Fast Motion Artifact Correction Using l_1-norm

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Purpose : Patient motion during magnetic resonance (MR) imaging is one of the major problems due to its long scan time. Entropy based post-processing motion correction techniques have been shown to correct motion artifact effectively. One of main limitations of these techniques however is its long processing time. In this study, we propose several methods to reduce this long processing time effectively.

Materials and Methods : To reduce the long processing time, we used the separability property of two dimensional Fourier transform (2-D FT). Also, a computationally light metric (sum of all image pixel intensity) was used instead of the entropy criterion. Finally, partial Fourier reconstruction, in particular the projection onto convex set (POCS) method, was combined thereby reducing the size of the data which should be processed and corrected.

Results : Time savings of each proposed method are presented with different data size of brain images. In vivo data were processed using the proposed method and showed similar image quality. The total processing time was reduced to 15% in two dimensional images and 30% in the three dimensional images.

Conclusion : The proposed methods can be useful in reducing image motion artifacts when only post-processing motion correction algorithms are available. The proposed methods can also be combined with parallel imaging technique to further reduce the processing times.

Index words : Motion artifact
Magnetic resonance (MR)
Post-processing
POCS

Introduction

Patient motion during MR scans remains as one of the major problems. While advanced correction methods using for example navigators have been developed (1), clinical institutions without these features exist. Even if these methods were available, cases where uncorrected motion remain and post-processing is the last resort can still be found. In

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addition, navigators are often accompanied with a longer scan time compared to standard sequence protocols.

Several post-processing motion correction techniques have previously been introduced to reduce motion artifacts (2–7). These methods rely on perturbing the k-space data acquired continuously to find a motion-free image. Metrics such as the entropy of the image are typically used to quantify the amount of motion present. These techniques known as autocorrection (also known as autofocusing) have been shown to reduce translational motion artifacts effectively. The main benefit of these techniques is that it does not need any additional data acquisition (e.g., navigator echo) which prolong the scan time. These techniques can also prevent the problem of re-scanning the patient and enable the use of the data which is difficult to reproduce (e.g., fMRI).

One of the main limitations of these techniques however is its long processing time required to find the optimal image. A huge number of Fourier transform (FT) steps are required since k-space re-phasing is iteratively applied and for each k-space correction and calculation of the metric in the image space needs to be performed. Thus, most of the processing time is spent on the FT operation and in calculating the image metric. The situation can be more problematic in three dimensional (3D) images due to the increased data size.

Here, we propose a simple method to reduce this total processing time for metric based motion correction techniques. The target is for two and three dimensional applications where motion artifacts are dominant in the phase encoded direction but extensions for correcting different motion components can be applied.

Theory

In this section, we introduce the elements that were implemented to reduce the processing time required for motion correction. The basic correction scheme of our approach and previous approaches are to apply trial phases to the raw data and find the image that minimizes (or maximizes) some given metric. In MR imaging of 2-D FT or 3-D FT data, in-plane rigid-body translational motion cause phase shifts in k-space data. If motion occurred along phase encoding (PE) direction (y-direction) by Δy during data acquisition of a view with index ky_i, that view will have additional phase of

$$\Delta\phi = 2\pi \frac{ky_i}{FOV_y} \Delta y \qquad [1]$$

where $ky_i = \{-\frac{N_{PE}}{2}, \ldots, -1, 0, 1, \ldots \frac{N_{PE}}{2} - 1\}$.

Therefore, motion correction process can be viewed as a re-phasing process. Normally, the acquisition time of one view is relatively smaller than the time between each view, and therefore we will ignore the intraview motion (i.e., motion along x-dimension). Therefore, it can be seen that phase correction need only be applied to phase encoded k-space domains and is independent of the other domain. Thus in 3-D FT imaging which has two phase-encoding directions, re-phasing of each view can correct for motion of two spatial dimensions simultaneously and also FT in the readout direction need not be performed because the re-phasing process can be applied after FT along readout direction. These features were used to save processing time.

Several metrics can be used to evaluate the post-processed images (4). Entropy is a commonly used metric which shows the measure of minimum number of bits to represent information. This concept was first used in autocorrection of MR image by Atkinson et al (2). The idea is that motion blurred images will have more gray value to represent an image than motion-free images. Thus the former will have larger entropy than latter. Therefore, entropy minimization results in motion compensated image.

