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REDUCING RESPIRATORY ARTIFACTS IN CHEST MR IMAGES THROUGH HYBRID SPACE MOTION TRACKING AND POST-PROCESSING

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ABSTRACT

A new post-processing method of correcting for respiratory motion induced artifacts in magnetic resonance imaging (MRI) is presented. The motion of the chest during respiration is modeled as a combination of translation and dilation. Displacements of the chest wall are tracked via a thin, MR-sensitive plate placed on the patient's chest during a scan. Scanning with phase encoding left/right (L/R) and frequency encoding anterior/posterior (A/P) causes the motion artifacts to be repeated in the L/R direction, thus not overlapping on the plate. By performing the inverse A/P Fourier transform, the resulting hybrid space data has A/P spatial data and L/R spatial frequency data, in which the motion of the plate is clearly visible as a nearly periodic waveform. Modeling the motion of the chest wall as an equal combination of translation and dilation allows corrections to the image to be made in k-space using properties of the Fourier transform and the measured displacement data. Noticeable reduction of the intensity of the motion artifacts is achieved, indicating the validity of the motion model and tracking method.

1.0 INTRODUCTION

Magnetic resonance imaging (MRI) is a non-invasive imaging modality used to view the structure of soft tissue. Despite many advances in the quality of this imaging technique, one continuing obstacle to generating high quality images is the effect of motion during a scan. The two major sources of physiologic motion during a scan are cardiac motion with associated blood flow and respiratory motion of the chest and abdomen. This paper addresses the reduction of artifacts due to respiratory motion.

Typical scan times in MR imaging are on the order of tens of minutes, during which time significant respiratory motion can occur. The effects of respiratory motion are well known to MRI professionals. This motion causes the formation of repeated artifacts called ghosts across the image that interfere with diagnosis, sometimes to the point of making the image useless. Because MRI of the chest and abdomen is an important diagnostic tool, much research has been done on the causes and potential solutions to this problem.^{2,6,10,12} In this paper, we present a new approach to reducing the ghosts caused by respiratory motion.

The breathing cycle can be viewed as approximately periodic which allows for the application of harmonic analysis to the presented problem. Several researchers have presented detailed mathematical analysis of the cause of ghosts in scans of objects exhibiting simple harmonic motion.^{1,5,11} It has been shown that exact knowledge of the nature and extent of such motion allows for the elimination of the ghost artifacts.

Our method involves an approach to tracking the motion of the body wall and modeling the nature of the motion. An MR sensitive plate placed on the chest of the patient during a scan provides a strong signal at the chest wall. Scanning with phase encoding left/right and frequency encoding anterior/posterior (A/P) causes the motion artifacts to be left/right, thus not blurring the plate. By performing the A/P Fourier transform, the resulting hybrid space data has A/P spatial data and L/R k-space in which the motion of the plate is clearly visible as a sinusoid. Modeling the motion of the chest wall as an equal combination of translation and dilation allows corrections to the image to be made in k-space using properties of the Fourier transform and the measured displacement data.

2.0 MOTION EFFECTS

Motion during a scan can seriously degrade the quality of the reconstructed image. Figure 2.1 shows an image of an abdominal scan without any motion compensation. It is clear that this image has lost much of its diagnostic value because of the

motion artifacts which are repeated at regular intervals in the y-direction. These artifacts are referred to as ghosts and are the result of phase errors due to motion. The motion is normally in all directions, but the ghosts are always in the phase encoding direction. This paper addresses only motion in the xy-plane, only in the y-direction.

Figure 2.1 Clinical Image Showing Respiratory Artifacts

Motion in the excited plane affects the frequency of precession of a proton. Because the field strength is changing with position due to the gradients, motion can cause the magnetization to be assigned an incorrect point in the image plane. The amount of movement due to respiratory motion during the time between the excitation pulse and the last sample of a view being taken (TE) has a negligible affect on the image because it is normally on the order of milliseconds [5–50]. This is called *intra-view* motion. However, the duration of one entire view (TR~500 msec) allows for significant respiratory motion (*inter-view* motion) to occur. Detailed mathematical explanation of motion in each direction of image space (x, y, and z) have been presented by Wood and Henkelman¹¹ and Haacke and Patrick.⁵

The methods of Fourier transform reconstruction in magnetic resonance imaging are well known, and there are many excellent references describing the details of this technique.^{3,7,9} Therefore, our discussion will begin with presenting the basic equation for MR imaging of stationary structures,

$$s(k_x, k_y) = \int \int_{-\infty}^{\infty} \rho(x, y) e^{-j2\pi(k_x x + k_y y)} dx dy \quad (2.1)$$

where s is the acquired MR signal and k_x and k_y are the frequency components of the spin density $\rho(x, y)$.

Using the equations for Fourier transform imaging, we can explore the effects motion has on an MR image. Our methods explore two types of motion in the xy-plane: translation and dilation. We will show that these types of motion affect the imaging equation in such a way that properties of the Fourier transform can be used to correct the images through post-processing.

