Slice-by-slice regularized registration for spinal cord MRI: SliceReg

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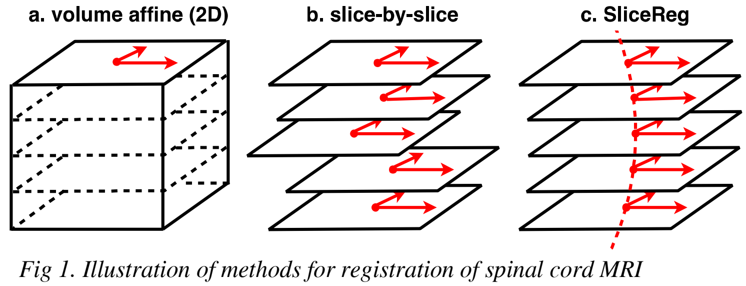


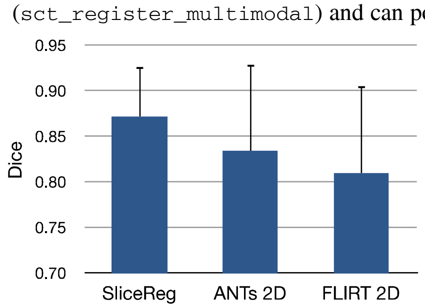
Fig 1. Illustration of methods for registration of spinal cord MRI

Purpose. Multimodal registration and motion correction in spinal cord MRI data if often performed using affine transformations constrained in the axial plane (Fig 1a). Although fairly robust, affine transformations often lack accuracy because of the articulated nature of the spine, which can produce non-rigid deformations. Moreover, respiratory-related changes of the B_0 field can induce slice-wise related shifts along the phase-encoding direction (typically anteroposterior), which is commonly seen in EPI-based functional or diffusion MRI protocols [1]. Slice-by-slice motion correction consists in estimating translations within the axial plane (Fig 1b) and was shown to produce accurate correction of spinal cord motion [2]. However, this approach is suboptimal because each slice is corrected independently, without considering the smooth nature of the deformation along z, hence reducing robustness compared to volume-based registration. In this study we propose a new registration method that estimates slice-by-slice translations while ensuring regularization constraints along z (SliceReg, see Fig 1c). All transformations are estimated within a single optimization process and hence provide consistent and biologically plausible transformations that may outperform volume-based methods while retaining computational efficiency.

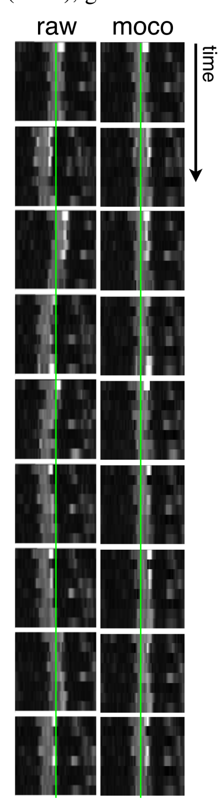
Methods. ***Registration algorithm***. Translations along x and y are estimated slice-by-slice using the convergence framework implemented in ITK (www.itk.org). The cost function includes a regularization term expressed as a polynomial function along z (assumed to be the spinal cord axis). Image metric (cross-correlation, mutual information and mean squares), shrink factor (data subsampling), smoothing and degree of polynomial function used for regularization can be specified. The software outputs the registered image, forward and backward warping fields as well as csv files with x and y translations per slice. ***Validation***. To evaluate the performance of SliceReg in a large variety of sequences and acquisition setups, data were acquired in 25 subjects in five different centers: UNF (Montreal, n=6), Martinos Center (Boston, n=5), FMRIB (Oxford, n=4), Western Hospital (Toronto, n=5) and Pitié-Salpêtrière Hospital (Paris, n=5). Sequences used were: diffusion-weighted EPI (n=7), spin echo EPI (n=10), gradient echo EPI (n=6) and magnetization transfer gradient echo FLASH (n=2) with variable amount of noise (different coils were used), spatial resolution (0.8 to 1.2mm in-plane) and coverage (varied between 4 to 7 vertebral levels). For each sequence, two volumes showing non-rigid deformations were selected as candidates for co-registration. The SliceReg method (3rd order polynomial) was compared against ANTs [3] and FSL FLIRT [4], the two latter being constrained to two degrees of freedom (in-plane translations). Mean square metric was used for all methods. Following within-pair registrations, the spinal cord was segmented automatically using PropSeg [5] and the estimated transformations were applied to the segmentations using nearest neighbor interpolation. Overlap between the two registered segmentations was assess using Dice coefficients.

Results. Dice was respectively 0.87±0.06, 0.83±0.10 and 0.81±0.10 for SliceReg, ANTs and FLIRT. Student's *t*-test (paired for dataset) showed significant difference between SliceReg and ANTs (p=0.004) and between SliceReg and FLIRT (p=0.00007). Average computation times were 0.92ms, 0.65ms and 0.63ms for SliceReg, ANTs and FLIRT, respectively. Fig 3 illustrates the performance of SliceReg for correcting motion in a long fMRI dataset with particularly large deformations.

Discussion. We introduced a novel approach to deal with non-rigid deformations in spinal cord datasets using slice-by-slice registration regularized along the spinal cord axis (SliceReg). The method is more accurate than rigid-body transformations and offers more robustness than non-regularized slice-by-slice registration. Despite ~40% increase of computation time compared to volume-based methods (because one transformation per slice is estimated as opposed to a single one), the average processing time is below 1 s, making it suitable for motion correction pipelines. The SliceReg method is freely available in ANTs [3] (`antsSliceRegularizedRegistration`) and in the Spinal Cord Toolbox [6] (`sct_register_multimodal`) and can potentially become a relevant tool for precise quantification of multiparametric data.



← Fig 2. Results of registration accuracy for SliceReg, ANTs 2D and FLIRT 2D methods. Students t-test show significantly higher Dice for SliceReg in comparison with ANTs (p=0.004) and FLIRT (p=0.00007).



→ Fig 3. Example of SliceReg applied to a long fMRI dataset (1600 volumes) with particularly large subject motion characterized by drifts, head tilting, swallowing and respiratory-related B_0 shifts. Vignettes show sagittal images with raw (left) and corrected (right) results. A green vertical line is overlaid for visual assessment.

References. **[1]** Verma T. and Cohen-Adad J., *Magn Reson Med*, 2014. doi: 10.1002/mrm.25075. **[2]** Cohen-Adad J. et al., *NeuroImage*, 2010. 50(3):1074-84. **[3]** Avants B.B. et al., *Neuroimage*, 2011. 54(3):2033-44. **[4]** Jenkinson M. et al., *NeuroImage*, 2002. 17(2):825-41. **[5]** De Leener B. et al., *Neuroimage*, 2014. 98:528-36. **[6]** Cohen-Adad J. et al., *Proc. OHBM, Hamburg, Germany*, 2014: p. 3633.

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