Gibbs-Ringing artifact removal based on local subpixel-shifts

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TARGET AUDIENCE: Developers of image reconstruction and artifact removal methods.

PURPOSE: To robustly remove Gibbs-ringing based on local subvoxel-shifts, while introducing minimal smoothing.

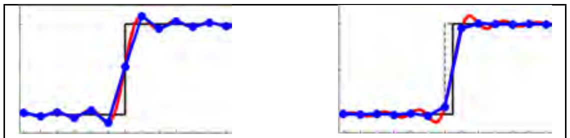

Fig 1. Discontinuity reconstructed a from finite k-space. The amplitude of the ringing depends on whether the sinc pattern is sampled at its extrema (left), or at the zero-crossings (right).

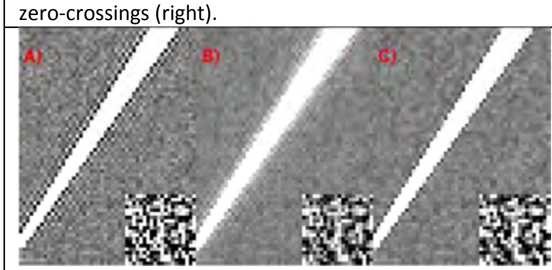

Fig 3. 2D Phantom. A) Original image. Compared to the standard Filtering Method (B), the proposed method (C) introduces less smoothing and removes the ringing more efficiently. Inserts demonstrate the noise correlation

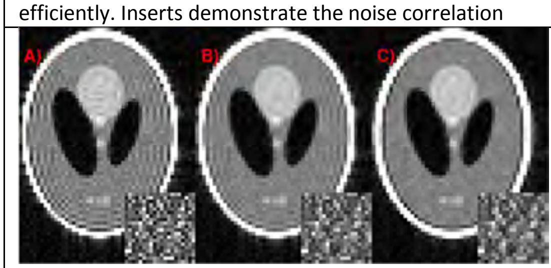

Fig. 4. Shepp-Logan Phantom. At the same noise correlation level, the proposed method (C) removes the ringing more efficiently than standard filtering (B). Inserts demonstrate the noise correlation.

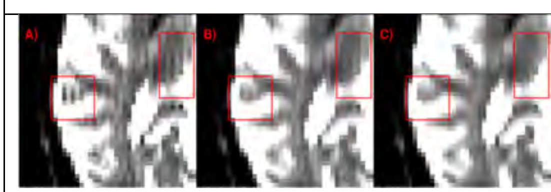

Fig. 5. EPI Measurement in the brain. Areas with significant differences between the original image (A), filtering (B) and the proposed method (C) are highlighted.

INTRODUCTION: In MRI, images are reconstructed from acquisitions of a bounded k-space, i.e. from a finite number of Fourier expansion coefficients. Zero-filling of the missing high frequency components corresponds to multiplication of the full k-space with a rectangular window, which is equivalent to a convolution with a sinc function in the image domain. The side lobes of the sinc cause oscillations ("ringing") in the neighborhood of sharp edges in the imaged object (see Fig.1). The artifact can straightforwardly be reduced by filter methods [1] (e.g. an exponential or a median filter). However, this approach comprises a global blurring, thus reducing the effective imaging resolution. More advanced methods have been developed based on piecewise re-reconstruction of smooth regions using Gegenbauer-Polynomials [2]. A drawback of these methods is the requirement of an edge detection and careful choice of parameters.

The method we propose in this work is based on a different view on the effect: In fact, the reconstructed image is not continuous, but sampled at discrete points in image space. If the side lobes of the sinc-pattern are sampled at its extrema, the ringing amplitude becomes maximal, whereas it disappears when sampled at the zero crossings (Fig. 1). Finding the optimal subvoxel-shift for pixels in the neighborhood of sharp edges in the image can therefore minimize the oscillations. As there are multiple edges present in an image, this must be performed on a local basis.