2.1 Translation

When the object being scanned experiences a translation, a phase error is introduced which causes improper assignment of the spin density and thus, artifacts. For example, a displacement of the entire image by an amount Δy in the y-direction (frequency encoding direction, for our purposes) would affect the imaging equation as follows:

$$s(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \rho(x_0, y_0) e^{-j2\pi k_x x_0 - j2\pi k_y (y_0 + \Delta y)} dx_0 dy_0 \quad (2.2)$$

The original image may be recovered by multiplying each (k_x, k_y) value in the image by

$$e^{-j2\pi k_y (-\Delta y)} \quad (2.3)$$

which is simply a phase shift. This is actually just an application of the Fourier transform shift property

$$x(t - t_0) \Leftrightarrow e^{-j2\pi f t_0} X(f) \quad (2.4)$$

Knowing the displacements of the translation motion makes the task of correcting the image relatively simple. Equation (2.3) shows that a translational shift is corrected by multiplying each element of each column of the k -space image by the $e^{-j2\pi k_y (-\Delta y)}$ phase shift where Δy is the known shift amount. Because we are dealing with discrete images and hence the Discrete Fourier Transform (DFT), the transform pair must be from the DFT. The DFT complement to Equation (2.4) is

$$x(n - l) \Leftrightarrow X(k) e^{-j2\pi k l / N} \quad (2.5)$$

where N is the number of points in the DFT and l is the shift amount.

This correction would completely remove the effect of motion. Likewise, when the amount of translation (Δy) varies with time, such as with sinusoidal motion, each column of data in the image is affected individually. Multiplying each column of raw data by the corresponding phase shift value will remove any resulting motion artifacts. Therefore, it is necessary to know the value of the displacement in each column to make this correction.

2.2 Dilation

The expanding and contracting chest cavity is also experiencing what we call dilation. This type of motion is typically thought of as an expansion (or contraction) of an object with a fixed center point that does not experience any motion. Our model places the constraint that the dilation is only in the y -direction. As with translation, we look to the properties of the Fourier transform for a method of correcting for dilation. Realizing that dilation is actually the same as scaling, we can use the Fourier transform pair relation for scaling, which is known to be

$$x(at) \Leftrightarrow \frac{1}{|a|} X\left(\frac{\omega}{a}\right) \quad (2.6)$$

where a is the scale factor and ω is the frequency in radians. From this we can see that a doubling in the time domain results in a halving in frequency. In this application, shrinking the object in the spatial domain corresponds to extending or spreading in the frequency domain. Likewise, a positive growth or expansion of the object in space coordinates is paired with a shrinking of the

frequency spacings.

The scaling property is thus used to correct for the dilation component of respiration. When this scaling is performed, the exact frequency components generated by the $\frac{\omega}{a}$ term will not necessarily be available from the DFT and some interpolation is used. By scaling and interpolating each column affected by dilation, the effects can be reduced or potentially eliminated. However, once again we must know the amount of dilation in order to accomplish this correction.

Thus, we now have an understanding of the components of respiratory motion and a concept of how to correct the affected image. In order to be able to use the applications of the Fourier transform developed in this section, we must know the amount of motion at each column of the image. The next section presents our method for detecting this information.

3.0 METHODS

In this section, the methods used to acquire information about the motion of the chest are shown. Once the characteristics of the motion are extracted, its origin must be determined. In this paper, respiratory motion is modeled as the combination of translation and dilation. With the correct analysis of the motion, steps can be taken based upon the developments of the previous section to remove the ghosts caused by the motion.

3.1 Motion Model

Having discussed the individual effects of translation and dilation, we are now ready to combine them and apply the concepts to a more complete model of the motion of the chest during respiration that assesses a fraction of the motion to translation and the remainder to dilation. Consider the motion of the chest during deep, chest breathing of a person lying on a flat surface. The cross section is approximated by the elliptical-shaped model. The bottom of the ellipse represents the back or spine area. This region is fixed during respiratory motion because of the fixed, flat surface. With the previous model for dilation, when a vertical expansion of y total pixels occurs it does so symmetrically about the horizontal center: $y/2$ pixels in each direction. If this same expansion were to happen to an ellipse with a fixed bottom, the top of the ellipse would expand y pixels relative to the bottom and the center point would raise by $y/2$ pixels (Figure 3.1). This same result of expansion and a translated center point could be equivalently produced by first translating the ellipse by $y/2$ pixels and then dilating by $y/2$ pixels in each direction (Figure 3.2). Thus, although the expansion occurs with the bottom fixed, it can be modeled as a translation

followed by a dilation. In this case, the total vertical position change of the top of the ellipse is y pixels. Half, or $y/2$ pixels, is due to the translation of the center point and the other half is due to the dilation.