The entropy focus criterion E was defined as

$$E = -\sum_{j=1}^{N} \frac{B_j}{B_{\max}} \ln\left(\frac{B_j}{B_{\max}}\right) \qquad [2]$$

where N is the number of image pixels and B_j is the magnitude of gray value of the j th image pixel, and

$$B_{\max} = \sqrt{\sum_{j=1}^{N} B_j^2}\ .$$

Entropy minimization tends to produce images that have a small number of bright pixels and many dark regions. This can sometimes spoil the images in case when the image has a large uniform signal intensity region. Nevertheless, the entropy shows good image quality relative to the other metrics (4). The problem lies in its relatively long processing time required to find the entropy. The entropy formula in Eq. 2 needs $5N$ operations when ignoring the computational complexity of the logarithm and the multiplication operation. Therefore, approximately $2\sqrt{N}\ \log_2\sqrt{N}$ (Fourier transform) + $4N$ (magnitude) + $5N$ operations are required to test for one trial phase.

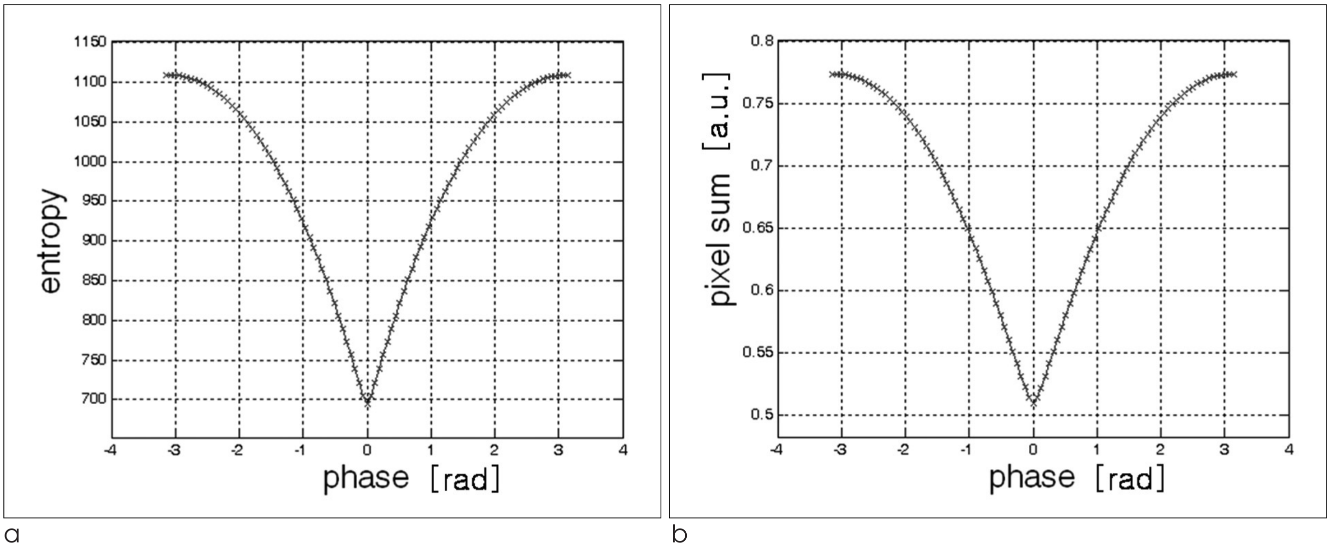
Thus, an alternative metric with simpler calculations can be advantageous. Here, we used the sum of pixel intensities (pixel sum) in the image as an alternative metric. This metric can be represented by

$$pixel\ sum = \sum_{j=1}^{N} B_j \qquad [3]$$

with same notation of N and B_j in equation 2. We can readily see the advantage of this metric in its computational simplicity.

The entropy metric and the pixel sum metric have similar characteristics in that minimizing one of them equally minimizes the other. Figure 1 shows this relationship of how entropy minimization and pixel sum minimization behave similarly. This relationship is from a block of 16 lines near the center of k-space of the analytic phantom image. However, similar relationships were observed in the in-vivo image data. On the left is the entropy as a function of applied phase while the right shows the behavior of the pixel sum. Intuitively, this is because minimization of the pixel sum of an image is related to enhancing the sparsity of an image. Entropy minimization, which results in refocusing also enhances the sparsity of an image. In regards to calculation time however, the metric pixel sum significantly reduces the overall computation time ($2\sqrt{N}\ \log_2\sqrt{N}$ + $4N$ + N operations) compared to entropy calculations to approximately 50% after Fourier transform due to the absence of the computationally intensive logarithm and multiplication operations.

