Intra Voxel Incoherent Motion (IVIM) MRI of the human spinal cord: preliminary results and potentiality

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INTRODUCTION: There is a lack of MR techniques able to provide human spinal cord (SC) haemodynamic information. Dedicated methods such as ASL or VASO techniques [1,2], which currently suffer from low sensitivity or CSF contamination in the absence of ECG-synchronization, need to be improved in order to provide reliable information. In this context, the IVIM (Intra Voxel Incoherent Motion) technique [3], which is a diffusion-based method that has largely been applied in the brain, but also in moving organs such as the liver [4] and heart [5] or in low-perfused tissue such as skeletal muscles [6], could be an alternative.
Whereas signal in diffusion experiments is described by: $S/S_0=\exp(-b.ADC)$ **(eq.1)**, with S is the signal amplitude attenuation arising from the application of diffusion encoding gradients, b the diffusion gradient weight (s/mm^2), S_0 the signal amplitude for b=0 s/mm², and ADC the apparent diffusion coefficient of water (mm²/s), the signal in IVIM experiments follows the expression: $S/S_0=(1-f).\exp(-b.D)+f.\exp(-b.(D+D^*))$ **(eq.2)**, where D is the molecular diffusion coefficient of water (mm^2/s), D* a pseudo-diffusion coefficient also called microvascular or blood velocity index (mm²/s) and f a vascular fraction (% of the total signal) related to the amount of active capillaries. Applied to the SC, the IVIM technique may thus be an alternative to get perfusion-related information (f, D*) that could help in a first approach for SC vascular descriptions and pathological characterizations.
The aim of this preliminary work was to investigate the possibility of collecting vascular information on human spinal cord by using the IVIM method.

METHOD: Experiments were conducted on healthy volunteers (n=5, mean age 30±6) on a 3T-system (Siemens, Erlangen) using multi-channel head and neck coils. Measurements were carried out at the cervical level (C2-C3, 6 transverse slices, 5-mm thickness, FOV 128x128, matrix 140x140, TE 80ms, 12 NEX) using a Stejskal-Tanner diffusion sequence (10 encoding gradients, b varying from 0 to 700 s/mm²) in 2 directions (parallel and perpendicular to the SC axis). Acquisitions were synchronized with ECG (RR 300 ms). IVIM parameters were analyzed in regions of interest (ROI) located in lateral white matter (lWM) and ventral gray matter (vGM). D and f were evaluated by fitting (eq2) to the data for large b-values (b≥500 s/mm^2 and assuming D*>>D). Corrections for T_1 and T_2 relaxations were taken into account [7]. D* was then extracted from (eq.2) using the previously determined D and f parameters. A Dfast coefficient, carrying information on both diffusion and perfusion, was also obtained using a mono-exponential fit on the low b-values (10≤b≤100s/mm^2). Finally, the ADC was calculated by conventional mono-exponential fit (eq.1) using b=0 and large b-values (b≥500 s/mm^2). Prior to *in vivo* experiments, acquisitions have been acquired on phantoms using the same protocol in order to verify the mono-exponential decay of the signal and check for systematic errors in the sequence design.

