Cancellation of MRI Motion Artifact in Image Plane

Eung-Kyeu Kim

Abstract

In this study, a new algorithm for canceling a MRI artifact due to the translational motion in the image plane is described. Unlike the conventional iterative phase retrieval algorithm, in which there is no guarantee for the convergence, a direct method for estimating the motion is presented. In previous approaches, the motions in the x(read out) direction and the y(phase encoding) direction were estimated simultaneously. However, the feature of x and y directional motions are different from each other. By analyzing their features, each x and y directional motion is canceled by the different algorithms in two steps. First, it is noticed that the x directional motion corresponds to a shift of the x directional spectrum of the MRI signal, and the non-zero area of the spectrum just corresponds to the projected area of the density function on the x axis. So the motion is estimated by tracing the edges between non-zero area and zero area of the spectrum, and the x directional motion is canceled by shifting the spectrum in an reverse direction. Next, the y directional motion is canceled by using a new constraint condition, with which the motion component and the true image component can be separated. This algorithm is shown to be effective by using a phantom image with simulated motion.

Keywords: MRI, Motion, Artifact, Shifting, Fourier spectrum, Phase spectrum, Reconstructed image, Density distribution, Constraint condition

I. Introduction

In MRI, since data acquisition takes several minutes, patient's motion such as occurs in this period. The motion causes some artifacts in the reconstructed image. The goal of this work is to cancel the MRI artifact due to the 2D translational motions in the image plane. A new approach using post-processing algorithm is proposed in this work.

Various approaches to correct the motion artifact have been proposed. Some of them use special pulse sequences for suppressing the motion artifact[1,2]. However, since the adjustment of the hardware is difficult, such an approach is not taken here. Some other approaches only using post-processing are also proposed for this purpose. In most of them, a prior knowledge of motion is required, such as periodic motion[3~5]. Hedley et al. proposed an artifact cancellation method for 2D translational rigid motions in an image plane[6~8]. The features of the method are as follows;

First, no prior knowledge of the motion is required,

Second, the motion may be either periodic or random,

Third, no modification is made to a standard pulse sequence.

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The region of the image is assumed to be known and to be used as a boundary condition. The phase of data is corrected using an iterative phase retrieval algorithm. Because the algorithm uses an iterative process, it may take a lot of time, and even has no guarantee for the convergence[9,10].

This method has the same restrictions of motion and the same features of the method as the Hedley's method. But the problem of convergence is avoided by not using any iterative procedure. Based on this MRI principle, the property of the influence of the motion in each of the x(signal readout) direction, and y(phase encoding) direction is analyzed, respectively. In order to correct the artifact due to the x directional motion, the x directional Fourier spectrum of the MRI signal is analyzed and utilized. It can be regarded as a Fourier weighted projection of the density function onto an x axis. Hence, the motion in x direction corresponds to the shift of the spectrum's edge, without regard to the motion in the y direction. Based on this important property, the motion in the x direction is estimated, and the artifact of the motion can be canceled by shifting the spectrum in the reverse direction. On the other hand, in this phase of the x directional spectrum, the relation between the motion component and the true image component is just an algebraic sum. Based on the feature of the density function and the property of the Fourier transform, a new constraint for the true image component is proposed in this study. With this constraint the y directional motion component can be extracted from the phase of the Fourier spectrum.

The effectiveness of the algorithm is shown by simulations using a phantom with 2D translational motions.

II. The MRI Signal and Motion Artifact

MR imaging takes N time intervals. The MRI signal obtained in the n^th^ time interval is expressed as follows:

$$f_n(t) = \frac{1}{N}\sum_x\sum_y \rho(x,y)\, e^{j\gamma(G_x tx + G_y \tau n y)} \qquad (1)$$

Where, $\rho(x,y)$ is the density distribution of the target, G_x and G_y are the gradients of the magnetic field in the x and y directions, respectively, and γ and τ are constants. Therefore, the MRI signal can be regarded as a 2D inverse Fourier transformation of the density distribution $\rho(x,y)$. Meanwhile, the MR image can be calculated by the 2D Fourier transformation of the MRI signal.

