2016 CMBEC39 Conference
Calgary AB
May 24–27, 2016

APPLICATION OF A FOURIER SHIFT PREPROCESSING STAGE TO IMPROVE THE RESOLUTION OF RESTING STATE fMRI IMAGES

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ABSTRACT

A comparison between two regions of interest is necessary when generating resting state fMRI markers (rs-fMRI) to distinguish between optical neuritis (ON) patients and healthy volunteers. However the spatial resolution of fMRI images degrades during the discrete Fourier transform reconstruction of the truncated *MRI* data captured when meeting the limited time resolution needed for rs-fMRI data. We provide preliminary results of an automated Fourier shift manipulation preprocessing stage. This provides the capability of avoiding the introduction of truncation artifacts into the low resolution rs-fMRI images rather than correcting them after they have been generated.

Index Terms— Discrete Fourier transform, Gibbs' artifacts, alternative fMRI reconstruction, spatial resolution enhancement, total variation

INTRODUCTION

Multiple sclerosis (MS) is a disease common in many northern-climate countries such as Canada [1]. Optical neuritis (ON) affects the properties of the visual pathways in the brain, is often a precursor to MS, and has been suggested as a system model for MS pathology [2]. We have investigated possible resting state functional magnetic resonance imaging (rs-fMRI) markers to track ON recovery or progression to MS [2].

To obtain the necessary rs-fMRI temporal resolution requires generation of images reconstructed using the discrete Fourier transform (DFT) applied to truncated (finite length) frequency domain MRI data sets. Additional DFTs must be applied to provide: A) correlation analysis of image time sequences to identify regions connected through the brain's optical pathways [3] and B) determination of signal gains and losses along the pathway to distinguish between ON patients and healthy volunteers. Truncation artifacts, Gibbs' ringing, appear at each DFT stage. These can be removed by windowing the data before DFT application, but this results in image resolution loss including smearing between adjacent regions of interest (ROI) [4]. A suggestion was made in [5] to take advantages of underlying digital signal processing (DSP) characteristics to avoid the generation of artifacts during DFT-based algorithms under certain circumstances. Recently we have begun the exploration of this idea to develop a Fourier shift manipulation (FSM) preprocessing stage generate certain features of MRI images from truncated data without artifacts, and without the resolution loss associated with windowing [6, 7]. In this paper we discuss the advantages and disadvantages of the FSM approach.

This paper is organized as follows: First, the essential features of our FSM approach and our total variation (TV) method are given. Then we provide preliminary results of applying or approach TV using experimental data from a modified GE phantom. This is followed by a conclusion and future research directions.

METHOD

The discrete Fourier transform (DFT) is a common and crucial component of algorithms in many research areas. High resolution images without truncation artifacts are generated when the DFT is applied to large MRI *k*-space data sets, see Fig. 1A. When applied to shorter length data sets, images with artifacts are produced, blurred tines in Figs. 1B. These can

