Prospective Phase Correction for Diffusion-Weighted SSFP Imaging In Vivo

Rafael O'Halloran[1], Murat Aksoy[1], Eric Aboussouan[1], Eric Peterson[1], Anh Van[1,2], and Roland Bammer[1]
[1]*Radiology, Stanford University, Stanford, CA, United States,* [2]*Zentralinstitut für Medizintechnik, Technische Universität München, Munich, Germany*

TARGET AUDIENCE – Researchers interested in high-resolution DWI, Diffusion-weighted SSFP (DW-SSFP) and real-time phase correction.

PURPOSE – The sensitivity of DW-SSFP to motion-induced phase is well known. Retrospective, navigator-based approaches have been shown to partially solve this problem[1,2,3], however retrospective corrections to DW-SSFP have a fundamental limitation: motion-induced phase causes disruption of the steady state and subsequent loss of signal magnitude and contrast. This can only be prevented by a prospective phase correction. Recently, a system to perform prospective phase correction (ProCo) was presented in phantoms experience simulated motion[4]. Here the ProCo methodology is extended to human DW-SSFP imaging *in vivo*.

METHODS – *MRI:* The DW-SSFP sequence and ProCo system are diagramed in Figure 1. Parameters were: Flip angle: 30°, Resolution 1.37x1.37x1.37 mm, FOV: 220x220x220 mm, TR: 34 ms, Diffusion gradient 0.4 G/cm x 6 ms. The readout was a spiral projection trajectory with 4000 interleaves. 6 Healthy volunteers were scanned. In 2 of them 1 b-0 image and 3 orthogonal diffusion direction were acquired. In the other four subjects, 7 directions were acquired to facilitate DTI.

Prospective correction: Data from the 3D navigator were sent to the real-time system for processing (Fig 1a). Then, the rigid-body-motion parameters are computed (Fig 1b). The linear terms are corrected on each axis by setting the amplitude of blip gradients (Fig 1c). The constant term is handled by adjusting the phase of the RF pulse and the readout filter (Fig 1d). All this happens in about 10 ms.

Image reconstruction: The imaging data are reconstructed using retrospective rigid-body and non-rigid-body phase correction using iterative-SENSE[3]. The retrospective correction is needed in addition to the retrospective one because corrections are applied after the imaging readout, and hence the readout interleaf is imprinted with the motion-induced phase. **The key advantage of ProCo is that these phases do not propagate into future coherence pathways and lead to destructive interference.**

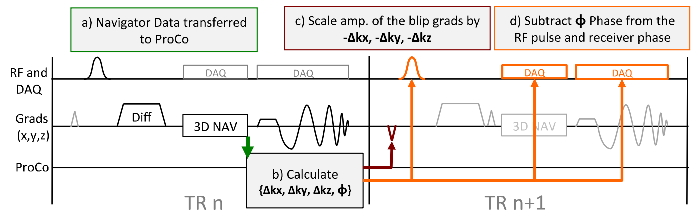

Fig. 1 – The sequence and the ProCo system. Navigator data acquired in a given TR are sent to the ProCo system (a) processed (b) and used to correct the rigid-body-motion induced phase before the RF pulse in the subsequent TR (c,d).