In the procedure of taking a MR image, the period of intraview is very short, just about dozens of milliseconds, but the period of interview is much longer, about 1 second. Hence, the interview motion is the main factor of the patient's motion, and the intraview motion is neglected. When the motion is translational motion in an image plane, the corrupted MRI signal $f'_n(t)$ is given by

$$f'_n(t) = \frac{1}{N}\sum_x\sum_y \rho(x,y)\cdot e^{j\gamma G_x(x+\Delta_x(n))t + G_y(y+\Delta_y(n))n\tau} \qquad (2)$$

Where, $\Delta_x(n)$ and $\Delta_y(n)$ is the translational motion in the x and y directions, respectively. Translational motion causes phase shift in the MRI signal. So some artifact will occur in the reconstructed image by the 2D FFT of the $f'_n(t)$, as shown in Fig. 1.

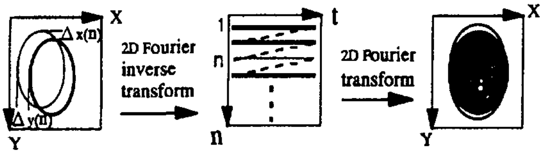

Fig. 1 Mathematical model of MRI

Ⅲ. Cancellation of the Artifact Due to 2D Translational Motion

Since the major motion is assumed to be the interview motion here, each MRI signal in one x directional line has the same motion. And the x directional Fourier spectrum F_{xn} of MRI signal can be calculated without data corruption. Further, the F_{xn} is analyzed here, instead of the general 2D FFT of the corrupted MRI signal. When motion does not exist, F_{xn} is given by

$$\begin{aligned} F_{xn} &= \Im_t[f_n(t)] \\ &= \frac{1}{\sqrt{N}} \sum_t f_n(t)\, e^{-jk_x tx} \\ &= \frac{1}{\sqrt{N}} \sum_y \rho(x,y)\, e^{jk_y n\tau y} \end{aligned} \tag{3}$$

However, if motion exists, the x directional Fourier spectrum of the corrupted signal $f'_n(t)$ will be given by

$$\begin{aligned} F'_{xn} &= \Im_t[f'_n(t)] \\ &= \frac{1}{\sqrt{N}} \sum_t f'_n(t)\, e^{-jk_x tx} \\ &= \frac{1}{\sqrt{N}} \sum_y \rho(x-\Delta_x(n),\ y)\cdot \\ &\quad e^{jk_y(y+\Delta_y(n))n} \\ &= F(x-\Delta_x(n),\ n)\, e^{jk_y\Delta_y(n)n} \end{aligned} \tag{4}$$

Regarding the F'_{xn}, the effect due to the x directional motion $\Delta_x(n)$ results in a position shift, and the effect due to the y directional motion $\Delta_y(n)$ results in a phase shift. The motion in different direction takes different form. By analyzing the F'_{xn}, the motion in each direction is extracted in different ways. If the motion components are known, the F'_{xn} can be corrected and the motion artifact is canceled in the MRI.

1. X Directional Cancellation Algorithm

One-shot x directional motion causes a shift of F_{xn} in the corresponding line. On the other hand, the x directional Fourier spectrum can be regarded as the projection of the density distribution onto the x axis. Therefore, the non-zero area of the amplitude of the F'_{xn} just corresponds to the projected position of the target at the nth view. When motion does not occur, the edges between zero and non-zero of the amplitude of the F_{xn} will take two strait lines along the y direction. When the target moves $\Delta_x(n)$ at the nth view, the F'_{xn} will shift a $\Delta_x(n)$ in the same direction, which is shown in fig. 2.
Further, the motion in the y direction only affects the phase of F'_{xn}, and it does not affect the amplitude, as shown in Eq. (4). So the x directional motion corresponds to the shift of the spectrum's edge, without regard to the y directional motion. Based on this important property, the x directional motion can be estimated by tracing the edge of the amplitude of the spectrum using a conventional algorithm no matter whether the y directional motion occurs or not. Therefore, the motion artifact in x direction can be canceled by shifting the Fourier spectrum in the opposite direction.