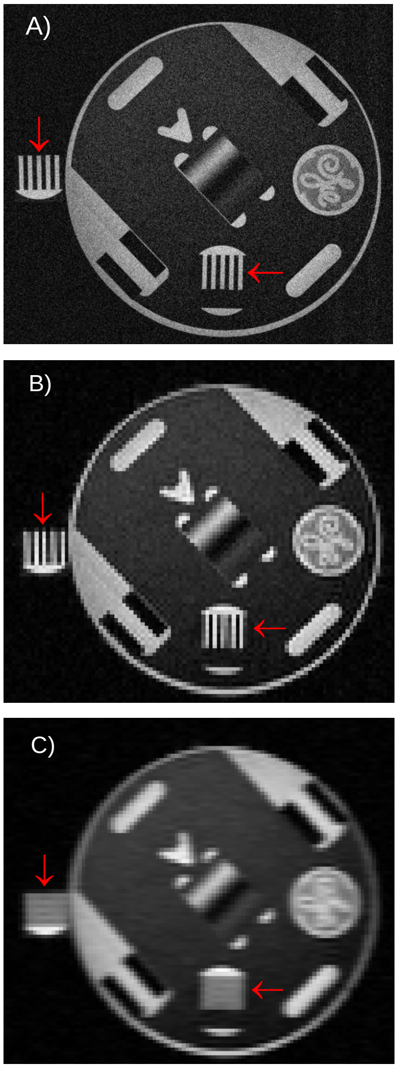

Figure 1: A) *High resolution 512 x 512 image without any truncation artifacts,* B) *Lower resolution 128 x 128 image with truncation artifacts,* C) *Low-pass filtered image*.

be removed with the application of a low pass filter but with an associated resolution loss, Fig. 1C.

The blurred tines arise from the side lobes of the point spread function (PSF), generated in one Fourier domain when the DFT is applied to truncated data in the other domain [4]. Smith [5] manipulated this PSF, *sinc( ),* to generate an improvement in the effectiveness of an 1D industrial frequency domain noise reduction algorithm. The length of the data was manually adjusted before the DFT so that the point spread function had sampling points at its zero-crossings rather than on the larger side lobes. A second and third advantage of this procedural change was that the PSF was sampled exactly at its peak value rather than at two points midway down the sides of its main lobe. Thus this PSF manipulation led to two improvements in the overall signal-to-noise (SNR) ratio of the DFT reconstruction, larger peak and smaller side lobe amplitudes, and generated a narrow, higher resolution image signal.

Recently we have begun to explore potential approaches to extend [5] and avoid the unnecessary loss of resolution that occurs with the use of a DFT global windowing during MRI reconstructions of truncated data. In [6] we demonstrated a *k*-space approach, Fourier shift manipulation (FSM), applied globally for the reconstruction of a GE phantom containing a single fine detailed feature. This comb had 5 tines which generated artifacts following reconstruction of truncated *k*-space data. In an MRI context, FSM involves multiplying *k*-space by a complex exponential. Through the properties of the Fourier transform, this multiplication is equivalent to a position shift in the other domain. Thus FSM provides a mechanism to manipulate the sampling positions along the DFT point spread function.

In Fig. 2, we demonstrate FSM applied to the DFT reconstruction of the GE phantom shown in Fig. 1. The *k*-space of this phantom was mathematically modified from the phantom used in [6] to include a second fine detailed comb feature capable of generating artifacts. Four different FSM shifts were applied to cause the reconstructed images to move by -0.25, 0.0, +0.25 and 0.5 pixel widths within the DFT reconstructed image.

We can see that the original truncated reconstruction, Fig. 2B, has both phantom combs distorted by different truncation artifacts. A FSM shift of -0.25 pixel widths, Fig. 2A, causes the PSF of the left comb enclosed in a red rectangle to be sampled at the zero crossings of the PSF, removing the artifacts. A +0.5 pixel width adjustment, Fig. 2D, removes the artifacts from the other comb. Other features are sharpest in Figs. 2B and 2C.

Unlike the single comb example we provided in [6] a global FSM adjustment does

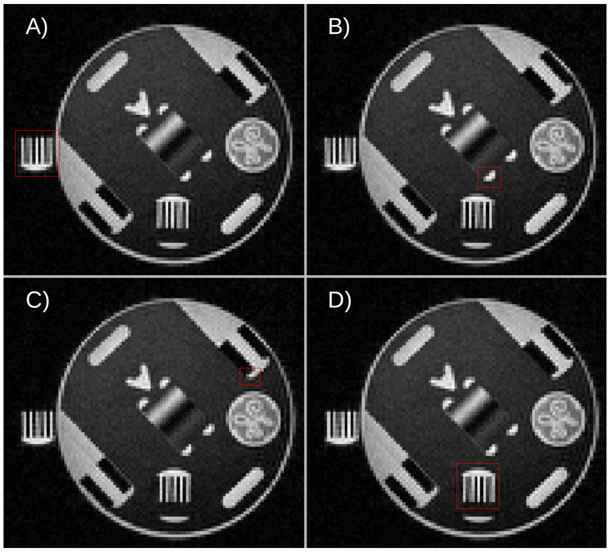

Figure 2: *Images obtained with FSM for 4 shifting values, (A) -0.25, (B) 0.0, (C) +0.25 and (D) 0.5 pixel widths, applied to a 128 x 128 DFT truncated reconstruction.*