Furthermore, we combined partial k-space reconstruction using the projection onto convex-set (POCS) method to further reduce the total processing time (8). Partial Fourier data acquisition has been widely used to reduce echo-time and/or total scan time (9–11). Partial acquisition along PE direction has the additional benefit of being less susceptibility to motion. The method adopted into the POCS routine is simple. If we have no motion in certain parts of k-space, we can construct a motion-free image from that part using partial reconstruction. In other words, we have to correct the motion component only in the partial k-space data. The remaining part of the data is discarded and will be reconstructed with the POCS method just as if it was not acquired. Therefore, we can save the total processing time by reducing the k-space lines that should be corrected. As motion itself can occur randomly, it is not obvious which lines of k-space are actually motion-free. Therefore, in this study we divided the whole k-space into two parts (four for 3-D FT), namely the upper and the lower partial k-space



a b

Fig. 1. Behavior of the entropy (a) and the pixel sum (b) value relative to the k-space phase offset. The metric pixel sum has similar characteristic with entropy. Therefore, minimizing entropy values is equivalent to minimizing the pixel sum value. Note that the pixel sum is the sum of all image pixel intensities (arbitrary unit (a.u.)).

segments (four quadrants for 3-D FT). From these two segments, we can detect which part has less motion by using the above metric with POCS reconstructed images. Taking the less corrupted segment, we perform the motion correction algorithm to that segment and reconstruct the image from the partially corrected k-space data. During the correction process of certain segments, zero-padding was not performed in the k-space domain to find the image metric value. Since the image size is directly related to the number of FT operations and the number of computations in the metric calculation, we can reduce the overall computation time by a large amount.

Methods

A summary of the conventional and proposed algorithm is shown in Fig. 2 with the detailed procedure illustrated for each step. The modified methods of the proposed algorithm are colored in red in Fig. 2(b). Specifically, these include the pixel sum metric, separated 2-D FT, and POCS reconstruction. Also, in the actual implementation, we applied phase variations rather than displacement variations (Eq. 1) to remove motion induced phase. By using this approach, it has an additional benefit of preventing the wrapping of image metric value (7).

We used a search strategy form center-to-out fashion that finds the phase of a block from the center of k-space to the edge of k-space in an orderly manner (5). After the size and position of a block is defined, a modified binary search method was used to find the optimal phase. The search started at a phase of +4 pixels shift according to the k-space position, with reduced phase by 0.25 times if the image metric does not reduce in that direction. The minimum phase resolution was 0.1 pixel shift. The same phase was applied to group of views in a block for the data set (as shown in Fig. 2). Our proposed autocorrection algorithm was implemented with MatLab R2007a on an Intel dual core processor (2.1GHz) with 2GB memory. The processing time savings were recorded for the various routines mentioned above. For POCS reconstruction, 12.5% of total PE lines were used for low-resolution phase correction for 2D data set and 16.81% (equivalent to 41% of each phase-encoding direction) for 3D data set.

To test our approach, we used a sagittal head image data by simulating randomly generated motion. In vivo data were also collected for 2D and 3D image using Turbo-Field echo (TFE) sequence from the Philips 3.0T scanner with following parameters: TR/TE = 2000 ms/10 ms; FOV = 230×183 mm; 512×408 matrix; 20 slice with 5 mm thickness; flip angle = 90°; single coil was used for 2D image and TR/TE = 9.9 ms/4.6 ms; FOV = 224×224×170 mm; 224×224×170 matrix; flip angle = 8° for 3D image. The volunteer was asked to produce small random motion of the size below 0.5 cm.

Results

Figure 3 shows the result from the simulated images. Motion was applied in the PE direction (left-right). As expected, the image of Fig. 3(b) is corrupted by motion, and its entropy was increased from 811.7 to 861.5.