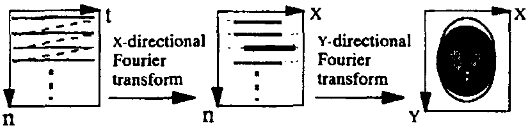

Fig. 2 The MRI signal, its Fourier spectrum and the MR image

2. Y Directional Cancellation Algorithm

Based on the features of the Fourier transform, a new constraint for the separation of the y directional motion is proposed in this section. After canceling the x directional motion component, the remaining motion component is only the y directional motion component. The Fourier spectrum F'_{xn} has become into F''_{xn} which is given by

$$\begin{aligned} F''_{xn} &= e^{jk_y \Delta_y(n)n} F_{xn} \\ &= e^{jk_y \Delta_y(n)n} \cdot A e^{j\phi_{xn}} \\ &= A e^{j\phi'_{xn}} \end{aligned} \tag{5}$$

where, A and ϕ_{xn} is the amplitude and the phase of F_{xn}, respectively. The ϕ_{xn} is the component of the true image, and it is called the phase of image here. ϕ'_{xn} is the phase of F''_{xn}, and it is called the phase of MRI here. The y directional motion component only occurs in the phase of the F''_{xn}. In the reconstructed image, one shot motion causes a complicated artifact. However, in the phase of F''_{xn}, the relation between the motion component and the true image component is just an algebraic sum as follows:

$$\phi'_{xn} = k_y n \Delta_n + \phi_{xn} \tag{6}$$

On the other hand, the phase of MRI ϕ'_{xn} can be calculated as follows:

$$\phi'_{xn} = \tan^{-1}\frac{Im[F'(x,n)]}{Re[F'(x,n)]} + m_n\pi \tag{7}$$

where, m_n is an integer. Hence, the left side of Eq. (6) is known. The problem is how to separate the motion component and the phase of image ϕ_{xn}.

To solve this problem, it is noticed that the F_{xn} is the x directional Fourier inverse transformation of the density function. According to the features of density function, a new constraint of the true image component F_{xn} is proposed as follows:

If the density function along a y directional line is symmetric, then the phase of image ϕ_{xn} on the line is a linear function of n (corresponding y position).

Hence, the departure part from the linear function is just the motion component. With this constraint, the artifact due to the y directional motion can be suppressed finally.

3. Explanation of the Constraints

Generally, the y directional density distribution is random, however, the density of a y directional slice line which passes through the subcutaneous fat area is nearly symmetric. As shown in Fig. 3(a), if density distribution is symmetric to the origin, it is a real even function. Based on the features of Fourier transformation, the imaginary of its Fourier transformation is zero, that is, the phase of the spectrum is zero. Furthermore, as shown in Fig. 3(b), if the density distribution $\rho'(x,y)$ is symmetric about the axis $y = y_c$, according to the Fourier transform shift theorem, the following relation is satisfied:

$$\Im_y[\rho'(x,y)] = e^{jk_y n y_c} \cdot \Im_y[\rho(x,y)] \tag{8}$$

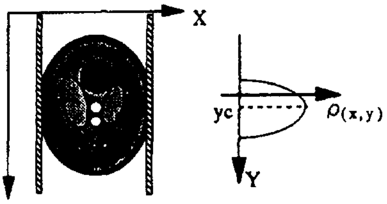

Fig. 3(a) Symmetric density distribution on a y directional line

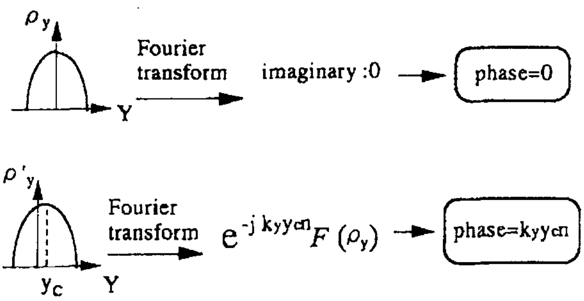

Fig. 3(b) Phase of the spectrum of the symmetric density distribution

Fig. 3 Explanational of the constraint conditions

Hence, if the density function along a y directional line is symmetric, then the phase of the image ϕ_{xn} on the line is a linear function of n, and i.e.,

$$\phi_{xn} = k_y n\, y_c \tag{9}$$

This relation is used as a constraint for the phase of the image. By substituting Eq. (9) in Eq. (6), the following relation is obtained.

$$\frac{\phi'_{xn}}{n\,k_y} = y_c + \Delta_n \tag{10}$$

where, y_c is a constant, which affects the reconstructed image as a position of symmetric axis of symmetric density distribution, but it does not cause any artifact in the image.

