Sub-second 3D Image Reconstruction with Gradwarp Correction in Moving Table MRI

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Introduction:

Large field of view (FOV) MR imaging using continuous table motion is susceptible to artifacts arising from the nonlinearities of image gradients. In fixed table MRI the gradient nonlinearities are manifest as image warping. Gradwarp correction for this spatial distortion involves both a spatial remapping as well as an intensity correction [1, 2]. In moving table MRI every measurement is made at a slightly different displacement between the object and the gradient field. The resulting reconstructed images contain spatially dependent blurring in addition to spatial distortion [3]. Ideally, reconstruction of a moving table image with gradwarp correction would require a separate 3D Fourier transform (FT) and gradwarp correction for each acquired phase encoding step. In practice, multiple phase encoding steps can be processed together with very little degradation in image sharpness. As is reported here, despite the seeming intense computational requirements, extended FOV moving table image reconstruction can be accomplished efficiently on current personal computer hardware. Further computational performance can be achieved in a multiple processor blade system.

Materials and Methods:

Gradwarp correction begins by using a 3D spherical harmonics model to produce a displacement map, **d**, for all image points. A common approach of resampling the warped image onto the correct grid is to apply a 1D cubic spline interpolation [4] along each of the three spatial dimensions. This produces a 4 point kernel for each image location that is convolved with the image data. An intensity correction factor δ is found for each pixel $\delta_i = \mathbf{d}_i - \mathbf{d}_{i+1}$, where $\mathbf{d}_i$ and $\mathbf{d}_{i+1}$ are successive pixel locations in the image. The kernel is then multiplied by the correction factor δ to correct for intensity “pileup”. Additionally the kernel is adjusted to remove edge pixels that are mapped outside of the reconstructed image. Sequentially acquired views are processed with a 3D FT, and gradwarp correction is done on the group as a whole. Table velocities can be as high as 4cm/s. Using a 5ms TR, 128 views (2.56mm of table motion) can be grouped together for processing. It is important to note that the spatial remapping and intensity correction described above is constant with scanner location. Therefore, all kernel values can be pre-calculated once and the same gradwarp correction applied on each group. The image reconstruction is demonstrated on two systems. The first system is an off-the-shelf Dell PC with a processor speed of 3.2GHz. The second system is an eight-node blade from Mercury Computer Systems, also with 3.2GHz processors. One blade acts as a root and divides up the processing among the other seven blades. The FFTW library is used for the Fourier transforms. Current generation microprocessors have additional capabilities that can increase performance. Two of these capabilities have been implemented in the gradwarp correction. Intel’s implementation of single instruction multiple data instructions allows for multiply or add operations on four floating point numbers with one instruction. Additionally, cache management directives can reduce memory access times by fetching data from memory onto the processor before it is needed.

Results:

Processing times are summarized in **Table 1**. Gradwarp correction provides increased sharpness and increased depiction of anatomy as seen in **Fig 1**.

Table 1: Timers were added to the software to provide processing times for a moving table data set with spatial dimensions of 256x128x16 for each group. A total of 64 groups were used to form the final reconstructed image with dimensions of 768x128x16. Each node on the blade system processes one group independently. This allows for seven groups to be processed in parallel.

	Off-the-shelf PC	Blade System
3D FT for one group	9.5ms	4.9ms
Gradwarp correction for one group	17.1ms	13.9ms
Reconstruction time for one group	35.9ms	22.9ms
Total image reconstruction	2.3s	.42s

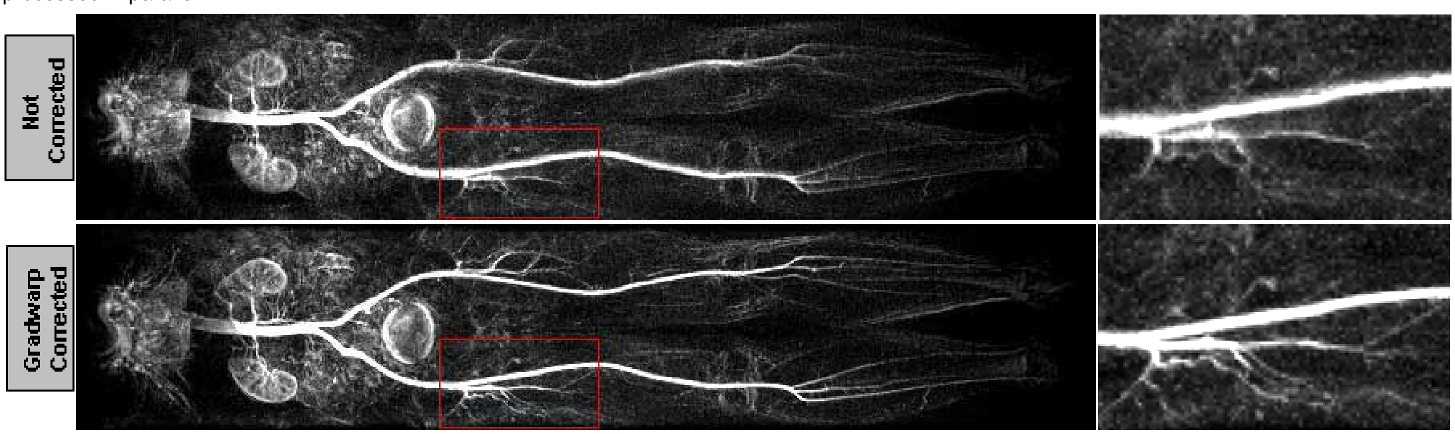

Fig 1: A comparison of a 3D extended FOV moving table image with and without gradwarp correction. These MR angiograms used a reference scan to allow for subtraction of the background signal. Thus, the processing time is twice that shown in **Table 1**. The top row shows the data set without correction with a magnification of the indicated region shown on the right. The bottom row shows the same images with correction. The increased sharpness along with additional distal arteries is clearly depicted in the gradwarp corrected images.

Discussion:

Since the kernel values for gradwarp correction can be pre-calculated once and applied to all groups of data, gradwarp correction reduces to a series of 1D convolutions. Efficient implementation of the gradwarp algorithm and freely available efficient FT libraries provide 3D reconstruction times of several seconds or less for a complete extended FOV study. With image acquisition times on the order of 10s of seconds or more, gradwarp could be implemented with an of-the-self PC in a real-time environment. Using a real-time blade system, gradwarp could potentially be applied for each TR or combined with additional techniques like SENSE.

References

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