Real-Time Gradient Warp Correction with OpenGL NURBS Surfaces

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Introduction: Gradient warp correction is computationally intensive, and therefore not always practical for real-time imaging [1-3]. For real-time MR applications, such as MR-guided endovascular therapy, gradient warping can reduce geometric fidelity, preventing accurate visual feedback to an interventionalist. OpenGL (Open Graphics Language) is a graphics display library with mathematical graphics functions called non-uniform rational B-splines (NURBS) that can project a 2D texture onto a 3D surface within the fast display framework [4]. Our hypothesis is that OpenGL NURBS surfaces can be used for fast, real-time gradient warp correction.

Materials and Methods: All imaging experiments were performed on a 3 T clinical MR scanner (GE Signa VH/*i*, GE Healthcare, Waukesha, WI) using a 2D FGRE sequence (TR = 3.8 ms, TE = 1.8 ms, $\alpha = 35°$). The acquisition matrix was 256×256 with a 48-cm field-of-view (the maximum allowed FOV) with a body transmit-receive coil. A real-time data acquisition client was built using G++ and Qt C++ libraries (Nokia, Oslo, Norway) on a Mac Mini computer (Mac OS 10.5, 2 GHz Core 2 Duo, 4 GB of RAM). Raw data was transferred in real time to the client through TCP/IP. The real-time program consisted of an OpenGL display widget containing a 3D NURBS surface created with a "saddle" shape using 16 control points (4×4). Inverse Fourier transform of the raw MR data produced an uncorrected image. This image was then projected onto the NURBS saddle for display. The control points for the NURBS saddle surface were calibrated until the resulting image matched the product-sequence corrected images. The calibrated NURBS algorithm was then applied to real-time uncorrected data and the resulting images qualitatively compared to the product-sequence corrected images.

Results: The resulting images are shown in Figure 1*a-f*. The gray boxes along the top row (*a-c*) show a zoomed view of the top-left section of the phantom. The NURBS processing corrects for the curved gradient warp artifact while preserving high-frequency information near the centre of the imaging FOV. The arrows in the bottom row (*d-f*) show some subtle differences near the edges of the imaging FOV between the NURBS corrected images and the product-sequence images.

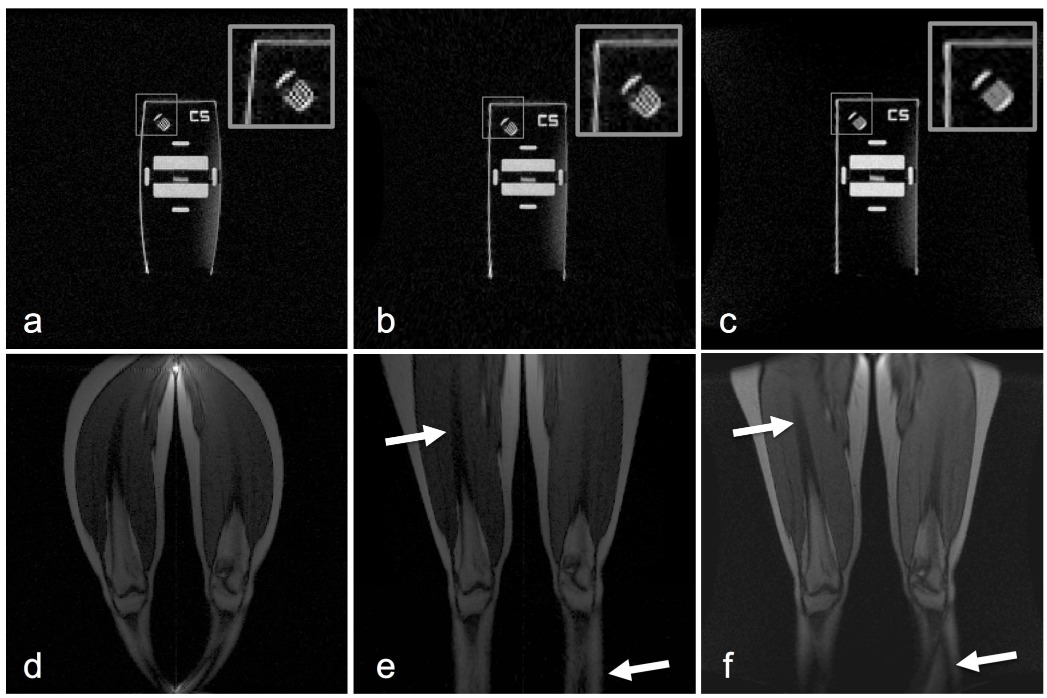

Figure 1: Phantom (a,b,c) and in vivo *(d,e,f) single coronal slice acquisitions using a 48-cm FOV with a 2D FGRE sequence. Images (a) and (d) were reconstructed in real time from the raw data with no gradient warp correction; images (b) and (e) have NURBS saddle gradient warp correction; images (c) and (f) are the product-sequence corrected images. Subtle differences towards the edges of the imaging FOV are seen (arrows, bottom row) between the NURBS saddle images and the product-sequence images. However, the NURBS saddle images preserve spatial information near the centre of the imaging FOV (gray boxes, top row).*

Discussion and Conclusion: The images shown in Figure 1 successfully support our hypothesis that NURBS surfaces have the capacity for real-time non-linear gradient warp correction. As the imaging FOV decreases, the severity of the gradient warp artifact decreases, and the effectiveness of the NURBS saddle correction algorithm increases (results not shown here). Although product-sequence correction algorithms will remain the gold standard for non-real-time imaging, NURBS correction algorithms may provide a suitable alternative for real-time applications, such as MR-guided endovascular therapy. Future work will test the effectiveness of using a NURBS surface with a larger number of control points. By using more control points in the NURBS surface, it may be possible to achieve images more comparable to the product-sequence gradient warp corrected images.

References: [1] O'Donnell M, *et al. Med Phys* 1985; **12**: 20. [2] Schad LR, *et al. Magn Reson Imaging* 1992; **10**: 609. [3] Doran SJ, *et al. Phys Med Biol* 2005: **50**: 1343. [4] Wright RS, *et al.,* OpenGL Super Bible, 2nd Ed, 1999 Waite Group Press.