Ⅳ. Simulation Results

The proposed method was evaluated by simulation experiments using a Shepp and Logan phantom shown in Fig. 4(a)[11,12]. The x and y directional motions were given by

$$\Delta_x(n) = 1.8\cos(16\,k_x n) + 1.8\sin(16\,k_x n) \tag{11}$$

$$\Delta_y(n) = 1.8\cos(16\,k_y n) + 1.8\sin(16\,k_y n) \tag{12}$$

$$(\,k_x = k_y = 2\pi/256)$$

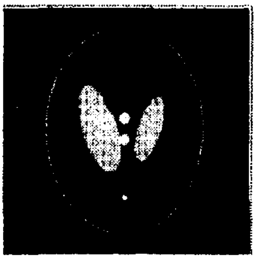

Fig. 4(a) Original image

Fig. 4(b) MR image image with artifact

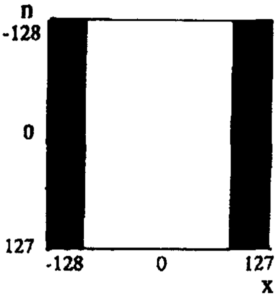

Fig. 4(c) Edge of amplitude of F_{xn}

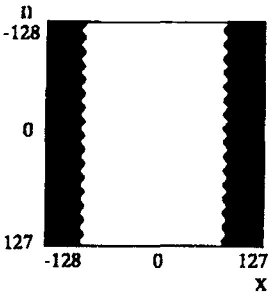

Fig. 4(d) Edge of amplitude of F'_{xn}

Fig. 4(e) Reconstructed image after shifting F'_{xn}

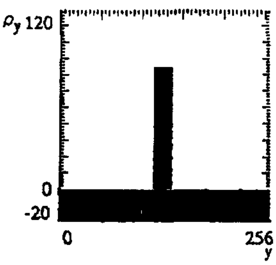

Fig. 4(f) Density distribution on a y directional line

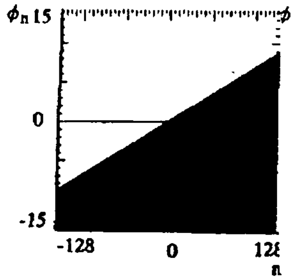

Fig. 4(g) Phase of $F_{xn}(\phi_{xn})$

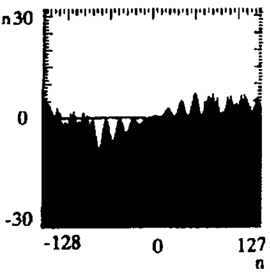

Fig. 4(h) Phase of $F'_{xn}(\phi'_{xn})$

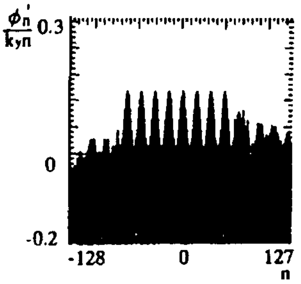

Fig. 4(i) Estimated y directional motion($\phi'_{xn}/k_y n$)