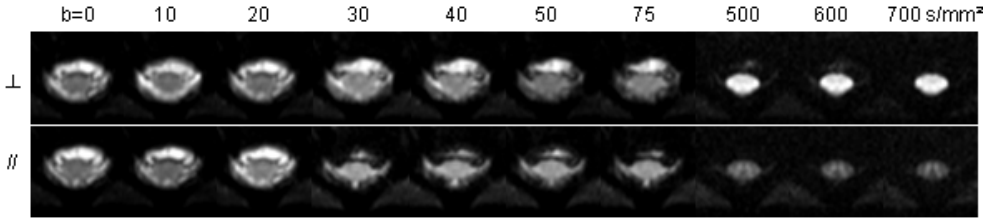
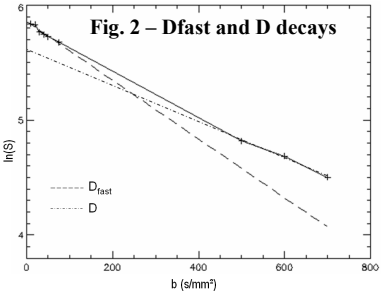
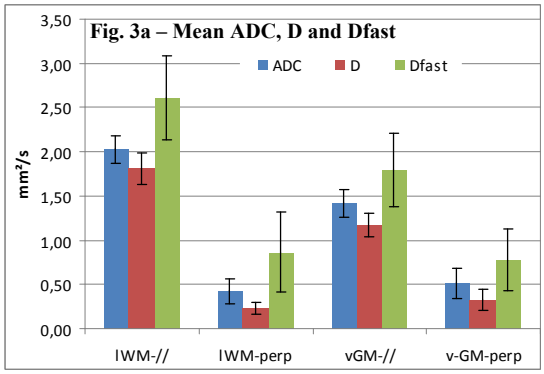
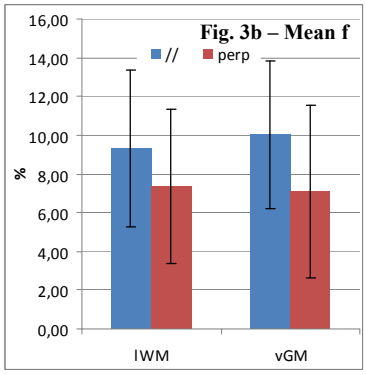


Fig. 1 – SC DW-images for the 10 diffusion encoding gradient values (// and ⊥ to the SC axis).



RESULTS: Figure 1 shows typical IVIM series collected at the cervical level. Figure 2 illustrates the logarithm of the signal evolution as a function of b for a ROI located in white matter (WM). Two curves with slopes Dfast for b<100s/mm^2 and D for b>500s/mm^2 can be clearly distinguished. Data were analyzed for the 5 volunteers in the lWM and vGM ROIs. As illustrated on fig. 3a, Dfast (microcirculation and diffusion effects) was systematically higher than ADC (apparent diffusion) ($p<0.005$) and ADC was higher than D (pure diffusion) ($p<0.001$). D* values (microvascular index) ranged from 3 to 6.10^{-3} mm²/s and the vascular fraction values were found in the order of 8% and 9% for the WM and GM, respectively (fig. 3b).





DISCUSSION: These preliminary IVIM experiments, performed at the cervical SC level, showed a clear bi-exponential decay, suggesting that the combination of both molecular diffusion (slow component) and capillary perfusion (fast component) contributions can be detected. The absence of vascular contribution would have led to f=0 and D=ADC=Dfast. Since vascular description of the spinal cord remains scarce, a comparison with the conventional methods is not an easy task. A blood volume of 4% has been reported using the VASO technique [2]. In our work, the vascular fraction was evaluated in the order of 8%. No human SC blood flow (BF) value has been reported, however from animal experiments, SCBF is expected to be within the same range than cerebral BF [8]. Although SCBF can not directly be measured with IVIM, the moderate blood velocity index (D* =6.10^{-3} mm²/s) measured in this study suggests lower perfusion in SC than in the brain, for which D* was measured equal to 17.10^{-3} mm²/s [9]. Further studies are needed to determine potential differences between animal and human physiology. Moreover, refine experiments should be conducted in various conditions (stress, pathology, ..) in order to evaluate the sensitivity of the method. Finally, anisotropy of the SC vasculature also remains to be evaluated with IVIM [5,6].

CONCLUSION: This work demonstrated that IVIM has the ability to easily provide information relative to the vascular status of the spinal cord (vascular blood fraction (f), blood velocity index (D*). Sub-millimetric data, allowing GM and WM delineation, were acquired in less than 10 minutes, with sufficient SNR. Acquisition performed during the quiescent phase of the CSF cycle insured a limited contribution of physiologic motion. Although IVIM parameters did not directly described perfusion, further investigation is worthy, since the technique may constitute an alternative method for haemodynamic investigation allowing describing alterations arising in pathologies such as SC trauma, ischemia or infarction.

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