not remove all of the major image artifacts. In[7], we suggested a 1D Total variation guided approach to identify which of several FSMs led to a DFT reconstruction with the minimum artifacts. TV can be defined as the sum of all of the absolute variations that occurs in the data

$$TV = \sum abs(I(n+1) - I(n))$$

where I(n) is the intensity of the n^{th} pixel. We assume that the major difference in TV values across the same line in the multiple FSM images are due to changes in their truncation artifacts. If this assumption is correct then selecting the line with the minimum TV corresponds to selecting the line showing the minimum truncation artifacts.

However, each line now identified as having minimum truncation artifacts corresponds to shifted data and needs to be repositioned to the correct position in the final image space. Our approach to solving this problem was to take advantage of the fact that the truncated images are typically small and must be pixel duplicated for convenient display. We produced a 4-fold pixel duplicated 512 x 512 image to hold the TV-selected regions from the four 128 x 128 FSM images shown in Fig. 2. Each selected FSM 1 x 128 image line was 4 fold duplicated to

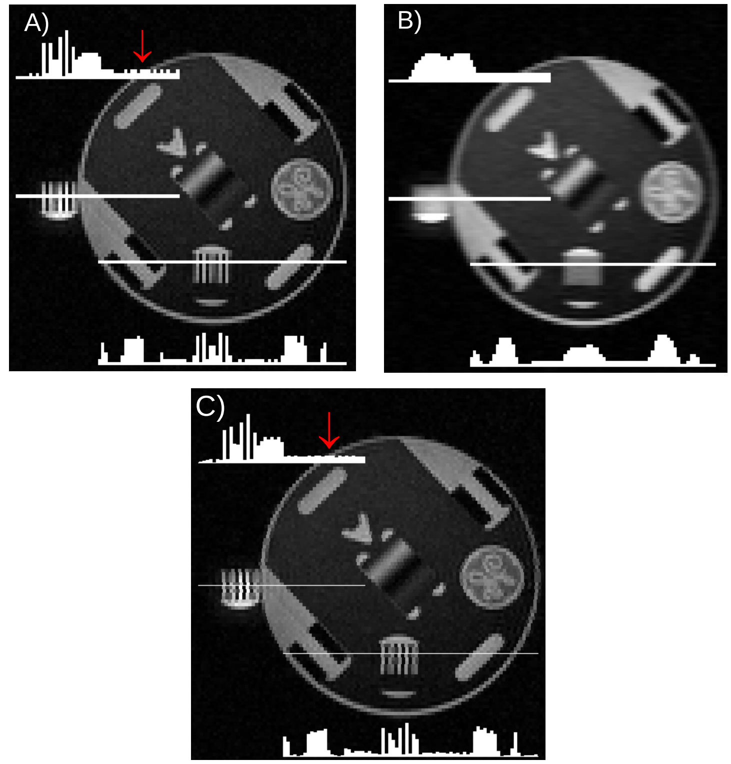

Figure 3: *A) the original truncated, B) the globally k-space filtered and C) our TV-assisted line-by-line FSM corrected image for a 128 x 128 IDFT reconstructions*

a size 4 x 512. This block was registered into the final 512 x 512 image after shifting to the left by 1 pixel for lines selected from the -0.25 FSM shifted image. Lines from the +0.25 and +0.5 FSM images were registered into the final image after shifts of 1 and 2 pixels to the right respectively.

