Comparison of BOLD censoring motion metrics when you know the motion (SimPACE)

Erik Beall[1] and Mark Lowe[1]
[1]*Imaging Institute, Cleveland Clinic, Cleveland, OH, United States*

Target Audience/Purpose: fMRI/connectivity researchers. To investigate problems with volumetric motion metrics used in BOLD motion methods

Introduction:

Head motion is a major problem for the analysis of BOLD fMRI and rs-fMRI. Current motion correction and characterization methods are incomplete due to the assumption that motion is synchronized to the volume acquisition[1-6] (or smoothly interpolated over slices[6]). In-scanner head motion can happen during any part of a volume acquisition[7] and, thus, is not volumetric, and the assumption that it is volumetric is unrealistic (see top of Fig 1). Intravolume motion (occurring on one or a few slices) is more realistic and this may be a major reason why current methods fail to robustly identify motion corruption. Using motion-injection pulse sequence data[1] in cadaver brains with a mix of intravolume and volume motion, we compare motion metrics based on the true motion with those based on retrospective volumetric parameters and volumetric BOLD signals and show that volumetric methods fail to capture slicewise motion. We conclude that the sensitivity and specificity of volumetric metrics is very poor and that at present these are unlikely to be adequate for identification of motion corruption. Since censoring methods depend on accurate identification, using data censoring as a motion correction method is not recommended at this time.

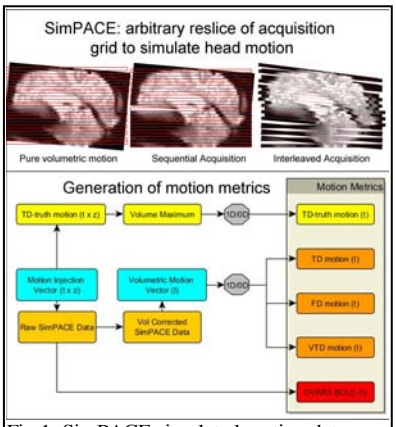

Fig 1: SimPACE simulated motion data schematic and metrics used in study.

Methods:

BOLD data with a known sequence of 6 degree-of-freedom (DOF) motion with preset impulses of 0.5, 1 and 1.5mm/degrees every 4th volume was obtained in 7 cadaver data with a motion-injection pulse sequence, described previously as SimPACE[1] (in short, SimPACE induces realistic head motion independently on each slice through updates in the gradient axes transformations). The induced motion was abrupt instantaneous slicewise or volumetric motion on the order of ~1mm and 1 degree in each of the 6 orthogonal degrees of freedom (DOF), separated by 4 volumes of random background motion on the order of 50 microns on the 3 translational DOF. One half of each scan consisted of injections on several non-adjacent slices within a given volume and the second half consisted of volumetric injections. SimPACE produces accurate signal disruptions due to spin history, phase-encode warping and non-volumetric motion. The BOLD data was corrected for volumetric motion using 3dvolreg from AFNI[2]. The resulting 6DOF volumetric motion file was converted to three popular motion metrics from literature: total displacement (TD)[3], framewise displacement (FD)[4], and volumetric translations only (VTD)[5]. Four additional BOLD signal-based metrics were also computed: the global signal (GS), root-mean-square (VARS) global signal and first derivative of VARS (DVARS)[4] were computed (Fig 1 bottom). GS is average of all brain voxels, VARS is square root of the average of the sum of squares of the detrended and de-meaned voxels and DVARS is the first derivative of the VARS. The truth motion parameters (original injected vector) were converted to TD for every slice motion (here truth is denoted as gold-standard, or GLD) and subsequently converted to volumetric metric by taking the maximum slice TD within a given volume as the TD for that volume (TD-GLD). All motion parameter-based metrics were also re-created after taking the first derivative of the parameters prior to conversion (denoted as 1D, for first derivative, to distinguish from metrics created without taking the derivative, denoted as 0D for no derivative). Corrupted volumes were identified using thresholds as used in literature (0.5 for BOLD signal-based metrics, 0.5 for TD and FD and 0.1 for VTD), and the indices were compared with the truth injected motion indices to compute the true positive and false positive rate of each metric using these thresholds.

