Enhanced Slice Resolution by Staggered Acquisitions with Z-Deblurring

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Target Audience This technique is suggested for clinicians and researchers desiring to improve through-plane resolution in multi-slice acquisitions.

Purpose 3D MRI data is increasingly desirable in clinical environments, however certain applications (i.e. EPI) must acquire volumetric data in the form of stacked 2D slices. When acquired in this fashion, the resolution in the slice direction is limited by the slice selection pulse width (on the order of a few mm) [1]. In a previous work we demonstrated a technique that could provide improvement of through-plane resolution for 3D multi-slice MRI data [2]. The technique refines the detail in the z-direction by subjecting a set of interleaved 2D slice sets to a deblurring matrix. However, the deblurring process resulted in erroneous propagation of signal, leading to streaking artifacts. Here we present a revised technique which approaches the problem of resolution enhancement from a different point of view. This technique avoids the complicated formulation of the deblurring matrix and the resulting streaking artifact.

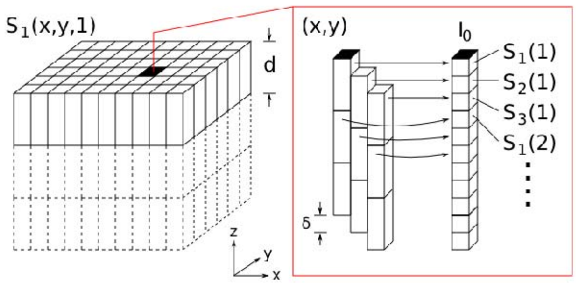

Figure 1 Acquisition and combination of staggered slice data. A set of slices S_1, with the slice z=1 highlighted. Additional slice sets (here showing N=3), staggered by an incremental fraction of the slice thickness, d, are interleaved to create a higher resolution image I_0. I_0 must then be deblurred as each pixel represents a thick slice.

Theory In normal 2D acquisitions the resolution in the z-direction is less than that in the x,y-directions and likely inadequate for diagnostic purposes. Fig. 1 shows a typical stacked slice acquisition $S_1(x,y,z)$; the thickness of a slice, d, is larger than the in-plane pixel size. The goal is to improve this through-plane resolution by incorporating additional stacks of slices (S_2, S_3, ...) staggered by a fraction of the slice thickness δ=d/N. The slices are interleaved to produce a composite image I_0 (shown in Fig. 1 at a single position (x,y) for simplicity). The image I_0 is a blurred representation of the underlying structure as a result of the overlap in the component slices.

To refine I_0, we consider the image in terms of high and low spatial frequency components ($I_0 = I_L + I_H$). A representation of I_L may be obtained by smoothing I_0 (this can be achieved by convolution with a square kernel or low pass filtering). Then we may compute the remaining component ($I_H = I_0 - I_L$). The next step is to create a new image, I_E, that has enhanced resolution. We increase the contribution from I_H by a factor, w:

$$I_E = I_0 + w(I_H) = I_0 + w(I_0 - I_L) \qquad (1)$$

The degree of resolution can be adjusted as desired by acquiring an appropriate number of additional slice stacks. The enhancement may be optimized by tuning the parameter, w.

Methods Staggered sets of 2D axial slices of a water phantom were obtained with a spin echo sequence on a 3T GE scanner (TR/TE = 1000/14ms). The phantom contained LEGO blocks to provide structural complexity and sponges to keep structure in place. Each axial set consisted of 24 slices with 4mm thickness along z. In total 4 slice sets were acquired, staggered by an incremental offset of 1mm. Axial slice image size in the (x,y) plane is 256x256, 1mm^2 resolution. We select a single (x,z) plane to represent a sagittal view of size 24x256, an example from one slice set is shown in Fig. 2a. N sets were interleaved to produce blurred images I_0 representing the sagittal (x,z) plane. A full resolution (1mm^2) sagittal acquisition was obtained for comparison (area of interest shown in Fig. 2d).

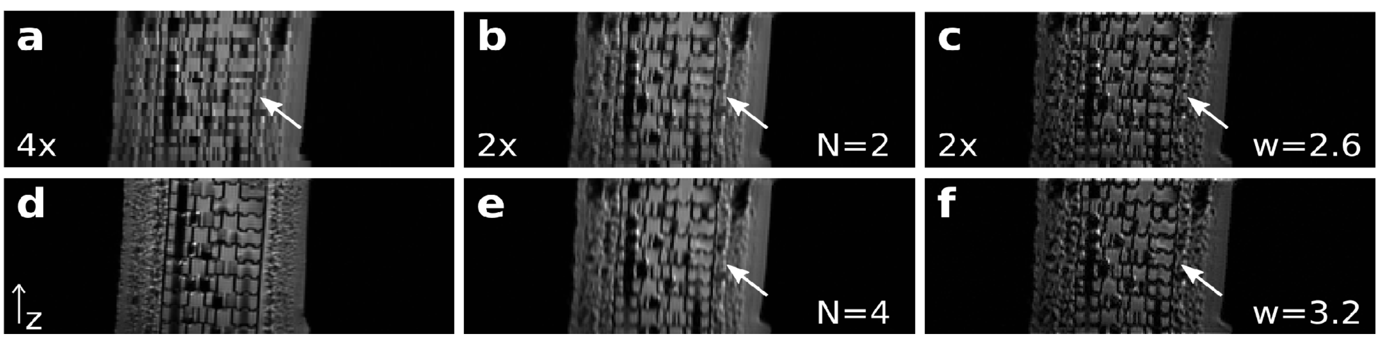

Figure 2 LEGO phantom deblurring. Z direction is vertical, lower resolution images have been magnified in z by a factor indicated in bottom left for comparison. (**a**) Sagittal view from a single set of axial slices (24x256; 4mm resolution in z). (**b**) Composite image I_0 with N=2 (48x256; 2mm resolution in z). (**c**) The enhanced image I_E for N=2 (48x256). (**d**) Reference sagittal acquisition (96x256; 1mm^2 resolution). (**e**) Composite image I_0 with N=4 (96x256; 1mm^2 resolution). (**f**) Deblurred image I_E for N=4 (96x256; 1mm^2 resolution). Note the considerable refinement of resolution indicated by the arrows.

Results Fig. 2b shows the composite image I_0 for N=2. The final image after enhancement, I_E, is shown in Fig. 2c. Fig. 2e&f show the results for N=4. In both cases, underlying resolution is restored with minimal adverse effect. The optimal images were visually selected, the corresponding tuning parameters were $w_{N=2}$ = 2.6 and $w_{N=4}$ = 3.2. When sufficient interleaves are incorporated (N=4; δ=1mm), the enhanced image (Fig. 2f) is comparable to the full resolution acquisition (Fig. 2d - Note: the sagittal slice here has a 4mm thickness and thus higher SNR, the other images represent slices that are 1mm thick exhibiting a few more signal voids).

Discussion A technique for improving through-plane resolution for multi-slice acquisitions was introduced. A scalable resolution enhancement is achievable by varying the number of acquired slice sets. Isotropic resolution can be approached when the number of interleaves results in a δ close to the in-plane pixel size.

References

[1] MA Bernstein, KF King & XJ Zhou, Handbook of MRI Pulse Sequences, Elsevier, 2004

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