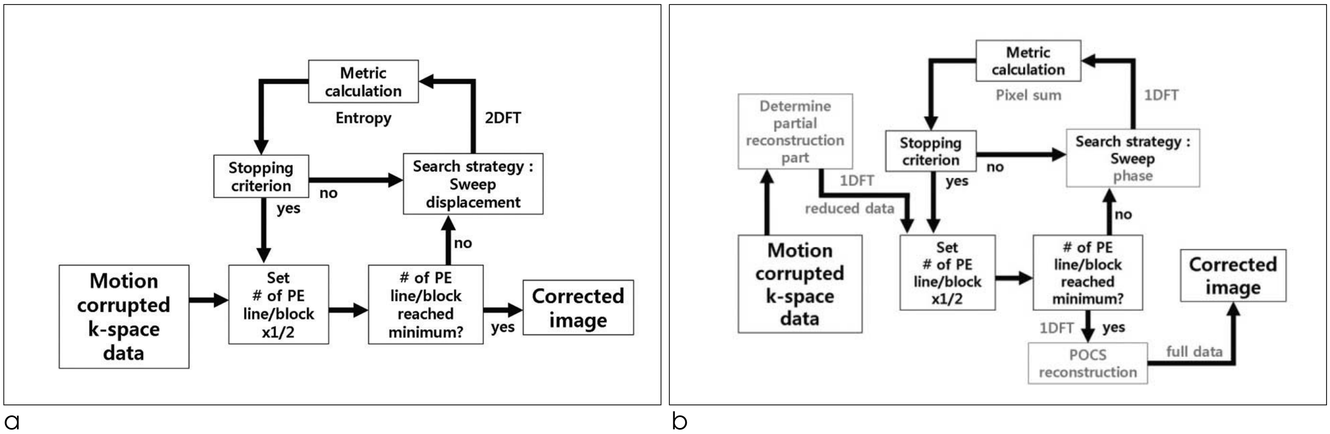


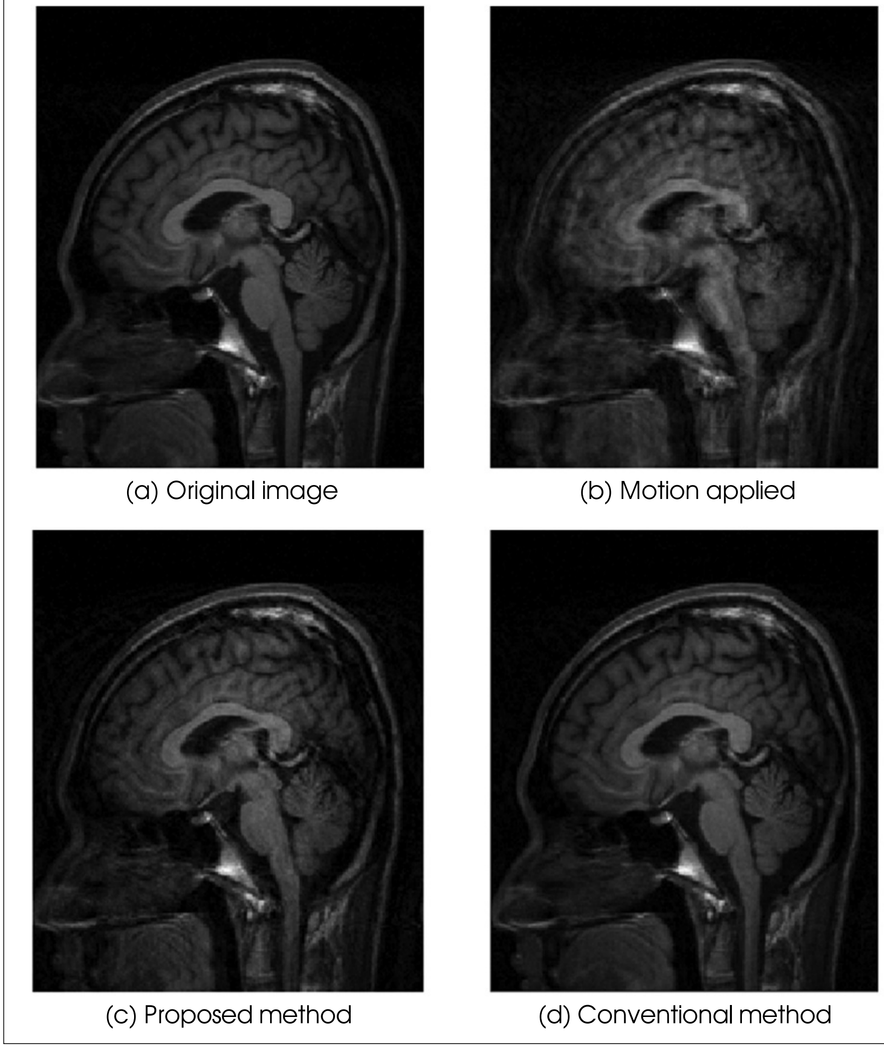
Fig. 2. Summary of the conventional (a) and the proposed (b) algorithm. Alteration from the conventional approach, specifically, the metric pixel sum, separated 2-D FT, combining POCS and application of phase are represented in red (b).