Fig. 4(j) Reconstructed MRI after canceling the motion

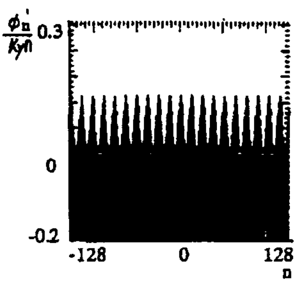

Fig. 4(k) $\phi'_{xn}/k_y n$ after extrapolation processing

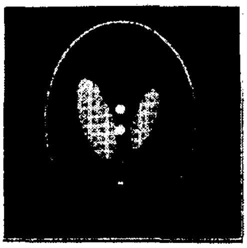

Fig. 4(l) Reconstructed MRI after canceling the extrapolated motion

Fig. 4 Cancellation of the 2D translational motion artifact

The reconstructed MR image with an artifact due to the above motion is shown in Fig. 4(b). First, the cancellation of the x directional motion component was done. The amplitude of the spectrum of the MRI signal without the x directional motion and with the x directional motion is shown in Fig. 4(c) and Fig. 4(d), respectively. The non-zero area of the amplitude is shown as a white area, and the zero area of the amplitude is shown as a black area. The edges between zero and non-zero in Fig. 4(c) show as a straight line, and the edges in Fig. 4(d) do not show as a straight line. The spectrum data in x direction is shifted to let the edge of the spectrum make a straight line. Based on this shifted spectrum data, the reconstructed MR image is shown in Fig. 4(e). The artifact was partly canceled.

The remaining motion component was y directional motion. It was canceled by the algorithm mentioned above. Fig. 4(f) shows the density function along a y directional line which passes through the edge of the phantom. Fig. 4(g) shows the phase of the spectrum along the y directional line without y directional motion, and the phase ϕ_{xn} is a linear function of n. Fig. 4(h) shows the phase ϕ'_{xn} when the y directional motion $\Delta_y(n)$ occured. Fig. 4(i) shows the $\phi'_x(n)/n\,k_y$, which is regarded as the y directional motion.

Regarding the cancellation of the y directional motion, the phase of MRI ϕ'_{xn} is calculated by Eq. (7). In order to decide the m, the ϕ'_n of two adjacent points are assumed to be continuous, shown as follows:

$$|\phi'_n - \phi'_{n-1}| = |n k_y(\Delta_n - \Delta_{n-1}) + k_y \Delta_n + \phi_n - \phi_{n-1}| < \pi \qquad (13)$$

When the n is large and the change of motion between two adjacent points is not small, Eq. (13) is not to be satisfied and the estimation of motion may cause some error. However, the error in the large n area only causes high frequency artifacts, shown as Fig. 4(j). It affected the quality of MRI a little bit. Further, if the change of motions is assumed to be smooth, the error of the estimation of ϕ'_{xn} can be corrected by extrapolation processing. The corrected ϕ'_{xn} is shown in Fig. 4(k), and the reconstructed MRI from the corrected ϕ'_{xn} is shown in Fig. 4(l). Further, the constraint condition requites symmetric density distribution along a y directional line.

Ⅴ. Discussion

Several problems in the above algorithm are discussed here. Regarding the cancellation of the x directional motion, only an integer pixel unit motion is canceled, that is, the subpixel motion is neglected here. This is also a part of the reason that some artifacts remain in the final reconstructed MRI. However, the subpixel motion does not cause a large artifact in the reconstructed MRI. This is shown in the following simulation result. Fig. 5(a) is the reconstructed MR image when there is the subpixel motion in x direction as follow:

$$\Delta_x(n) = 0.3\cos(16\,k_x n) + 0.3\sin(16\,k_x n) \tag{14}$$

Fig. 5(b) is the reconstructed MR image when there is the same subpixel motion as $\Delta_x(n)$ in the y direction.

$$\Delta_y(n) = 0.3\cos(16\,k_y n) + 0.3\sin(16\,k_y n) \tag{15}$$

In the case of the comparision of artifacts due to subpixel motion as shown in Fig. 5(a) and Fig. 5(b), it can mean that the affection due to y directional motion is bigger than it due to x directional motion.

