Assessment of non-rigid registration in diffusion tensor tractography of human spinal cord at 3T.

M. Kavec[1], I. Delpierre[1], G. Cunha[1,2], T. Metens[1], and D. Balériaux[1]
[1]Hôpital Erasme, Université Libre de Bruxelles, Brussels, Belgium, [2]Hospitais Universidade, Coimbra, Portugal

Introduction
Detection of restricted Brownian motion of water molecules *in vivo* by means of MRI became in recent years an important clinical and research tool in a wide spectrum of diseases of central nervous system including stroke, tumours and neurodegeneration. Diffusion-weighted (DW) sequences apply strong dephasing gradients to encode random motion of spins. This approach is however, coupled with artefacts caused by bulk motion of an object of interest. The echo planar imaging (EPI) is usually efficient in acquiring snapshots of motion-artefact free images. However, during lengthy examinations, such as diffusion tensor imaging (DTI), involuntary movement of the subject is almost always observed between consecutive diffusion gradient orientations. Rigid-body image registration is helpful and often applied in brain activation studies, yet this method is ineffective in DTI of the spinal cord, where breathing motion and cord motion within spinal channel are non-rigid and depend on the phase of a breathing cycle. Physiologic triggering of image acquisition could potentially reduce this problem, but with penalty of even longer imaging time.
In this study, we assessed the value of the non-rigid image registration [1] to correct for subject motion during DTI of cervical spinal cord. The method employs carefully tuned free-form deformations and has been used in MRI applications of breast cancer, brain morphology in HIV infection, grey matter development of preterm infants, and recently for the voxelwise group statistical analysis of human brain DTI [2, 3].

Methods
Study of cervical spine in 4 healthy volunteers was carried out on a 3T Philips Achieva MR system using a 16-channel neuro-vascular coil. Diffusion-weighted images (b = 700 s/mm^2, 15 diffusion gradient orientations) were acquired in axial orientation using a single-shot spin-echo EPI sequence (TR/TE = 11700/79 ms, SENSE factor = 2, NSA = 2, phase-encoding direction in AP, acquisition time – 7.3 minutes). Seventy-five consecutive slices with scan resolution 1.3 x 1.3 x 2 mm^3 covered the entire cervical spine, starting at the level of the medulla oblongata.
To minimize the impact of a subject's motion, DW images were coregistered with respect to the b = 0 s/mm^2 image, using non-rigid registration driven by normalized mutual information cost function [1-3]. Accuracy of the realignment was verified by visual inspection for all subjects.
Diffusion tensor fiber tracking and statistical analysis of the calculated maps was performed using DTI Studio 2.4. Regions of interest (ROIs) were placed at the level of C1 and C6 (block arrows in Fig. 1A) and fibers passing through the ROIs were reconstructed, if their local FA > 0.25 and deflection < 50°. In order to estimate effectiveness of the motion correction, fractional anisotropy (FA), trace of diffusion tensor (Trace) and eigenvectors (E1-3) along the tracked fibers, and number and length of the reconstructed fibers, respectively, were compared before and after non-rigid registration.

Results
Visual inspection of images after co-registration was satisfactory in all 4 subjects and successfully corrected for motion observed in the original DW images. Figure 1 demonstrates the effect of non-rigid realignment on results of tractography, where apparently more fibres were reconstructed in realigned (Fig. 1B) than in non-realigned (Fig. 1A) images, respectively. Fractional anisotropy, Trace and eigenvalues of diffusion tensor along the generated fibre tracts, and averaged over the subjects did not change after image registration. We found however more than three-fold average increase (from 1.2 to 8.6) in the number of reconstructed fibres N, after the image treatment (see Table 1).

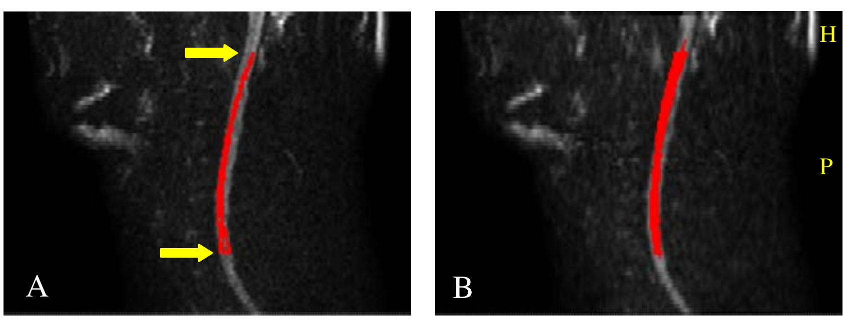

Figure 1. Sagital reconstructions of DW image overlayed by fibers tracked before (A) and after (B) non-rigid registration.

	Before registration	After registration
FA	0.739 (0.032)	0.697 (0.015)
Trace * [mm^2/s]	2.9 (0.2)	3.1 (0.2)
E1 *	2.0 (0.1)	2.0 (0.1)
E2 *	0.6 (0.1)	0.7 (0.1)
E3 *	0.3 (0.1)	0.4 (0.1)
N [%]	100	**335 (300)**
L [mm]	102.0 (1.0)	101.8 (0.7)

Table. Mean (SD) diffusion tensor indices along fibres and parameters of fibres. * $\cdot 10^{-3}$

Discussion
Image registration methods are generally difficult to validate due to the lack of the "golden standard" reference method. This holds even more in case of non-rigid registration where, depending on the amount of allowed deformation, the overall structure in image may not be preserved. In this study, we used the same well-tested registration parameters as those used for tractography based voxelwise morphometry [2, 3]. Additionally, only intra-subject image registration was carried out, which further reduces possibility of an unrealistic image deformation. Importantly, the image realignment did not result in any changes of diffusion tensor indices.

Conclusion
Based on the presented results it seems that non-rigid image realignment could potentially improve spinal cord tractography by correcting for breathing motion in relatively high resolution DTI images obtained at 3T. This hypothesis could be scrutinized against results obtained using physiologic triggering however, by paying the penalty of substantially prolonged examination time.

Acknowledgements
This work was supported by a grant from the "To Walk Again" foundation, http://www.towalkagain.org

References
[1] Rueckert D. et al., IEEE Trans Med Imaging 1999, 18:712-721 [2] Smith S. et al., NeuroImage 2006, 31:1487-1505 [3] FMRIB Software Library, Oxford University, UK; http://www.fmrib.ox.ac.uk/fsl