were as described in the Background section and in Magnetic Resonance in Medicine, 18; 371-383 (1991).

In some embodiments, there may still be time in the sequence for acquiring more k-space data, e.g., by acquiring several field-echoes before the 180° refocusing pulse. This will be a useful feature of the sequence for separating multiple components such as water-fat-silicone.

The proposed sequence is fully capable of multiple-slice multiple-echo acquisition. However, the gradients need to be carefully balanced so that echo signals are correctly positioned corresponding to full refocusing of the field inhomogeneities in S_0. This technique is compatible with many multi echo, multi scanning methods, such as that described in "<u>RARE</u>

Imaging: A Fast Imaging Method For Clinical MR, Henning, et al., Magn. Reson. Med. 1986; 3: 823-833.

In addition, image distortion due to field inhomogeneities is different between the middle echo and the outside echoes due to the inversion of the read gradient. When this becomes a problem for separation of water and fat images, the field inhomogeneity map produced for water/fat separation can also be used to correct the distortion. This is described in Sumanaweera, et al., IEEE Transc. Med. Imag. 12, 251 (1993), which is incorporated herein by reference. Another solution is to only readout the echoes with the readout gradient in one polarity and force the tuning bumps (80) to be large and oppoing polarity.

The invention is not limited to low-field or mid-field systems nor to the exact sequencing shown in Figure 8, but may be used in any system in which the T2 relaxation time permits the sandwiching of the spin echo by two field echoes.

While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment, but on the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims.

CLAIMS:

1. A method of obtaining signals for use in separating images of fat-based nuclei and water-based nuclei in an MRI signal, in which the fat-based nuclei precess out-of-phase with the water-based nuclei by an amount π after a time τ', comprising the steps of:

1) magnetically aligning the nuclei in a first direction by a static magnetic field;

2) imposing a slice gradient on the nuclei to select a planar slice for imaging;

3) nutating the nuclei by a first RF transmission signal;

4) removing the first RF transmission signal and slice gradient;

5) imposing a phase distribution with a phase-encode and a readout gradient field pulse on the selected nuclei;

6) nutating the nuclei by a second RF transmission signal to induce a spin echo;

7) before the spin echo, imposing a read gradient on the selected nuclei to induce a first field echo at a time τ' before the spin echo and receiving the echo;

8) after the field echo, imposing an inverted read gradient on the selected nuclei to read out the spin echo;

9) after the spin echo, again reversing the read gradient on the selected nuclei to induce a second field echo at a time τ' after the spin echo and receiving the echo; and

10) repeating steps 2-9 with various phase encoding gradient pulses to acquire the complete spatial data for an encode direction.

2. The method according to claim 1, wherein the first RF transmission is a 90° pulse and the second RF transmission is a 180° pulse.

3. The method according to claim 1, wherein the slice gradient, readout gradient and the phase-encode gradient directions are mutually perpendicular.

4. The method according to claim 1, further comprising the step (after step 10) of, before imposing another nutating first RF transmission signal, again nutating the nuclei by additional second RF transmission signals to induce additional spin echos and then repeating steps 7-9 for each additional second RF transmission.

5. The method according to claim 4, further comprising the use of additional phase-encode axis pulses to each set of spin echo plus 2 field echoes to reduce total scan time.

6. A method of obtaining signals for use in separating images of fat-based nuclei and water-based nuclei in an MRI signal substantially as hereinbefore described.

Application No:	GB 9615571.8
Claims searched:	1-6
Examiner:	K. Sylvan
Date of search:	5 November 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1N (NG54A)

Int Cl (Ed.6): G01R (33/54)

Other: Online:WPI,INSPEC,JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	JP040079938	(Toshiba) See Patent Abstract of Japan Section C, Section 957, Vol. 16, No. 295, page 102, June 30th 1992.	-
A	JP020063434	(Toshiba) See Patent Abstracts of Japan Section C, Section 721, Vol. 14, No. 242, page 80, May 23rd 1990.	-

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.