After motion correction however (Fig. 3(c) and 3(d)), the images have been corrected and its entropy value has been decreased to 806.2 and 809.3 respectively. We can see that the proposed method shows similar image quality and entropy, but the total processing time was reduced to about 15% from the conventional method.

Figure 4 shows in vivo results obtained before (a) and after (b) applying our proposed method from a subject with voluntary motion. The PE direction is same as that of Fig. 3. The proposed method even shows region where motion artifact is reduced (indicated by the arrow). The motion induced blurring artifact in the outside region of head was reduced. Entropy was also reduced to 1884.5 from 1905.3.

The proposed algorithm was also implemented for 3D version. Figure 5 illustrates corrected and absolute difference images using different methods. The PE direction is anterior-posterior and the slice-encoding direction is left to right. The Minimum block size that was used was set to one slice (224 lines) which corresponds to a time resolution of 2.2 seconds due to the relatively long processing time. The Motion corrupted images is also shown in the left-most column of Fig. 5 for comparison. The Initial entropy of the motion corrupted image was 14383.4, which was reduced after motion correction. Although the reduction of motion artifact is not clearly observable in the corrected images themselves, we can see some artifact reduction in the difference images for all types of method.

Table 1 summarizes the total processing time for each reduction method applied to the data of Fig. 3, 4 and 5. The processing times shown in Table 1 can be used as a reference for comparing the time efficiency of each method. Here we have used the entropy as the final metric for image quality evaluation. For each image


(a) Original image

(b) Motion applied

(c) Proposed method

(d) Conventional method

Fig. 3. Result of the simulated image. Randomly generated motion was applied in (b) in the PE direction (left to right), and the corrected images with conventional (d) and proposed (c) methods are shown. The entropy value after correction is 806.2 (c) and 809.3 (d). The corrected image shows similar image quality and entropy. But processing time of (c) is only 15% of the conventional method (d).

Table 1. Total Processing Time for Various Routines with Different Image Size. Each Method Shows Different Time Reduction according to Image Size. The Total Processing Time Can be Reduced to as Short as 15% with All Proposed Methods

Image size		Separated 2-D FT	Metric used	Partial recon	Entropy	Process time (s)	Time reduction (%)
224 × 200 size (Fig. 3)	1	X	Entropy	X	809.3	65	100
	2	O	Entropy	X	〃	59	91
	3	X	Pixel sum	X	810.4	35	54
	4	O	Pixel sum	X	〃	29	45
	5	O	Pixel sum	O	806.2	9	14
512 × 408 size (Fig. 4)	1	X	Entropy	X	1893.7	719	100
	2	O	Entropy	X	〃	654	91
	3	X	Pixel sum	X	1893.6	415	58
	4	O	Pixel sum	X	〃	350	49
	5	O	Pixel sum	O	1884.5	164	23
224 × 224 × 170 size (Fig. 5)	1	X	Entropy	X	14374.4	4h 52m 26s	100
	4	O	Pixel sum	X	14374.8	3h 29m 50s	72
	5	O	Pixel sum	O	13877.6	1h 30m 5s	31

