Prospective motion correction in 3D-encoded FLASH using a combination of Cloverleaf and Volumetric Navigators (vNavs)

M. Dylan Tisdall[1,2], Himanshu Bhat[3], Tobias Kober[4,5], Gunnar Krueger[4,5], Keith Heberlein[3], and André J. W. van der Kouwe[1,2]

[1]A. A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, MA, USA
[2]Radiology, Harvard Medical School, Boston, MA, USA
[3]Siemens Healthcare USA, Charlestown, MA, USA
[4]Advanced Clinical Imaging Technology, Siemens Healthcare IM BM PI, Lausanne, Switzerland
[5]CIBM-AIT, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

Target Audience Researchers interested in navigator-based prospective motion correction and users of sequences based on 3D FLASH who are interested in improving the motion-resistance of their scans.

Purpose This work presents a method for combining a rapid Cloverleaf navigator [1] and a more time-intensive 3D-EPI-based volumetric navigator (vNav) to provide time-efficient prospective motion correction in 3D-encoded FLASH. vNavs have previously been demonstrated in a variety of sequences with sufficient "dead time" (normally ~500 ms) to fit in the navigate-and-update block [2,3], where the use of a small flip angle does not disturb the parent sequence's spin history. In these applications, the navigators provide real-time updates to patient position and resonance frequency [4] each time they are played, at no additional scan time cost. We have recently demonstrated a method for interleaving vNavs into 3D-encoded FLASH, switching between FLASH and EPI TRs while maintaining constant non-selective pulses and thus the necessary steady state [5]. However, unlike in previous sequences, this method accrues a scan time cost, as the interleaved EPI navigators add to the total number of TRs played, instead of filling vacant blocks. In the present work, we demonstrate the use of a short Cloverleaf navigator as a motion-detector, and then only play a higher-cost vNav when motion occurs. This significantly reduces the time-cost associated with using vNavs in 3D FLASH, ideally without a trade-off in motion-tracking accuracy. A similar concept was previously demonstrated in diffusion, where FID navigators were used to trigger b=0 scans to enable prospective or retrospective motion-correction [6].

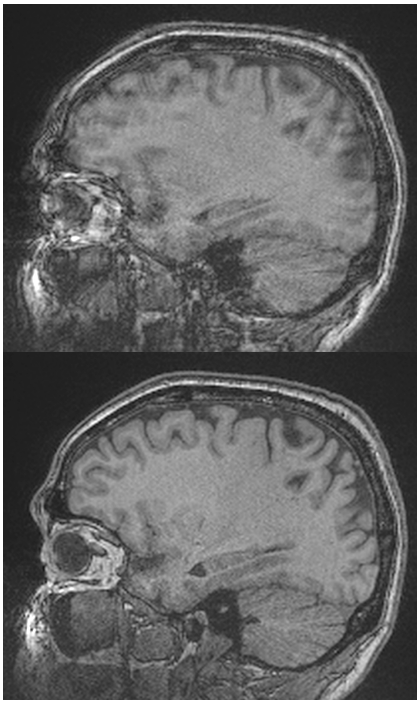

Fig. 1 Equivalent slice from FLASH without navs (top), and FLASH with navs and prospective motion-correction (bottom).

Methods Cloverleaf navigators were originally demonstrated in 3D FLASH for stand-alone use correcting motion and resonance frequency [1]. Sharing the excitation pulse of the FLASH scan, the Cloverleaf gradient pattern can be played out in approximately 4.5 ms, allowing it to be inserted into each FLASH TR between the excitation pulse and main FLASH readout. When used as the primary navigator for motion correction, Cloverleafs require a map be computed from initial scans where the subject remains still. However, without a reference map, two Cloverleaf readouts can be compared in terms of normalized RMS difference to provide a high-quality motion detector. We have employed them in this second format, where each TR receives a "motion score" based on the RMS difference from a single "reference" Cloverleaf TR. This difference can be computed and returned to the sequence within one FLASH TR, providing an effective prospective motion-detector. As in previous applications, we used vNavs to estimate subject position and correct prospectively for motion. Once in steady state, but immediately before the first FLASH TR, a vNav (25 TRs of 3D EPI) is acquired as a reference for the subject's initial position. The sequence then switches to FLASH TRs with embedded Cloverleafs and proceeds with normal imaging. When subject motion is detected by the Cloverleafs, the sequence responds by immediately playing a vNav (with TR and excitation pulse matched to the FLASH to preserve steady state). The sequence then idles by playing "dummy" FLASH TRs while it awaits the estimated new patient position (normally ~80ms); when it receives the update it corrects its coordinates and continues with the FLASH scan. Whenever the imaging coordinates are updated, the next Cloverleaf is chosen as the new "reference", providing a new patient position from which to judge relative motion.