3.2 Motion Tracking

Several methods have been used to track motion during scans.⁸ These include the hydrostatic pressure transducer system used with the R.O.P.E. technique and navigator echoes which are encoded into the pulse sequence.⁴ The technique presented in this paper is unique in its method of using data extracted from the acquired image to measure displacement. We have found that placing an MR sensitive plate on the chest of the patient provides a point of reference for the maximum height of the chest, and the displacement of the plate reflects the amount of motion of the chest.

Conventional scans frequently select the phase encode direction to be in the anterior/posterior (A/P) direction so that ghosts due to cardiac motion do not interfere with the view of the liver and other organs. Since it is known that the ghosts due to motion will be in the same direction as the phase encoding, these ghosts will blur the motion of the plate, as shown in the computer simulated image of Figure 3.3. However, by selecting the phase encode direction to be left/right and frequency encode to be A/P, the ghosts will not interfere with the view of the plate. (Figure 3.4).

Figure 3.3 Simulated Motion Artifacts (A/P)

Conventional x,y space viewing of the image does not show the motion on a column-by-column basis. In order to extract this information from the image, it is converted to what is referred to as hybrid space by performing the Fourier transform in one direction only. Hybrid space images display frequency information in one direction and spatial information in the other direction. Specifically, we take the inverse column Fourier transform of the raw k-space data which generates an image with frequency data along the rows and spatial data along the columns.

Figure 3.5 shows a hybrid space image of the computer phantom with ghosts L/R. Keeping the columns in the spatial domain shows the height of the phantom but the width is represented by its frequency data. Thus, when there is motion by the chest and hence the plate, the peak of each column is the position of the top of the plate at the time of the corresponding phase encoding view. If the rows were transformed to the spatial domain as well, the distinction of the peak of each column would be eliminated by the transform. The triangular wave of motion shown at the top of the image in Figure 3.5 is then the simulated breathing cycle.

3.3 Correction

The hybrid-space motion tracking provides a method of determining the amount of displacement in each column, allowing for a column-by-column correction. Because the breathing cycle is shown by the top of the plate in the hybrid-space images, we can extract the displacement from these images. The method is as follows: The position of the top of the plate in each column is determined through edge detection and stored in memory. A mean value is determined for this array of peak values, which becomes the reference position. Our goal is correct the image such that the resulting hybrid-space image has a level plate-top. Thus, each column must be translated and scaled to the reference position. By computing the difference between the measured peak position for each column and the reference position, we can determine the Δy value for each column.

Having determined Δy for each column, we can use the concepts developed in sections 2.1 and 2.2 to correct the image. In our model for motion, we approximate respiratory motion as an equal combination of translation and dilation. When correcting, the effects of translation are removed first, then the dilation correction is applied. The reason for this is that the translation correction aligns the center frequency of each column along the same line. Therefore allowing for a uniform application of the scaling and interpolation used for dilation correction.

Figure 3.4 Simulated Motion Artifacts (L/R)

Figure 3.5 Simulated Hybrid-Space Image

4.0 RESULTS

The correction methods described in the previous section were applied to the computer model image shown in Figure 3.4 and its corresponding hybrid space image (Figure 3.5). Figure 4.1 is the corrected image.

Figure 4.1 Corrected Computer Simulation Image

This method was also applied to clinical images of a normal volunteer. Figure 4.2 shows the original clinical image with no motion compensation. The corresponding hybrid-space image in Figure 4.3. As with the simulations, the motion of the chest wall is tracked by the MR-sensitive plate. The outer frequencies (left and right edges) begin to fade for lack of signal strength in the plate. Because of this fading, some of the edge detection on the peak positions was done by hand. Figure 4.4 shows the final corrected clinical image. Results show a reduction in the intensity of the artifacts, especially those due to the motion of the chest wall. Note the reduction in the chest-wall artifacts repeated within the chest cavity. The improvements are not as obvious as

those seen in the computer model. Perhaps the most important result regarding the clinical image was that the motion of the chest was clearly visible when viewed in hybrid space.

Figure 4.2 Clinical Image with Artifacts

Figure 4.3 Hybrid Space of Clinical Image

Figure 4.4 Corrected Clinical Image

5.0 CONCLUSIONS

Respiratory motion can be tracked through use of a thin, MR-sensitive plate placed on the chest of the patient during scanning. If phase encoding is selected to be L/R, the output, when viewed in hybrid space, shows the plate's (and hence that of the chest wall) path of motion. Motion modeled as a combination of translation and dilation, where translation is corrected through a phase-shift and dilation through scaling of the spatial frequency data, provides a method for using Fourier transform properties to correct the image. The parameters required by the correction algorithm can be extracted from the hybrid space image using edge detection.

The proposed model is simple enough to allow the corrections to be implemented quickly and with well-known properties of the Fourier transform. However, a more complicated model may be necessary to achieve greater improvements in clinical images.

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