Phase unbanding in bSSFP for Liver conductivity imaging at 3.0T

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Introduction: Electric properties such as permittivity and conductivity can be measured by MR using spatial information of B1[1]. In MR electric property tomography (MREPT), conductivity mainly on B1 phase ($\angle B1^{+}$)[2] which can be measured by spin-echo (SE) or balanced steady-state free precession (bSSFP) sequences under the assumption that transmit and receive B1 phases are identical[3]. The bSSFP sequence is preferred since it provides higher time-efficiency and signal-to-noise ratio (SNR). However, bSSFP suffers from banding artifacts due to off-resonance effect which can be more significant for abdomen imaging in high tesla scanner beyond 1.5T. Banding artifacts appear as black bands in magnitude image and stair-like pattern in phase image. Previous studies were done to compensate the magnitude banding artifacts using RF phase-cycled images[4]. Here, we present a phase unbanding technique for conductivity reconstruction focused especially on liver imaging.

Methods: Phase-based conductivity value can be derived by calculating $\mathrm{Im}\{\Delta e^{i\varphi}/e^{i\varphi}\}/2\mu_0\omega$ (1) where φ is B1 phase (μ_0: air permeability, ω: frequency). Phase information of bSSFP image shows slow varying pattern due to its balancing and refocusing properties. At the banding boundaries, step-wise π discontinuities can be observed (Fig.1b). This constant phase difference does not affect phase-based conductivity processing since it uses Laplacian of B1. However, there exist discontinuities at the banding boundaries due to noise-like magnitude data which result in artifacts in conductivity image (Fig.1c). To reduce the artifact, a phase unbanding process is suggested that fills the phase information at the boundary. Our proposed procedures are shown in Fig.1d-f. The first step is to make a flat region mask by extracting banding boundaries from the gradient of phase image (Fig. 1d). The next step is a phase balancing step (Fig.1e) which adds or subtracts π phase at each region which were segmented in step 1 (Fig.1e). Finally, fill the boundary regions with a 2D second-order fitting (Fig.1f). Since conductivity is dominated by the second-order term of phase a simple 2D second-order polynomial fitting is used to fill the banding boundaries. All experiments are performed on a 3T scanner (Tim Trio, Siemens Medical Solutions, Erlangen, Germany) with TrueFISP sequence. The imaging parameters are TR/TE = 4.0/2.0ms, FA=60°, resolution = 2.0 x 2.0 mm^2, slice thickness = 5.0 mm and readout bandwidth = 1260Hz/pixel. The cylindrical phantom is filled with NaCl solution which has 2.0 S/m (left), 1.5 S/m(center) and 1.0 S/m (right). For phantom experiment, first-order shim values are arbitrary controlled to generate banding artifact artificially. Liver image of healthy volunteer is acquired with exhaled breath-hold situation to avoid motion-induced artifact and to reduce field inhomogeneity artifact.

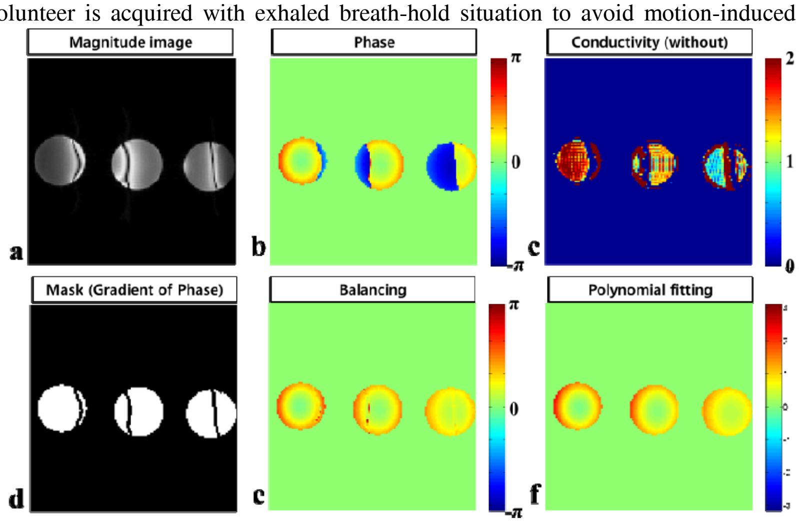

Figure 1. **a**: Magnitude image. **b**: Phase image. **c**: Conductivity image without phase unbanding. **d**: Mask image using gradient of phase information. **e**: Phase balancing using (d). **f**: Polynomial fitting result by filling discontinuous part. **g**: Conductivity image with (f).

Results: In Fig. 1, banding boundaries are successively extracted using the gradient of phase and the flat phase regions are also segmented. A ±π phase terms are added for each segmented region followed by polynomial fitting. After applying the proposed unbanding technique, conductivity of phantom is well-reconstructed (Fig.1g) compared to direct conductivity reconstruction (Fig.1c). In in vivo liver experiment, banding artifacts are observed (Fig.2a). Without the proposed unbanding process, abnormally high conductivity values are observed in the reconstructed conductivity image due to presence of banding (Fig.2b). These high estimated values were corrected using our proposed method. However, some residual errors following fitting error still seem to be observable in Fig.2c.

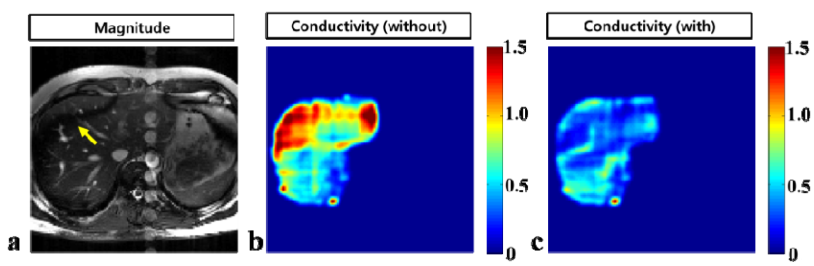

Figure 2. Liver bSSFP image (**a**) with banding artifact (yellow arrow), conductivity images without (**b**) and with (**c**) phase unbanding..

Conclusion: Phase-based conductivity imaging using bSSFP is stabilized by compensating banding boundary by the proposed unbanding method in phantom and invivo liver experiments. In conductivity reconstruction, a large size smoothing filter is an integral part due to its high sensitivity to noise. Conductivity distortion due to banding artifact gets more significant when applying a smoothing filter. More robust unbanding processes should be developed to overcome the artifacts such as by extending the proposed technique to three-dimension fitting. The proposed unbanding technique can be useful for alleviating conductivity estimation error using bSSFP sequences in high field scanners.

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