Novel Anisotropic Diffusion MRI Phantom

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Introduction:
Diffusion MRI (DMRI) comprises a growing list of acronyms, e.g., ADC mapping, DTI, DOT, DSI, Q-Ball MRI, CHARMED MRI, AxCaliber MRI, PAS-MRI. Despite their widespread use, the lack of reliable and robust MRI phantoms with which one can calibrate and validate these methods can raise doubts about them being quantitative, reproducible, and reliable. Isotropic phantoms are necessary but not sufficient to validate and calibrate more advanced DMRI applications. Anisotropic diffusion MRI phantoms, whose expected response can be predicted from basic physical principles and known phantom morphology, provide a more exacting test of any proposed DMRI acquisition and analysis pipeline. Here we describe the development of a novel anisotropic diffusion MRI phantom that can be put to service to calibrate and validate a variety of advanced DMRI methods. We have demonstrated its applicability by producing fractional anisotropy (FA) maps using DTI[1] and average pore diameter maps using double Pulsed Field Gradient (d-PFG) MRI[2].

Materials and Methods:
The DMRI phantom consists of four 2-mm thick water-filled glass capillary arrays (GCA) (Photonis, USA). The nominal pore diameter of two wafers is 10 μm; that of the other two is 25 μm.The disks were placed in a 15mm tube with susceptibility-matched plugs (New Era LTD., USA)(Fig 1a). D-PFG filtered MRI sequences were acquired by applying two wave vectors sequentially, and by varying the angle, ϕ, between them from 0° to 360°. A 7T vertical-bore Bruker DRX microimager was used for MRI acquisition. The PFG NMR parameters were: δ=3.15ms, Δ=75ms, and G between 0 and 221 mT/m^{-1}; and MRI parameters: TR/TE=7000/14.2 ms, FOV=12 X 15.5 mm and slice thickness = 1 mm. An operator-based modeling framework [3-5], which predicts the MRI signal attenuation due to restricted diffusion within packs of impermeable cylinders, as well as a free water compartment for each d-PFG filtered MRI sequence, was used to estimate the pore diameter map. ROI analysis was used to measure the average pore diameter and pixel-by-pixel analysis was applied to create a mean pore diameter map. For DTI the DWI parameters were: δ=3 ms, Δ=50 ms, a 24 gradient directions scheme was used with two b-values of 100 and 1000 s/m^{-2}, TR/TE=7000/58.6 ms, FOV=12 X 15.5 mm and slice thickness = 1mm. Diffusion tensors were estimated in each voxel. Direction-encoded color maps along with FA maps were obtained.

Results
ROI analysis of the d-PFG experiments yielded pore diameters of 10.4 and 10.3 ± 0.2 μm, and 25.4 and 25.5 ± 0.5 μm. Fig. 1b shows the average pore diameter map of the phantom. Fig 1c shows the FA map of the phantom whose average FA in the 10 μm pore wafers was 0.92 while in the 25 μm pore wafers was 0.5.

Discussion
This phantom can be used to calibrate and validate various diffusion MRI methods, which typically consists of a pipeline, DWI acquisition, artifact correction, model generation, computation of model parameters, and mapping and analysis of such parameters. Another critical application that this work addresses is to provide a way to perform quality control or assurance tests in the clinic or in a biological research environment. By using a more complex phantom having stacked GCA wafers with different, but known microcapillary diameters, methods such as AxCaliber[6] MRI can also be validated, by acquiring DWI data with a slice thickness that encompasses all such wafers, which create voxels having known diameter distributions.

Conclusion
The proposed anisotropic diffusion MRI phantom is intended to provide the "ground truth" for a growing number of advanced DMRI application

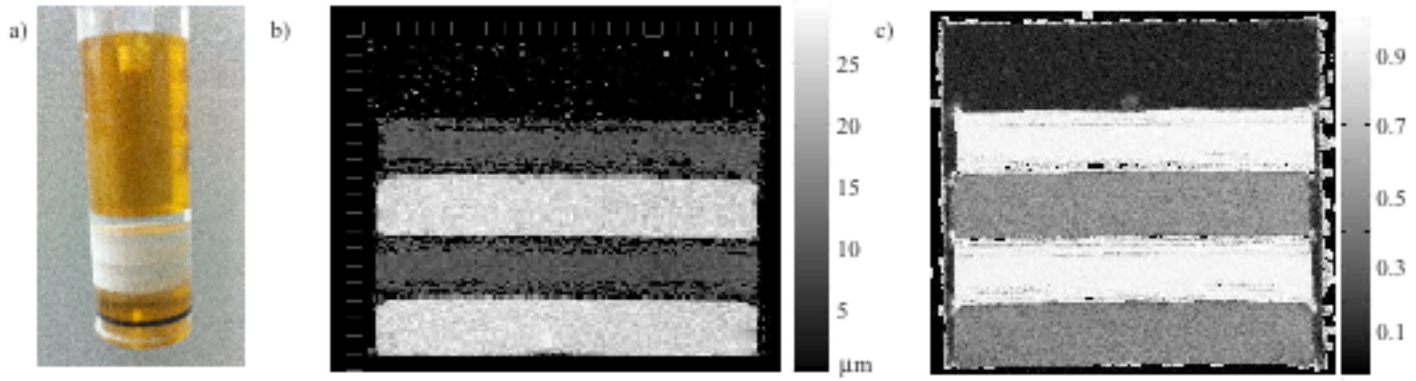

Figure 1: a) The anisotropic diffusion MRI phantom. b) Average pore diameter map calculated from d-PFG filtered MRI experiment. c) FA map obtained from DTI analysis.

References:
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