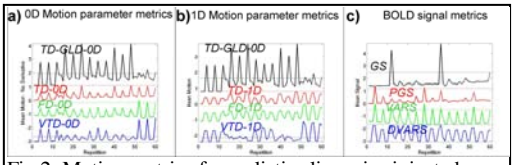

Fig 2. Motion metrics for realistic slice-wise injected motion. a) 0D volumetric motion parameter metrics (TD-0D, FD-0D, VTD-0D) and truth (injected) metric (TD-GLD-0D). b) 1D and truth metrics. c) BOLD signal-based metrics. Literature thresholds shown for each metric.

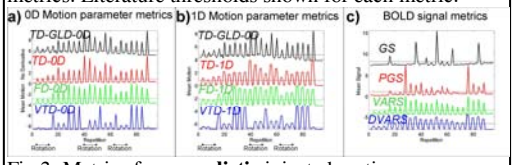

Fig 3: Metrics for **unrealistic** injected motion, same as Fig 2. Segments with rotational motion are indicated with "Rotation" at bottom a) and b), showing poor sensitivity of VTD to rotational motion.

	% Corrupted	TPR	FPR
TD-0D-GLD	24	100	0
TD-1D-GLD	48	100	31.6
TD-0D	2	8.3	0
TD-1D	0	0	0
FD-0D	0	0	0
FD-1D	0	0	0
VTD-0D	24	66.7	10.5
VTD-1D	42	83.3	28.9
GS	52	58.3	50
PGS	0	0	0
VARS	98	100	97.4
DVARS	98	100	97.4

Table 1: volumes identified as corrupted during realistic motion injection. Motion was injected on 1/4th of nonadjacent slices within a volume in 24% of volumes (12 out of 50 volumes). VTD and all BOLD signal-based metrics suffer from high false positive rates and reduced sensitivity.

Results: Figs 2c and 3c show that BOLD signal-based metrics mostly fail to capture realistic (slice) motion, with VARS obtaining the best performance. Note that DVARS assigns nearly equal weight to adjacent volumes despite motion being injected on only one volume. It is true there is a spin-history effect from out-of-plane motion that is very important and this is often the justification for using a derivative-based method, but the spin-history effect is typically smaller than the initial signal change, and critically, with signal-based methods, that due to out-of-plane motion is not separable. The equal assignment to adjacent volumes is not appropriately model-based and is an artifact of the method. Figs 2/3 a and b show that motion metrics have poor sensitivity to realistic (slicewise) motion, and furthermore that the use of translations only in creating a motion metric has, predictably, poor performance at identification of rotational motion, and thus should be discouraged. Table 1 shows the overall performance of these metrics and thresholds at correctly identifying intentionally corrupted volumes. Threshold optimization could improve FPR/TPR, but note all of the volumetric metrics clearly have some FPR in the presence of reduced TPR.

Conclusions:

The use of volumetric motion- or signal-based metrics to identify or characterize motion corruption is popular due to a lack of alternatives, but we have shown here with our motion-injection data that this is highly problematic. In particular, censoring is critically dependent upon accurate identification of motion corruption, but due to the poor specificity/sensitivity of prevailing metrics, censoring cannot work in its present form. Unfortunately, **all our motion methods at present are based on volumetric motion parameters or BOLD signal**. It is likely that accurate motion characterization methods require slicewise information, and further progress on methods reliant on motion characterization will be hindered until this information becomes available, ideally with a robust retrospective method.

Acknowledgements: The authors would like to gratefully acknowledge support from NIH grant 5P50NS038667-14 for MRI acquisition of cadaver tissue and the staff of the Mellen Center for acquiring the cadaver data, including John Cowan, Tami Gaebelein, Sarah Gallucci and Derrek Tew.

References: 1) Beall, EB and Lowe, MJ, "BOLD motion injection shows total correction possible with accurate parameters and parameterization", OHBM 2013, 2) Cox, RW et al, MRM 1999; 42:1014–1018., 3) Jiang A et al, HBM 3, 224-235., 4) Power JD et al, Neuroimage 59, 2142-2154, 5) Van Dijk KR et al, Neuroimage 59, 431-438. 6) Roche A et al, 2011 IEEE IEEE Trans Med Imaging 30, 1546-1554. 7) Matthew BA et al, "Fast head tracking shows volumetric motion parameters are unrealistic (and fundamentally wrong)." ISMRM 2014.