METHODS: *1-D Application*: Starting with the original image *I*, a set of images with subsequent subvoxel-shifts is created by multiplication with phase-ramps in Fourier-space: $I_\Delta(s) = \sum_k \tilde{I}(\mathrm{k}) \exp\left[\frac{\mathrm{i}2\pi}{N} k(s+\Delta)\right]$, where s denotes the pixel index and the shift Δ ranges from -0.5 to +0.5 pixels. From this dataset, for each pixel *s*, the optimal shift which minimizes potential oscillations in the neighborhood is determined. The corresponding measure can be calculated with any oscillation-sensitive kernel, e.g. total variation TV. This results in the field of local shifts $r(s) = argmin_\Delta\{\ \mathrm{TV}[I_\Delta(s)]\ \}$. From this, an image $J(s) = I_{r(s)}(s)$ with minimal oscillations can be derived. As this new image is defined on the locally distorted grid *s+r(s)*, the final image is calculated by interpolating the image *J(s)* at the points of the original Cartesian grid *s*. The order of the interpolation balances the induced blurring against the strength of oscillation removal. We found Legendre-polynomials with n=2 to constitute a good compromise.

2-D Application: In 2 dimensions, diagonal edges produce checkerboard-like ringing patterns, see Fig. 3A. Hence, it is not possible to find the optimal shift in both directions simultaneously. As a solution, we correct the image *I* in both directions separately, resulting in J_x and J_y. We then combine these images in Fourier Space via $J_{\mathrm{final}} = \mathrm{FT}^{-1}\{\ \mathrm{FT}\{J_x\}\, G_x + \mathrm{FT}\{J_y\} G_y\ \}$ with the weighting filters $G_x = \frac{(1+\cos k_y)}{[(1+\cos k_y)+(1+\cos k_x)]}$ and $G_y = \frac{(1+\cos k_x)}{[(1+\cos k_y)+(1+\cos k_x)]}$. These filters with a saddle-like structure in Fourier Space enhance the high frequency components along the direction of the correction, while it dampens the contributions along the non-corrected direction.

RESULTS: Results are given for numerical phantoms and a gradient echo EPI measurement (3T Siemens TIM TRIO scanner, TE=107ms, matrix size 104x104 resolution 2mm^3). As a reference method, we remove the ringing with an exponentially decaying filter, given by $\exp\left(-a\sqrt{k_x^2+k_y^2}\ \right)$. The value for *a* is chosen such that the noise correlation is equal for both, the proposed and the filtering method (see inserts in Figs 3 and 4). For the phantoms, noise with SNR=100 is added. Another filtering approach, application of a median filter results in much stronger smoothing at this resolution (data not shown).

DISCUSSION AND CONCLUSIONS: We proposed a method for ringing removal based on local subvoxel pixel shifts. They optimized such that the origin of the ringing pattern - the sinc-function - is sampled at the zero-crossings. Apparently, compared to the popular global filtering approach, the proposed method only acts on oscillations truly arising from edge ringing. Therefore, it significantly better removes the artifact, while it introduces less smoothing and preserves the edges. Another advantage is that the method is hardly sensitive to the choice of parameters (e.g. the kernel width in filtering methods) and can hence be applied in a very robust fashion.

[1] Liang Z and Lauterbur P. Principles of magnetic resonance imaging, a signal processing perspective. Piscataway, NJ: IEEE Press, 2000. [2] Gottlieb D, Shu CW, Solomonoff A, and Vandeven H. On the Gibbs phenomenon I: recovering exponential accuracy from the Fourier partial sum of a nonperiodic analytic function. J. Comput. Appl. Math., vol. 43, pp. 81–98. [3] Ferreira, P, Gatehouse, P, Kellman, P, Bucciarelli-Ducci, C, & Firmin, D. Variability of myocardial perfusion dark rim Gibbs artifacts due to sub-pixel shifts. Journal of Cardiovascular Magnetic Resonance, 11(1), 1-10.