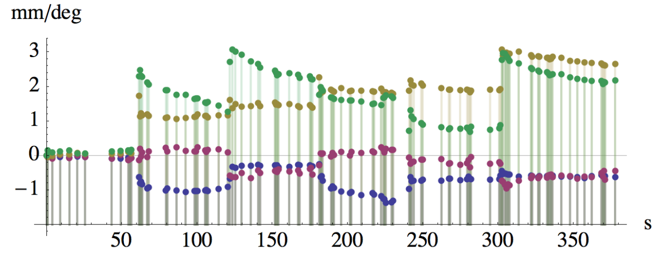

Fig. 2 Translation in x (blue), y (red) and z (yellow) and rotation (green) in mm and deg respectively, as measured with vNavs. Vertical lines identify times when vNavs were played.

Results One volunteer, having given informed consent, was scanned on a 1.5 T Siemens Avanto (Siemens Medical Systems, Erlangen, Germany) using the 32-channel head coil. We acquired two volumes: one with the standard FLASH sequence on the scanner, and one with a matched protocol using our Cloverleaf-and-vNav FLASH. Both volumes had FOV 256 mm × 256 mm × 176 mm, 1 mm isotropic voxels, 3× GRAPPA acceleration in the outer phase-encoded loop with 24 reference lines, 200 Hz/px bandwidth, TR 18 ms, TE 7.82 ms, and 30° flip angle. Total scan time for the sequence without navigators was 5:30; the shortest our navigated scan could be was 5:40 as we added 10 s of dummy scans at the beginning to ensure steady state was reached before the reference vNav is acquired. During both scans the subject was prompted to reposition their head once every minute. In the navigated scan, the system used a total of 109 vNavs during the scan, compared to 256 that were used in our previous method [5], making the final scan-time for the navigated scan 6:40. Fig. 1 shows a roughly equivalent slice from each scan. The estimated translation of the subject is shown in Fig. 2.

Discussion Fig. 1 shows that our motion-corrected sequence provides obvious improvements in image quality compared to the standard FLASH. Fig. 2 shows that the vNavs were played immediately when the subject was directed to move (at 1:10 and every minute thereafter). At other times, the vNavs were triggered due to either small subject motions, or respiration-induced changes in B0. The Cloverleafs have been previously demonstrated to be accurate for estimating B0 change [1], so in principle B0 frequency shifts could be corrected and removed, reducing the number of false triggers and further improving scan efficiency. At present, these extra vNavs cost time, but do not otherwise impact image contrast or quality of motion tracking.

Conclusion We have demonstrated the use of Cloverleaf navigators to detect motion to reduce the time-cost of using vNavs for prospective motion correction in 3D-encoded FLASH scans. Further work is required to reduce spurious vNav triggering due to respiration-induced changes in B0.

References [1] van der Kouwe et al. (2006) "Real-Time Rigid Body Motion Correction and Shimming Using Cloverleaf Navigators", MRM 56:1019–1032 [2] Hess et al. (2011) "Real-time motion and B0 corrected single voxel spectroscopy using volumetric navigators", MRM 66(2):314-323, [3] Tisdall et al. (2012) "Volumetric Navigators (vNavs) for prospective motion correction and selective reacquisition in neuroanatomical MRI", MRM 68(2):389-399 [4] Tisdall et al. (2014) "High-accuracy off-resonance estimation from EPI, with application to volumetric navigators (vNavs) enabling real-time motion and frequency correction", Annual Meeting of the ISMRM 2014 [5] Tisdall et al. (2014) "Prospective head motion correction in 3D FLASH using EPI-based volumetric navigators (vNavs)", Annual Meeting of the ISMRM 2014 [6] Kober et al. (2012) "Prospective and retrospective motion correction in diffusion magnetic resonance imaging of the human brain", NeuroImage 59:389-398

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