RESULTS

Fig. 3 compares images from A) the original, B) the globally *k*-space filtered and C) our TV-assisted line-by-line FSM corrected image for a 128 x 128 IDFT reconstructions. Figs. 4 show similar results for 96 x 96 TV-assisted FSM IDFT reconstructions.

We have mathematically increased the intensity of the upper comb in Fig. 3A in order to enhance the ringing artifacts it casts into the flat area beside it and beyond into the background (arrow). This generates a more stringent test of the algorithm. The low pass filtering, Fig. 3B, removes the truncation artifacts but totally destroys the resolution of the tines. Fig. 3C shows that after the line-by-

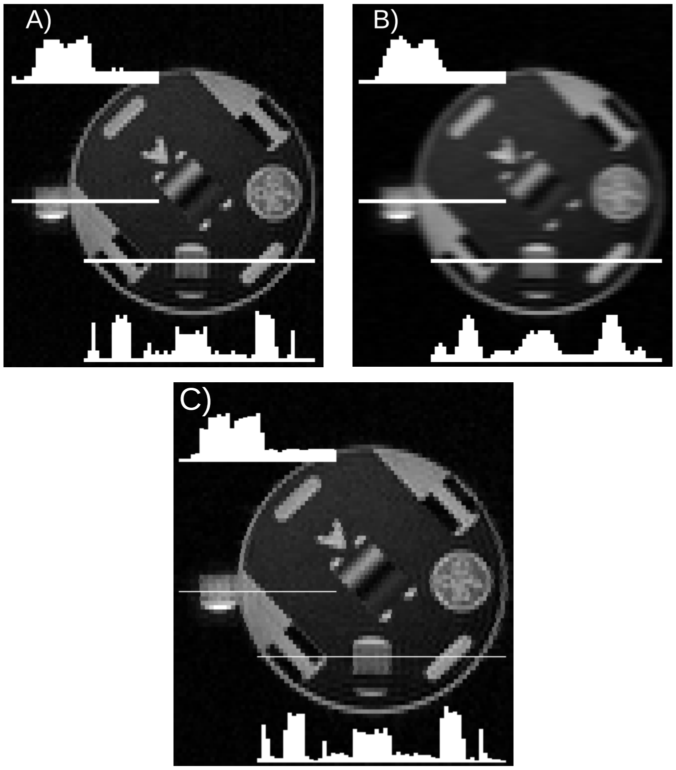

Figure 4: *A) the original, B) the globally k-space filtered and C) our TV-assisted line-by-line FSM corrected image for a 96 x 96 IDFT reconstructions*

line *FSM* correction causes the comb tines to be more resolved than Fig. 3B, and a little better resolved than Fig. 3A. The artifacts in the background near the upper comb, red arrow, and those near the lower comb are reduced. The circle edges are sharper as their artifacts have been reduced. However there are still residual artifacts remaining in the flat area beside the upper comb. Similar sharper circle edges, lower background artifacts, marginally improved tine resolution and residual artifacts are seen in the 96 x 96 IDFT reconstructions presented in Fig. 4.

As shown in Fig. 2, the addition of post-processing Fourier shift manipulation stage provides a route to generate an image series each with different regions showing minimum truncation artifacts. However our current line-by-line TV-assisted approach to selecting the correct artifact-reduced parts of those images does not provide the performance desired. We are currently investigating a region-of-interest (ROI) based TV metric which has the potential to be more appropriate for our proposed rs-fMRI study which compares multiple ROIs.

CONCLUSION

We have shown that a Fourier shift manipulation post-processing stage can generate a series of images with different regions having reduced DFT truncation artifacts. A proposed line-by-line TV assisted selection of those reduced artifact regions did not provide the performance required to improve the accuracy of our proposed rs-fMRI study. We are planning to quantitatively compare a region based approach with the Kellner et al. [8] point-by-point approach.

ACKNOWLEDGEMENTS

Funding was provided by the Natural Sciences and Engineering Research Council of Canada and the University of Calgary, The authors thank Dr. E. McDonald for providing the data used in this paper.

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