The Bermuda Triangle of d- and f-MRI sailors - software for susceptibility distortions (SDCFlows)

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Introduction: Echo-Planar Imaging (EPI) allows very fast acquisition of whole-brain data, which enables standard functional & diffusion MRI (f/dMRI). However, EPI is notably sensitive to variations in the base B_0 field. Small deviations in parts-per-million from the nominal B_0 caused by steps in magnetic susceptibility (tissue interfaces) introduce misplacements in the registered location of voxels of up to some cm in standard settings along the phase-encoding direction (PE), apparent as local geometrical distortions of the imaged specimen. In humans, the susceptibility distortion (SD) is prominent starting at the petrous bone and extending towards the ear canals, defining a sort of triangle where signal vanishes (Fig. 1). SD is well-known, but existing solutions require mapping B_0 deviations and are sensitive to several imaging parameters. In practice, addressing SDs is error-prone and often overlooked. Here, we introduce *SDCFlows* (*SD Correction Flows*), an open-source utility that leverages BIDS¹ and several existing software tools to provide standardized, best-effort SD correction.

Methods: *SDCFlows* defines a clear application programming interface (API) that divides the problem into 2 stages:

1) Estimation - the MRI acquisitions in the protocol for SD are discovered and preprocessed to estimate a map of B_0 non-uniformity in Hz (ΔB_0). The theory behind these distortions is well described in the literature^{3,4} (Fig. 1). *SDCFlows* builds on freely-available software to implement three major strategies for estimating ΔB_0 (Eq. 1). The first strategy uses spiral-echo imaging, which directly produces ΔB_0 maps, or other schemes such as gradient-recalled echo imaging that measure the voxel-wise phase drift (proportional to ΔB_0) between two subsequent echoes. These techniques stem from the analytical solution to the distortion (Eq. 1), and *SDCFlows* refines the widespread workflow based on FSL⁵ (PRELUDE+FUGUE). The second strategy uses methods exploiting the symmetry of the distortion when the PE polarity is reversed, offering two implementations based on FSL TOPUP⁶ and AFNI 3dQwarp⁷. Third, *SDCFlows* integrates *fMRIPrep*'s "fieldmap-less" technique⁸ that nonlinearly registers the EPI scan to the same subject's anatomical MRI.

2) Application - the estimated ΔB_0 map is aligned to the target EPI scan to be corrected and used to generate a displacement field in NIfTI format that is compatible with ANTs². The voxel location error along the PE will be proportional to $\Delta B_0 T_{ro}$ (Fig. 1).

Results:

A standard software tool that democratizes the implementation of an otherwise elusive problem. We have refactored *SDCFlows* from *fMRIPrep*'s codebase and built an effective API for reuse in any workflow for preprocessing EPI images. The API is split into 1) estimation and 2) correction, so that workflow developers may combine the effects of SD with other spatial corrections of the image and implement "1-step" resamplings. The API minimizes computational duplication; e.g., *fMRIPrep* runs estimation for each target image to be corrected.

A thoroughly tested tool that leverages existing implementations. *SDCFlows* implements workflows leveraging existing tools and supports them to cover a wide range of protocols. We are pushing the BIDS specifications to better capture fieldmaps⁹. All estimation strategies are regularized through B-Spline approximation, which makes the outputs consistent across strategies and opens new avenues for a systematic comparison of corrections.

A thoroughly documented and self-reporting tool. *SDCFlows* follows “glass-box” principles⁸ and produces “reportlets” to visually assess the results (Fig. 2).

Conclusion: *SDCFlows* documents the susceptibility distortion artifact and equips d/fMRI researchers with a reliable and transparent tool to address the problem.

References:

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Figure 1. The problem of susceptibility distortions. The annotated panels show one EPI image from one subject (with identifier 101006) of the Human Connectome Project. The views on the right-hand side also have an overlay of the field map estimated with the PEPOLAR (PE-Polarity) technique based on FSL TOPUP.

Figure 2. *SDCFlows* produces self-contained, dynamic visualizations of the estimated ΔB_0 maps in scalable-vector graphics (SVG) format. These “reportlets” (or “mini-reports”) are easily embedded in HTML visual reports, such as those produced by *fMRIPrep* and *dMRIPrep*.