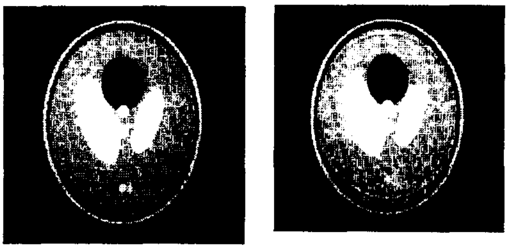

Fig. 5(a) MR image with artifact due to x directional subpixel motion

Fig. 5(b) MR image with artifact due to y directional subpixel motion

Fig. 5 Comparision of artifacts due to x and y directional motion

Fig. 6 shows the simulation result of which the density distribution along a y directional line through a subcutaneous fat area is not perfectly symmetrical and the motions are the same as Eq. (11)~(12). Fig. 6(a) shows the original MRI. Fig. 6(b) shows the MRI before canceling the artifact. Fig. 6(c) shows the asymmetric density distribution along a y directional line. Fig. 6(d) shows the phase of x directional spectrum without motion. Fig. 6(e) shows the estimation of y directional motions ($\phi'_x(n)/n\,k_y$), after canceling x directional motions. Fig. 6(f) shows the reconstructed MRI after canceling the y directional motion component. The result shows the proposed method to be still effective in such a general case.

Fig. 6(a) Original image

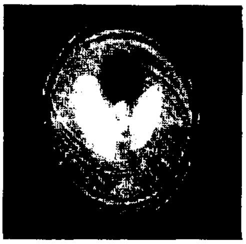

Fig. 6(b) MR image with artifact

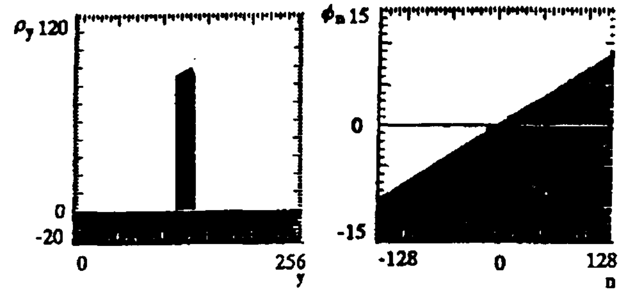

Fig. 6(c) Asymmetric density distribution on y directional line

Fig. 6(d) Phase of x directional spectrum without motion

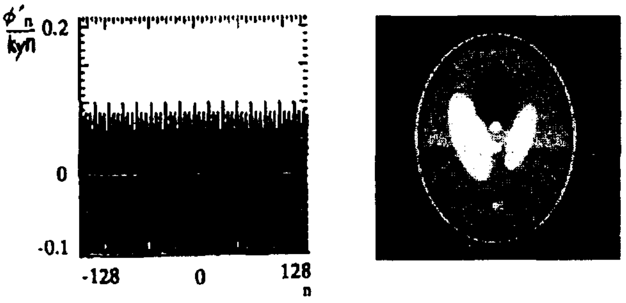

Fig. 6(e) Estimation of y directional motions($\phi'_{xn}/k_y n$)

Fig. 6(f) Reconstructed image after canceling the motion artifact

Fig. 6 Simulation for Asymmetric Density Distribution

VI. Conclusions

Based on the principles of MRI, a new algorithm for canceling the MRI artifact due to 2D translational motion in the image plane is described. Unlike the conventional iterative phase retrieval algorithm, in which there is no guarantee for the convergence, a direct method for estimating the motion is presented. In previous approaches, the motions in the x direction and the y direction are estimated simultaneously. However, the features of the x and y directional motions are different from each other. By analyzing their features, each x and y directional motion is canceled by different algorithms. It is noticed that the x directional motion corresponds to a shift of the x directional spectrum of the MRI signal, and the non-zero area of the spectrum just corresponds to the projected area of the density function on the x axis. So the motion is estimated by tracing the edges between the non-zero area and zero area of the spectrum, and the x directional motion is canceled by shifting the spectrum in opposite directions. The y directional motion is canceled by using a new constraint condition, with which the motion component and the true image component can be separated. The effectiveness of this algorithm was shown by using a phantom image with simulated motion. On the other hand, this algorithm was only applied to rigid motions, and it must be further studied to apply this algorithm to non-rigid motions. This algorithm was only tested with simulations until now, it must be tested with a real MRI experiment. Further, the algorithm requires a symmetric density distribution along a y directional line. If such a line does not exist, an isotropic object is appended on the target prior to the imaging test. The y directional motion will be estimated by a line passing through the object, and the effectiveness of that algorithm will be tested.

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