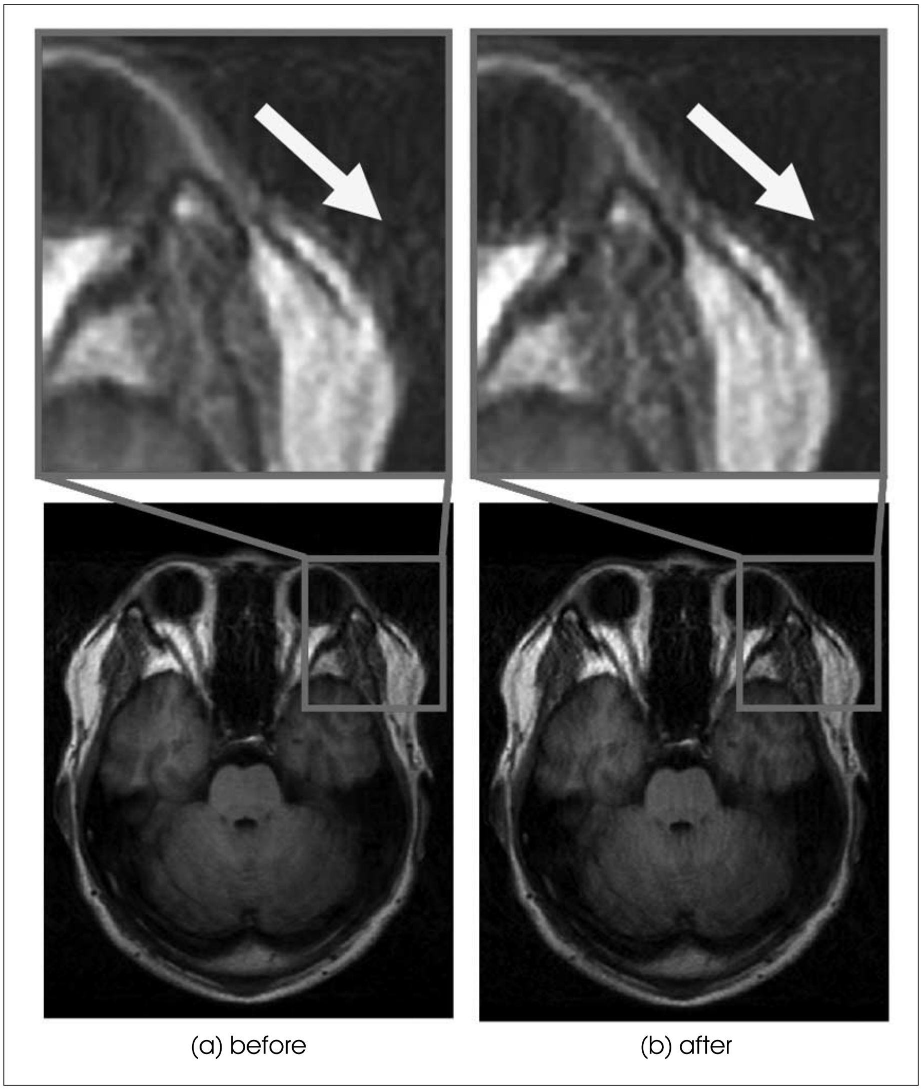


Fig. 4. Result of the in vivo 2D data using proposed method. Voluntary motion caused blurring artifact in (a) and this was reduced after correction in (b). Enlarged image (indicated by the arrow) shows region where blurring artifact was reduced.

