Verification of the intra-voxel incoherent motion (IVIM) model in the porcine heart

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Introduction: The concept of intra-voxel incoherent motion (IVIM) [1] for perfusion measurement has gained significant momentum in recent years. However, cardiac and respiratory motion render IVIM acquisitions of the heart very challenging, requiring dedicated acquisition and post-processing methods [2]. The objective of this work was to validate the IVIM model in the heart using pre- and post-mortem measurements in a pig model of cardiac infarction.

Methods: Data from two pigs (heart rate 62±7 bpm, weight 65±5 kg) with an apical myocardial infarct were acquired on a 1.5T Philips Achieva system (Philips Healthcare, Best, The Netherlands) equipped with a 5-channel cardiac receiver array. Diffusion imaging was performed with an ECG triggered single-shot spin echo sequence with second order motion compensated diffusion encoding gradients [3]. Two slices (Figure 1) in healthy and infarcted region (equatorial and apical area, respectively) were acquired in short axis view orientation during free breathing. The imaging parameters were as follows: spatial resolution: 2.4×2.4mm^2, slice thickness: 10mm, reduced field-of-view (FOV): 230×120mm^2, TR/TE: 2R-R/94ms, 8 signal averages, spectral-spatial water-only excitation. Data were acquired for 16 optimized b-values [4] along 6 diffusion encoding directions [5] during early systole.
In order to delineate the infarct region, dynamic contrast-enhanced myocardial perfusion imaging was performed using a saturation-recovery single-shot gradient echo sequence triggered to mid-systole. Imaging parameters were: spatial resolution: 1.5x1.5mm^2, slice thickness: 10mm, flip angle: 15°, TR/TE: 2.7/1.3ms, 5x k-t acceleration, saturation delay: 215ms.
Upon completion of in-vivo scanning, the pigs were euthanized by a potassium injection inside the MR scanner bore and the imaging protocol was repeated. The animal experiments were performed in adherence to the Swiss law of Animal Protection and approved by the Zurich cantonal veterinary office.
In post-processing, affine image registration was performed [6] and signal intensities S(b) were fitted using the IVIM model [1]:

$$S(b)/S_0 = f * \exp(-b(D+D^*)) + (1-f) * \exp(-bD))$$

using the constrained fitting Matlab (MathWorks, Natick, MA) toolbox (S_0: b=0 s/mm^2 image, f: perfusion fraction, D: diffusion constant, D*: pseudo diffusion constant).

Results: Acute myocardial infarcted area in the septum is clearly visible in both the dynamic contrast enhanced measurement and the perfusion fraction map upon pixel wise IVIM fitting (Figure 2 A,B). Perfusion in the infarcted zone is significantly reduced compared to healthy tissue as shown by f values close to zero. In the post mortem case, S(b) follows an almost mono-exponential decay with f =(0.05 ± 0.16). The change in diffusion constant between in-vivo (1.4± 0.2)x10^{-3}mm^2/s and post mortem data (1.2 ± 0.3)x10^{-3}mm^2/s is within one standard deviation (Figure 2 D,E). Fitting results are summarized for both subjects in Figure 3. Due to the low perfusion fraction f in the post mortem data, fitting D* is badly conditioned.

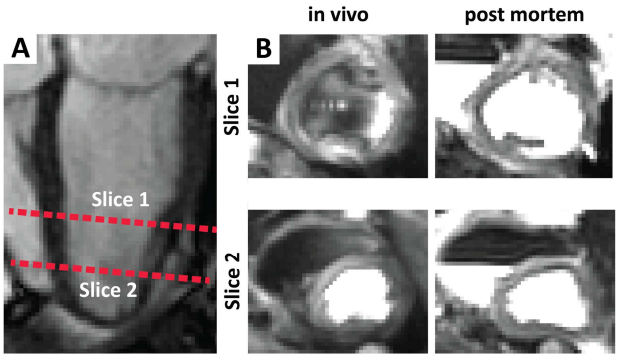

Fig. 1: Slice locations of apical and equatorial slice (A) with corresponding short axis views (B).

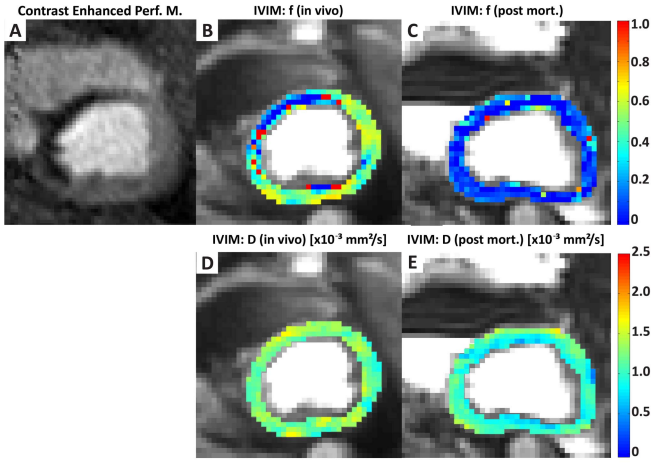

Fig. 2: Contrast enhanced perfusion imaging showing infarcted area in septum (A), perfusion fraction (f) and diffusion (D) maps derived from IVIM fitting in-vivo (B,D) and post mortem (C,E).

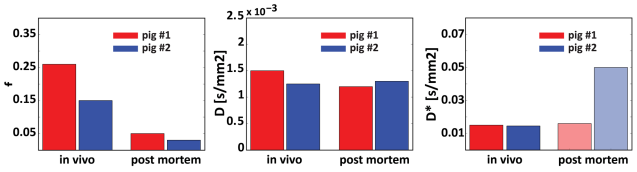

*Fig. 3: In-vivo and post mortem comparison of IVIM fit results: f, D and D**

Conclusion: The data presented here confirmed the IVIM model in porcine hearts assuming perfusion can be modeled as pseudo diffusion. Reduced perfusion due to myocardial infarction was localized by a pixel-wise fitting of the signal to the IVIM model. Infarcted area was determined by low f values in agreement with dynamic contrast-enhanced myocardial perfusion imaging. Complete termination of perfusion post mortem was correctly described by the fitting results as well as similar values for D obtained in-vivo and post mortem.

References: 1. Le Bihan et al., Radiology 1988, 2. Delattre et al., Inv. Radiology 2012, 3. Welsh et al., ISMRM 2014, 4. Lemke et al., MRM 2011., 5. Jones et al. MRM 1999, 6. Klein et al., IEEE TMI 2010, 7. Ogg et al., JMR B 1994

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