Referenceless Reconstruction of Spatiotemporally-Encoded Imaging Data

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Introduction: Hybrid spatiotemporal encoding (SPEN) sequences have shown more robustness to B_0 inhomogeneities than single-shot echo planar imaging (EPI) at similar scan durations.[2] These hybrid sequences combine k-space encoding along the readout (RO) direction, SPEN encoding along the orthogonal low-bandwidth direction, and an acquisition similar to that of EPI. The SPEN encoding is based on imparting a quadratic phase $\varphi = ay^2 + by + c$ which leads to an acquired signal proportional to the image itself; resolution, however, is then limited to $\sqrt{\pi/a}$.[1] Improved processing leading to a resolution similar to that achieved with EPI, can still be reached by resolution-enhancement algorithms.[3-6] Unfortunately, the same hardware imperfections which lead to Nyquist-ghosting in EPI may also affect these reconstruction techniques, resulting in stripes and ghost artifacts. In this work we show that unlike what happens in EPI, the ultrafast SPEN sequences do not require a reference scan to correct for these hardware errors. This is a consequence of the fact that under-sampling along the SPEN direction does not generate aliasing, but rather lower resolution images. The principles of the ensuing referenceless SPEN MRI method and representative results are here presented.

Background: Out of the different resolution enhancement algorithms proposed for processing SPEN data we use the super-resolution (SR) method.[3] In a 1D implementation, SR relates the collected signal S to the desired image $\hat{\rho}$ by a 'Super-Resolution' matrix A, through $S = A\hat{\rho}$. The final (1D) image is then given by $\hat{\rho} = A^{(-1)}S$, where $A^{(-1)}$ stands for the SR process, typically incorporating some kind of regularization. In 2D Hybrid-SPEN sequences a 2D signal S is acquired, with k-encoded rows along the RO direction and columns encoded by SPEN. Once Fourier transform is applied along the rows the new "signal" $\tilde{S}$ obeys the SR relation $\tilde{S} = A\hat{\rho}$.

Methods: Although the even and odd rows of the signal $\tilde{S}$ may – as in the case of EPI – be inconsistent due to hardware imperfections, the set of even rows and the set of odd rows can each be reconstructed separately to give identical low resolution images, i.e. $\hat{\rho}^{\text{even}} = (A^{\text{even}})^{(-1)}\tilde{S}^{\text{even}}$ and $\hat{\rho}^{\text{odd}} = (A^{\text{odd}})^{(-1)}\tilde{S}^{\text{odd}}$. It can be shown that for imaging parameters typically used in conjunction with SR, the inconsistency between the even and odd rows should translate to a 2D phase difference ϕ_{mn} linear in the row and column indices m and n; i.e. $\hat{\rho}_{mn}^{\text{even}}/\hat{\rho}_{mn}^{\text{odd}} = \exp\{i\phi_{mn}\}$ (in practice, a 2nd order polynomial fit to the phase of $\hat{\rho}^{\text{even}}/\hat{\rho}^{\text{odd}}$ was used to generate a smooth ϕ_{mn}). Having found ϕ_{mn}, the even image can be "fixed" to be consistent with the odd one through $\hat{\rho}_{mn}^{\text{even.corr.}} \equiv \hat{\rho}_{mn}^{\text{even}}\exp\{-i\phi_{mn}\}$, and from there a corrected/consistent even "signal" can be defined as $\tilde{S}^{\text{even.corr.}} \equiv A^{\text{even}}\rho^{\text{even.corr.}}$. Combining this corrected even signal with the original odd signal now gives a full set that can be reconstructed without artifacts using the SR process $A^{(-1)}$. Note that although the method proposed corrects for a 2D-dependent phase ϕ_{mn}, in many cases – as in EPI – only a 1D phase dependence along the RO direction will be observed. In such a 1D case the correction estimated by the method above can be applied onto the signal $\tilde{S}^{\text{even}}$ directly, instead of going through $\hat{\rho}^{\text{even.corr.}}$, improving the results. The general 2D algorithm is depicted in Fig. 1.

Results: Representative results of the referenceless SPEN correction on phantom and human subjects, can be seen in Figs. 2 and 3. The method was also exemplified with the acquisition of a large set (~3000) of real-time images acquired during a 15 minute perfusion experiment on mice kidneys at 9.4 T.

Conclusions: A new referenceless method to process Hybrid-SPEN images has been demonstrated. This method requires no ancillary measurements, and should prove most valuable when collecting large sets of consecutive images which may be detrimentally affected by the acquisition of reference navigator scans; application areas in cardiac MRI, fMRI, diffusion, and perfusion imaging could benefit from it.

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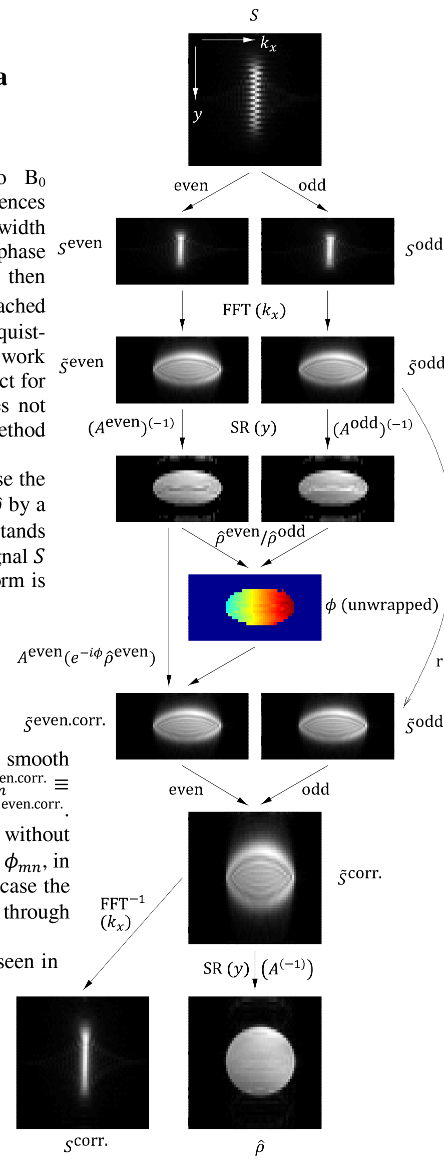

Figure 1: The referenceless algorithm.

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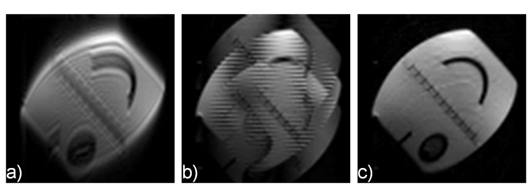

Figure 2: Hybrid-SPEN imaging (oblique scan) of a phantom: (a) No SR. (b) SR with no correction. (c) SR with the now referenceless correction.

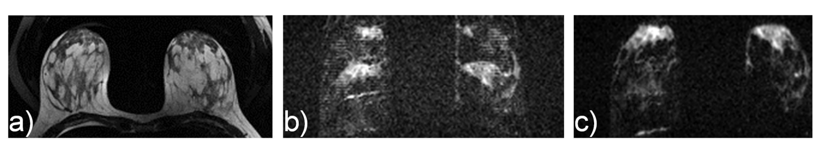

Figure 3: Breast imaging: (a) T_2 weighted image (Turbo SE). (b) Hybrid-SPEN, fat-saturated image, from a diffusion experiment (b=0) using SR, but no correction. (c) same SR image with referenceless correction. (Same windowing was applied to both images (b) and (c).)