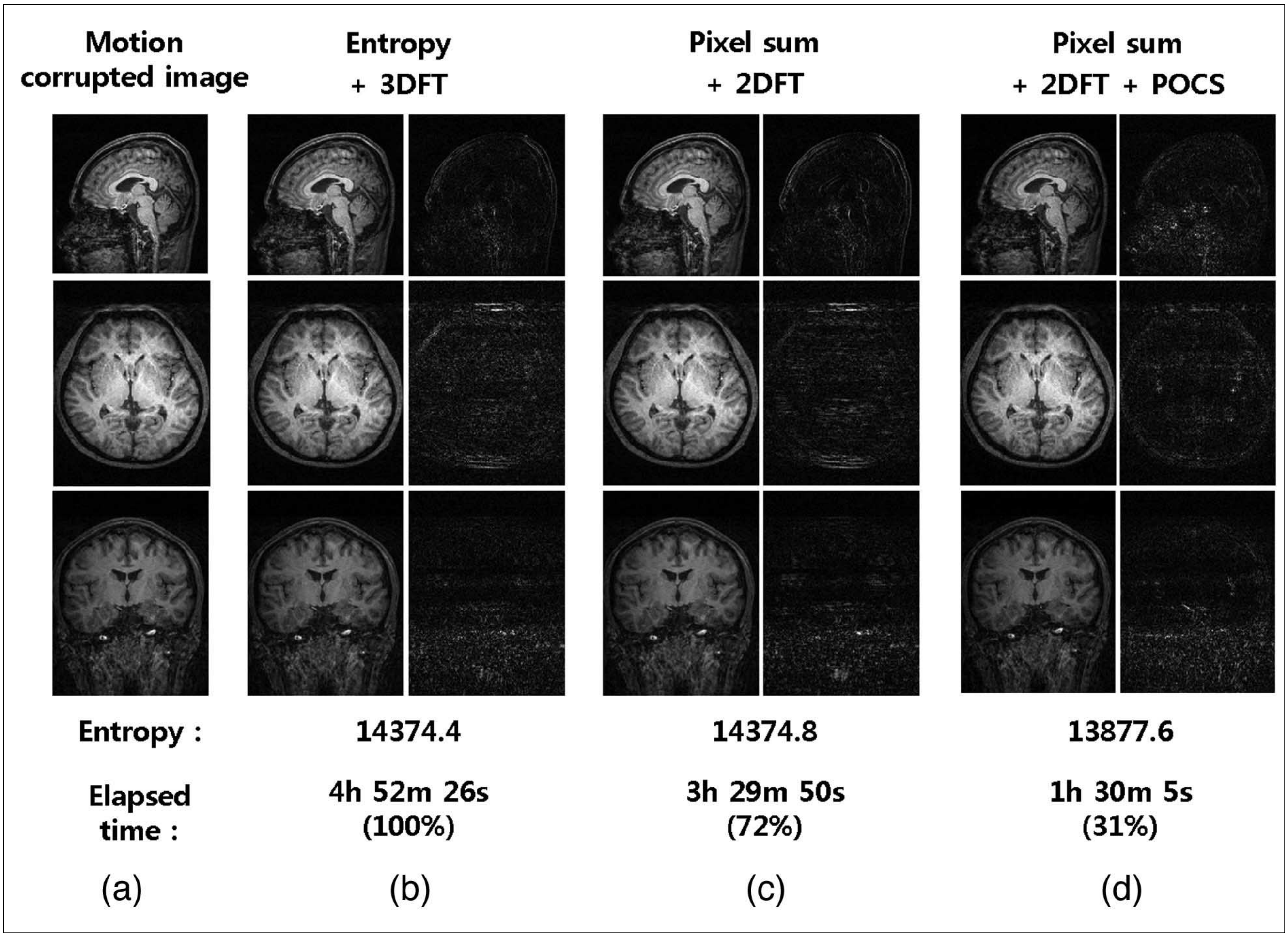


Fig. 5. Results obtained from the 3D data set. Images of three orthogonal views and difference images are shown for various methods along with the entropy of the final image and elapsed reconstruction time. The conventional method is given in (b) while (c) shows the result obtained without the POCS algorithm. With our proposed method (d), similar image quality can be obtained while the processing time can be reduced to about 30% of the conventional method.

size, the "conventional" routine using entropy as its metric and 2-D FT is numbered 1 in the first row. By comparing routine 1 with routine 2 or routine 3 with 4, separated 2-D FT reduces the total processing time to about 10%. Similarly, processing time can be reduced to about 60% by using the pixel sum as its metric. Finally, by combining with the POCS reconstruction, the total processing time can be reduced to as short as 15% of its conventional method. The processing time reduction of 3D image is also shown in the bottom block of Table 1. With the proposed method, our correction algorithm takes only one third of the conventional method's processing time.

Discussion

In this study, a simple method to reduce the processing time of entropy based post-processing motion correction algorithm has been presented. As seen from the results, the major benefit of this approach is in its computational speed, which reduces the processing time to as short as 15% compared to the conventional schemes.

To achieve the processing time savings, the most critical components our proposed method are the pixel sum metric and the inclusion of the POCS algorithm. As shown in Table 1, each of these two methods can reduce the processing time to at least one-third individually. The pixel sum metric also considerably saves process time. In regards to its performance, comparing routine 1 with 4 in Table 1, we can see the pixel sum works quite similarly with entropy as the image metric. The quality performance similarity of the pixel sum and the entropy metric can be seen in Fig. 5(b) and (c). One caution would be that entropy itself may not be suffice as the absolute criterion for motion correction (12).

