In-vivo free-breathing DTI & IVIM of the whole human heart using a real-time slice-followed SE-EPI navigator-based sequence: a reproducibility study in healthy volunteers.

Kévin Moulin[1,2], Pierre Croisille[1,3], Thorsten Feiweier[4], Benedicte M.A. Delattre[1], Hongjiang Wei[1], Benjamin Robert[2], Olivier Beuf[1], and Magalie Viallon[1,3]
[1]*CREATIS; CNRS (UMR 5220); INSERM (U1044); INSA Lyon; Université de Lyon, Lyon, France,* [2]*Siemens Healthcare France, Saint-Denis, France,*
[3]*Department of Radiology, Centre Hospitalier Universitaire de Saint- Etienne, Université Jean-Monnet, France,* [4]*Healthcare, Siemens AG, Erlangen, Germany*

Purpose:
In-vivo cardiac diffusion analysis using either the Intra-Voxel Incoherent Motion (IVIM) model or the Diffusion Tensor Imaging (DTI) model shows promise to provide new insights into heart pathologies. However, due to the combined challenge of respiratory and heart motion (1, 2), currently proposed acquisition methods are quite demanding for unhealthy patients. In this study, we propose to use the motion information provided by a navigator to prospectively update in real time the position of the diffusion-weighted slices in order to offer an efficient free-breathing strategy for rapid and efficient cardiac diffusion acquisition using a single-shot Spin-Echo EPI sequence (SE-EPI).

Materials and methods:
The proposed technique was evaluated twice on 10 healthy volunteers with a DTI and an IVIM protocol to evaluate the reproducibility of the diffusion parameters (*FA, MD, f, D* and *D**). Acquisition was performed on a 1.5T MAGNETOM Avanto (Siemens AG, Erlangen Germany) using a custom-built SE-EPI diffusion sequence. Double-oblique short-axis DW images were acquired with a 128 × 80 pixel matrix and rectangular FoV of 350 × 220 mm². Short-axis DW slices (6 mm thick) were obtained with an in-plane spatial resolution of 2.7 × 2.7 mm² interpolated in-plane to 1.35 x 1.35 mm²; the bandwidth was 2442 Hz/pixel, monopolar diffusion preparation and parallel imaging were used (GRAPPA factor 2). No averaging was performed, but multiple TDs shifted by 10 ms were acquired for PCAtMIP reconstruction (3). A pencil beam navigator was placed on the top of the liver, and the tracking factor was fixed to 0.6. Before acquisition, 2 complete dummy scans were performed for each slice for steady state consideration. DTI acquisitions parameters were: interleaved multi-slice mode with 10 contiguous slices; TE=45 ms; TR= number of slices x RR-interval = 10s (e.g., for a heart rate equal to 60 bpm); and 12 diffusion directions with a b-value of 350 s/mm² and 10 TDs for a total acquisition time of 22 min (considering a 60-bpm heart rate). The IVIM acquisition parameters were: 5 slices with a gap of 100% in the interleaved multi-slice mode; TE=42 ms; TR= number of slices x RR-interval = 5 s (e.g., for a heart rate equal to 60 bpm); and 6 diffusion directions with b-values 0, 15, 30, 50, 75, 100, 200, 300, 400 s/mm². Only 5 TDs were acquired, leading to a total acquisition time of 20 min. Inter-measurement reproducibility among repeated measures was assessed by the Lin concordance coefficient (LinCC) and the complementary Bland-Altman method with LinCC coefficient ρ_c, r (a measure of precision) and C_b (a measure of accuracy). Performance of the head-foot motion correction technique was evaluated on coronal view with diffusion weighting of b-value=30 s/mm² to avoid the blood hyper-signal. Top and bottom inboard interface of the heart cavity were segmented and compare with and without slice following (fig.1).

Results:
The slice-following technique is a powerful head-foot respiratory motion management solution for SE-EPI cardiac diffusion offering a 100% breathing cycle scanning efficiency (against 30% for a gating approach). Residual head-foot motion was evaluated to 2mm using the slice-following approach against 8mm of motion without correction. From the DTI dataset (fig. 2), the Mean Diffusivity (*MD*) was measured to $1.57\pm0.13\text{x}10^{-3}$ mm²/s and the Fractional Anisotropy (*FA*) to 0.35±0.04 which was found accurate (ρ_c=0.075, r=0.12, C_b=0.56) but less reproducible than MD (ρ_c=0.69,r= 0.70,C_b=0.99). From the IVIM protocol (fig. 3), vascular fraction *f* and diffusion coefficients *D* and *D** were determined to be 0.115±0.017, $1.23\pm0.19\text{x}10^{-3}$ mm²/s and $35.6\pm11.9\text{x}10^{-3}$ mm²/s, respectively. The vascular fraction *f* was highly reproducible and accurate (ρ_c=0.92, r=0.99, C_b=0.93), a good reproducibility and lower precision was found for D (ρ_c=0.69, r=0.75, C_b=0.91). Pseudo-diffusion coefficient *D** was the less reproducible among all IVIM parameters while remaining highly accurate (ρ_c=-0.214, r=-0.229, C_b=0.93).