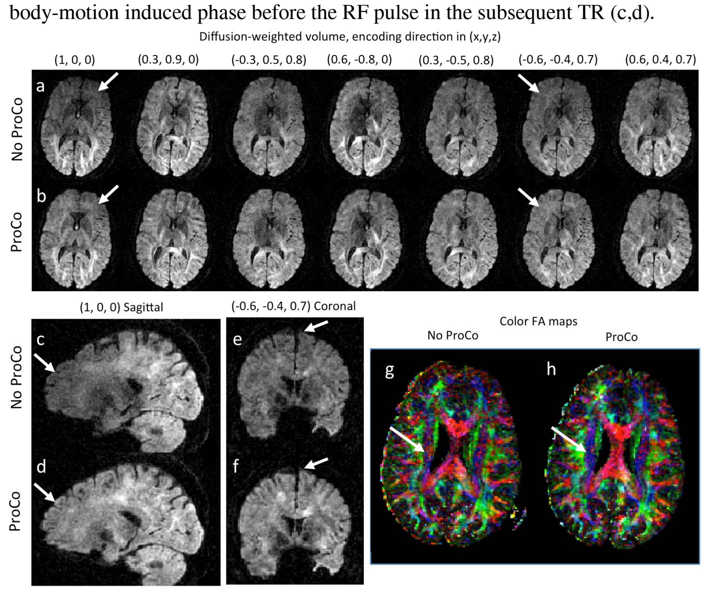

Fig. 2 – Axial reformats of all 7 diffusion directions acquired in subject 2 are compared without ProCo (a) and with ProCo (b). Note the higher signal apparent with ProCo particularly in the highlighted volumes (arrows). Sagittal reformats of volume 1 (c,d arrows) and coronal reformats of volume 6 (e,f) have the same trend. The color FA maps are more subtly different (g,h) however notable regions include the internal capsule in which ProCo results in a more accurate principle eigenvector direction (blue for S/I).

RESULTS– Diffusion-weighted images with and without ProCo are compared in Figure 3. Axial reformats of all 7 diffusion directions acquired in one subject are compared without ProCo (a) and with ProCo (b). In certain volumes (a,b, arrows) the increase in signal with ProCo is quite apparent, particularly in the first volume (a,b, far left) in which the phase-errors cause by left-right motion of the frontal part of the head were corrected by the ProCo system. The same can be appreciated of this volume in a sagittal reformat (c,d arrows); ProCo gives higher signal in the frontal part of the brain. Coronal reformats of volume six (e,f) have the same trend. The effect of the extra signal in the image on the color FA maps is less profound but manifests itself in more accurate representation of the principle eigenvector such as is the case with the internal capsule (Fig 2g,h arrows) which should have a blue color indicating its S/I orientation.

The extra signal in the images shown in Figure 2 comes as a direct result of the increased phase coherence achieved with ProCo. In Figure 3 this is shown more directly. The maximum signal in the navigator is plotted for the first 300 TR's of each volume acquired in Subject 1. Note that due to the cardiac motion there is a periodic dip in the signal for each volume that is most pronounced in the S/I-encoded volume (Fig 3, green). After ProCo is turned on at TR 100 (Fig 3 grey line and arrow), these dips are reduced indicating that ProCo is working to maintain phase coherence. There are residual dips even with ProCo, most likely due to the uncorrected non-rigid-body component on the motion.

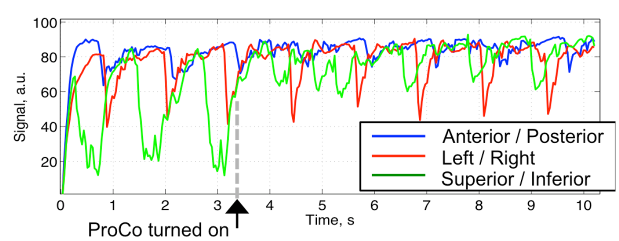

Fig. 3 – The steady state signal from the first 10 seconds of the three diffusion-encoded volumes acquired in subject 1 for the scan with ProCo. Note the large periodic drops in the signal due to pulsatile cardiac motion. These are most visibly reduced in the S/I direction (green line) after the ProCo is turned on (to the right of the grey line).

DISCUSSION and CONCLUSIONS – The prospective correction of rigid-body motion presented here represents a significant step in the development of DW-SSFP as a competitor to spin-echo EPI.

REFERENCES – [1] Jung et al. 3D diffusion tensor MRI with isotropic resolution using a steady-state radial acquisition. JMRI 2009; 29:1175–1184. [2] McNab et al. 3D steady-state diffusion-weighted imaging with trajectory using radially batched internal navigator echoes (TURBINE). MRM 2010; 63:235–242. [3] O'Halloran et al. 3D Isotropic High-Resolution Diffusion-Weighted MRI of the Whole Brain with a Motion-Corrected Steady-State Free Precession Sequence. MRM 2013, 70:466–478. [4] O'Halloran et al. Prospective Correction Rigid Body Motion-Induced Phase for Diffusion-Weighted SSFP Imaging In Proc ISMRM 2013 #3210.

FUNDING – NIH (5R01EB011654, 5R01EB008706, 5R01EB002711, P41 RR009784), the Center of Advanced MR Technology at Stanford (P41RR09784), Lucas Foundation, Oak Foundation.