Combining POCS reduces the whole data size which is directly related to the entire process, therefore we can expect large amount of time savings using with this method. One issue of combining POCS is that by just using POCS reconstruction can reduce the metric value even in motionless data. This can be seen for routine 5 for the 3D image in Table 1, where the entropy of the final corrected image is much smaller than the image of method without using POCS. Therefore, a direct comparison of metric value between the initial corrupted image and the final corrected image with POCS reconstruction may not be meaningful particularly in 3D image.

Another issue of combining POCS is the zero-padding of partial dataset in k-space domain before getting the image metric value during the correction process. Fig. 3(c) shows residual artifacts due to this issue. Because highly asymmetric off-centered k-space data is encoded to the image by Fourier transform, the original influence of the phase in specific k-space views can be modified and this effect makes uncorrected artifacts in the image. However, zero-padding increases the computation time of Fourier transform.

The concept of using partial Fourier reconstruction can also be substituted with parallel imaging techniques. If we assume an acceleration factor of two, the PE lines to be corrected will be reduced to half from the fully sampled dataset, which will further reduce the total processing times. Specifically in T2-weighted TSE imaging for example, the use of parallel imaging techniques can be more effective in the entire correction process. In case of other sequences that are not interleaved, combining both techniques will further reduce the total processing time (13).

Proposed methods can combine with parallel programming on multi-CPU or GPU to make processing time even shorter. One simple approach of parallel programming is finding less corrupted k-space part in parallel. This can also be adopted to applying trial phase if binary search or similar optimization strategy is used. Pipelined programming can also be helpful in processing step which cannot separate parallel. Combining GPU may further reduce processing time by distributing the process of CPU (e.g., Fourier transform).

Conclusion

We have presented a simple method to effectively reduce the processing time of entropy based post-processing motion correction algorithm. The primary advantage of this approach is in its computational speed, which reduces the processing time to as short as 15% compared to the conventional schemes. The primary use of this approach would be on post-processing correction of large 2D image sizes or with 3-D FT k-space acquisition data sets. The method can be useful when alternative methods such as navigators are not available or even be used together with them to further reduce motion degraded artifacts.

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l_1-norm을 이용한 움직임 인공물의 고속 보정

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목적 : 자기공명영상화는 보통 긴 스캔 시간으로 인해 환자의 움직임이 큰 문제가 된다. 이러한 환자의 움직임을 보정하기 위한 한가지 방법인 영상의 엔트로피(entropy)를 이용한 후처리 방법은 다른 추가 데이터 획득 없이 효과적으로 움직임 인공물을 줄일 수 있음을 보였다. 하지만 이 방법의 가장 큰 문제는 처리 시간이 매우 길다는데 있다. 본 연구에서는 움직임 보정 처리시간을 줄이는 방법을 제안한다.

대상 및 방법 : 전체적인 보정 시간을 줄이기 위한 첫 번째 방법은, 퓨리에 변환의 분리성을 이용하여 전체적인 퓨리에 변환시간을 줄일 수 있다. 영상의 엔트로피 기준을 대신해 영상의 전체 화소의 합(pixel sum)을 움직임 보정의 기준으로 이용하여 영상 기준을 계산하는 시간을 절반 이하로 줄일 수 있다. 마지막으로 부분 퓨리에 재구성 방법을 조합하여 움직임의 영향을 보정하는 k-공간의 데이터 량을 줄임으로써 전체적인 처리 시간을 큰 폭으로 줄일 수 있다.

결과 : 제안한 방법을 사용하여 보정한 영상의 품질은 엔트로피를 이용한 보정 방법과 거의 흡사했으며, 대신 전체적인 처리 시간을 2차원 영상에서 15%로, 3차원 영상에서 30%로 줄일 수 있었다.

결론 : 제안한 방법을 병렬 영상화 기법 등과 결합하여 영상 보정 시간을 더욱 줄일 수 있을 것으로 기대한다. 제안하는 방법은 다른 보정 기법을 사용할 수 없을 때, 영상에서 움직임의 영향을 줄이는 방법으로 유용할 것으로 기대한다.

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