Discussion & conclusion:
While reducing the acquisition time, the slice-following approach allows robust multi-slice acquisition with increased TR and thus SNR. The slice-followed SE-EPI cardiac diffusion sequence is hence a promising solution for clinical implementation, allowing unprecedented acquisition speed that could be tailored to specific needs.

Reference: (1)Nielles-Vallespin S, et al., Magn Reson Med. 2013;70:454–465. (2)Stoeck CT, et al. PLoS One. 2014;9(9):e107159. (3) Pai VM al. Magn Reson Med. 2011;65(6):1611-9.

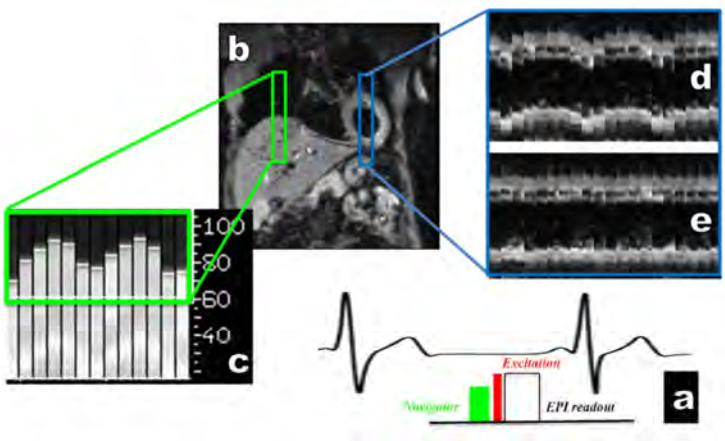

Figure 1 (left): a) A pencil beam navigator is played out before each acquisition and placed on the top of the liver b). The information given by the navigator c) is used, through a tracking factor of 0.6, to move the slice in real time during the breathing cycle. Performance of the respiratory head-foot motion correction for SE-EPI diffusion with slice following was evaluated on coronal slice orientation with b-value=30 s/mm² image from a series of diffusion-weighted images acquired over 1 min. d) and e) free-breathing coronal acquisition without and with slice following.

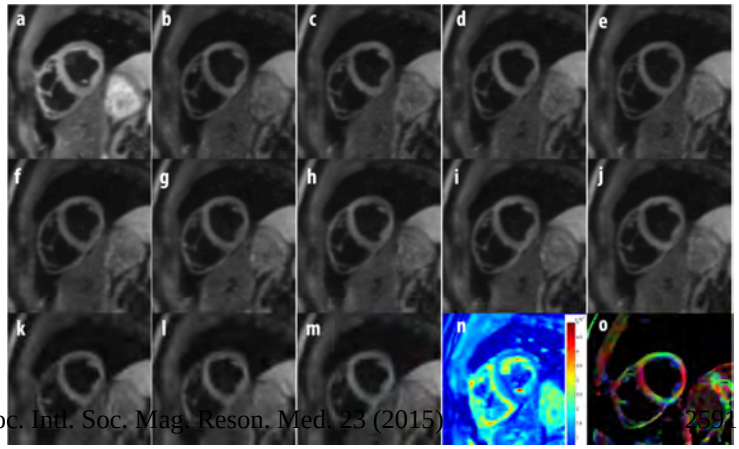

Figure 2 (bottom left): Example of DTI raw images a) dark blood b-value=~5 s/mm²: b-m), 12 directions of the central mid-ventricular short-axis slices with b-value=350 s/mm² and calculated parametric maps: n) mean diffusivity *MD*, and p) colored *FA* maps displaying the classical fiber orientation.

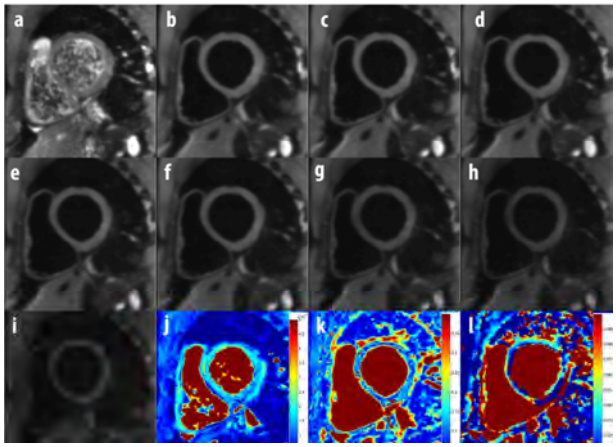

Figure 3 (bottom right): Example of IVIM raw images of basal-ventricular short-axis slices: a) b-value=0 image b-i) trace images with b-values=15, 30, 50, 75, 100, 200, 300, 400 s/mm² and calculated parametric maps: j) diffusion *D*, k) perfusion fraction *f*, and i) *D** maps.