Retrospective nonlinear spin history motion artifact modeling and correction with SLOMOCO

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Target Audience/Purpose: functional connectivity. Correcting motion in BOLD by moving beyond linear models to physical models

Introduction: Head motion in BOLD functional imaging is a serious problem that threatens to halt progress made in fundamental neuroscience[1-3]. Current methods assume artifact is linearly related to head motion. We show the linear approximation is seriously problematic and estimates signals that can be *orthogonal to the true, nonlinear motion artifact* arising from out-of-plane motion. Roughly half of all motion is out-of-plane, therefore linear modeling is incomplete. We demonstrate a *fully retrospective spin-history simulator* that produces estimates that correspond to signals in known-motion BOLD data collected in cadavers using SimPACE[3]. We estimate that current modeling methods account for only 20-50% of the motion artifact[3], and that the proposed modeling can account for the spin history motion artifact.

Motion model: The Bloch equations are well known[4-6]. Typical BOLD has TR < ~3*T1 and thus signal is partially saturated and dependent on history of excitation times and flip angles. Out-of-plane motion produces a pseudorandom sequence of excitation times and flip angles. Our spin history simulator (Fig 1) solves signal evolution independently for 100 sub-slices (in the slice-encoding direction) of each voxel, from the T1, timing and flip angle seen by this 1% sub-slice of the voxel. To include spins moving into and out of the intended voxel, a 3-slice-thick simulation environment is used covering the voxel of interest and voxels in immediately adjacent slices (e.g. superior and inferior for axials). T1 from tissue-segmented anatomic images was customized per subject with information from an EPI-based T1 map[7]. T1 was interpolated from the anatomic grid (1mm) to 1% of the EPI grid (EPI grid was 4mm thick, resulting in a 0.04mm simulation grid). For each of the 300 sub-slices within this 3-voxel chunk, the excitation timing was determined, and signal evolution solved at each excitation. Timepoints corresponding only to the desired voxel excitation times were summed together. Thus, for 100,000 voxels of interest with 100 timepoints, the signal evolution is solved for 30,000,000 wedges of 40 micron-thick wedges of tissue. The simulation of an entire volume is now performed in 2 hours on a single 2.33GHz Xeon core in MATLAB. Note that the method can be parallelized and is being applied to a range of typical BOLD data at 3T and 7T..

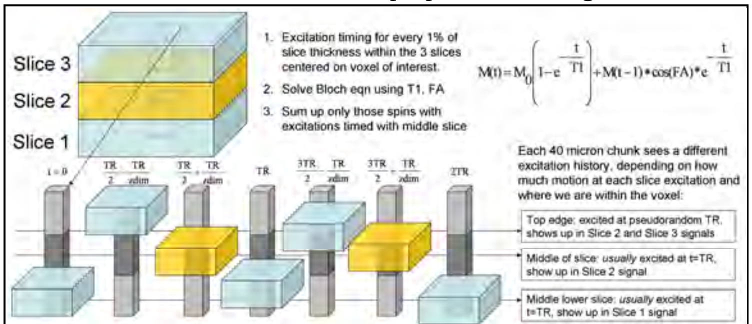

Fig 1: simulation of voxel in slice 2 using slices 1 through 3. Out-of-plane motion = altered timing/flip angles. Slice 2 excitations (yellow) are summed to get the simulated received voxel signal.

Data acquisition/validation: Cadaver data with known in-plane and out-of-plane motion was acquired[3]. Partial volume and spin history simulations with this motion were generated, and resulting signals regressed from acquired SimPACE data. A similar procedure was performed in live subjects using SLOMOCO[3] to derive the slicewise motion parameters for use in the linear partial volume model and the nonlinear spin history model. Seed-based connectivity was used to examine motion corruption present in the simulations and data after 3 motion corrections. In Fig 2, the linear model-based correction reduces corruption in both live subject and cadaver datasets (as compared with Moco), but less than nonlinear SpinHist model regression. As evidence that linear motion correction methods are based on incorrect assumptions about the characteristics of motion artifact in data, we compare the observed artifact in cadaver data corrupted using only the assumption used by linear motion correction methods (i.e. our partial volume simulation) to the observed artifact seen in real data. Fig 2 shows connectivity for 5 adjacent seeds for linear simulation, Spin Hist simulation, SimPACE motion (i.e. "real" motion) and the SimPACE data corrected using our nonlinear model. It is clear that the alteration in correlation patterns caused by motion is much more accurately modeled by Spin Hist (row 2) than by the linear model (row 1).

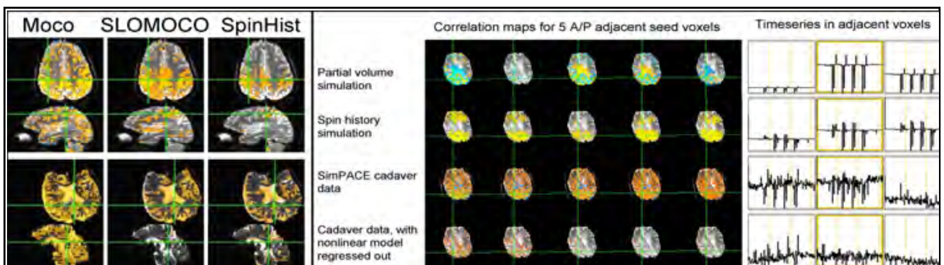

Fig 2: Left: effect of SPM's realign, SLOMOCO linear model and spin-hist correction in live (top) and cadaver (bottom). Mid: seed-correlation in partial volume (top) and spin history (top mid) simulation, cadaver data with same motion (bottom mid) and corrected cadaver data (bottom) in adjacent seed voxels. Right: timeseries of same.

Conclusions: We demonstrate that linear motion correction models cannot address out-of-plane motion. Spin history artifact must be modeled appropriately in order to remove it. Our future plan is to 1) cover motion greater than slice thickness, 2) incorporate flip angles and 3) use a signal dictionary to reduce time. Software is now available at www.nitrc.org/projects/pestica for performing these simulations. We gratefully acknowledge NIH grant 5P50NS038667-14 for MRI of cadaver tissue.

References: 1) Power JD, NI. 2012;59:2142. 2) van Dijk KR, NI 2012;59:431. 3) Beall EB, NI 2014;101:21. 4) Muresan L, IEEE TBE 2005;52:1450. 5) Yancey S, Med. Phys. 2011 38, 4634. 6) Ferrazzi G, NI 2014;101:555. 7) Bodurka J, NI 2007;34:542.