New diffusion phantoms dedicated to study and validation of HARDI diffusion models

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Introduction

Since the introduction of DTI MRI that gave the first in vivo access to structural information of tissues, several models have been introduced in order to give more and more realistic description of the underlying diffusion process. Among them are HARDI models, attempting to overcome DTI limitations for depicting heterogeneous orientations inside a single voxel. A set of new diffusion phantoms was designed in order to provide a powerful tool for studying and validating HARDI diffusion models.

Material and Methods

Despite an apparent easy process, manufacturing a diffusion phantom is a challenging task [1][2] that relies on some basic parameters such as the nature of the fibers (dialysis fibers, rayon, silk, acrylic, ...), the geometry of the target bundle (bending, kissing, crossing, ...), the characteristics of the liquid (water, alcane, ...) and the volume of the phantom. But the quality of a phantom also depends on the acquisition protocol (EPI pulse sequence, stability of the temperature, robustness to mechanical vibrations), as well as on the control of the braiding and tightening of fibers and the control of the filling procedure for susceptibility artifact removal [3].

After testing a huge set of textile fibers, we focused on acrylic fibers used for manufacturing quilted bed covers. They are made up of thin textile filaments that are juxtaposed and collinear, whereas most textile fibers are twisted, yielding complex anisotropic structures. Their diameter is close to axon size (20µm) and their geometry is cylindrical (but not tubular) leading to phantoms with only one "extra-cellular" compartment (Fig 1). A polyurethane medium containing a print of the (crossing, kissing, bending) bundle shape was designed in order to control the density of fibers (1900 fibers per mm^2 section). The medium was put in a cylindrical container (Fig 2) and filled with distilled water dope with gadolinium in a vacuum chamber thus removing any air bubble responsible for susceptibility artifacts. Last, the phantom is exposed to ultrasonic waves.

Two phantoms were built depicting two bundles with 30mm × 15mm section crossing configurations respectively at 90° and 45°. All acquisitions were performed on a GE Healthcare Signa 1.5T Excite II scanner provided with a 40mT/m / 150T/m/s gradient system and an 8-channel head coil. T1 and T2 characteristics of the phantom were determined using a spin echo pulse sequence. The first acquisition was done with a constant repetition time TR=6s long enough to consider T1 weighting negligible and TE varying from 25ms to 4s, leading to a constant T2=104ms. The second acquisition was performed with a constant minimum echo time TE=25ms and TR varying from 0.5s to 9s, leading to the characteristic T1=1.1s. The previous NMR characteristics makes that phantom quite compatible with standard DW EPI acquisitions used for brain imaging where T2 is close to 90ms inside white matter. The apparent diffusion coefficient and anisotropy were estimated inside the crossing area with a diffusion-weighted dual spin echo EPI pulse sequence at b=2000s/mm^2, yielding ADC=1.4×10^{-9} m^2/s, FA=0.3.

Results and Discussion

A HARDI acquisition was performed with both phantoms using a DW Dual Spin Echo EPI pulse sequence, compensating Eddy currents to the first order and developed in our laboratory (sequence NmrDwDualSpinEchoEpi available on demand to cyril.poupon@cea.fr). Use of EPI acquisition was made possible thanks to the robust air bubble removal process. A SNR study was driven in order to determine the best couple spatial resolution/b-value and yields the following acquisition parameters: TR=3s, TE=122ms, FOV=32cm, matrix 32×32, slice thickness=14mm, RBW=62.5kHz, 4000 uniformly distributed diffusion gradient orientations at b=8000s/mm^2, 10 acquisitions at b=0s/mm^2. The SNR of diffusion weighted images at b=8000s/mm^2 is 8.81.

This phantom is dedicated to investigate any diffusion model based upon NMR measurements and we decided to illustrate its efficiency on the Q-ball model. Min-Max normalized q-balls were reconstructed for a set of voxels covering the crossing area and the two perpendicular unidirectional areas (Fig 3 and 4), according to the algorithm provided in [4]. Unidirectional areas display orientation distribution functions (ODF) with only one lobe clearly aligned with the fiber direction and crossing areas depict two lobes which axis form respectively a 90 degrees angle and a 45 degrees angle and aligned with the underlying structure of the crossings.

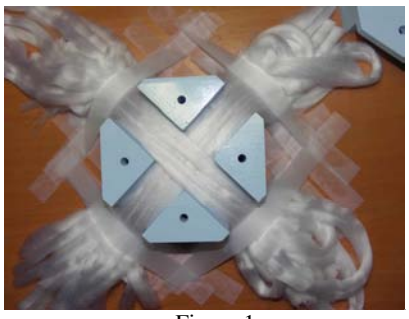

Figure 1

Figure 2

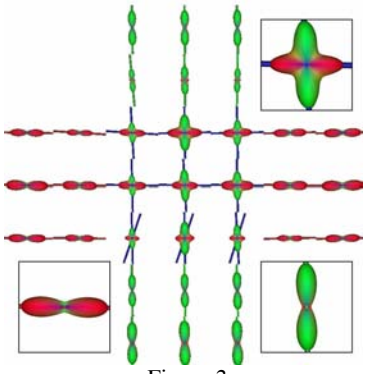

Figure 3

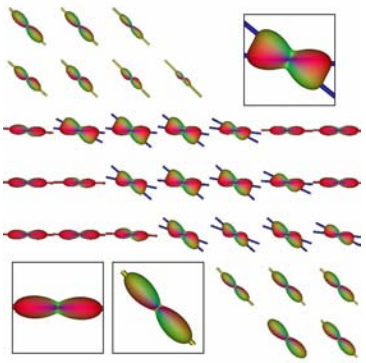

Figure 4

Conclusion

Several phantoms have been developed in the past, and it appears that their design is different according to their purpose: tractography testing or local model investigation. The phantom technology presented here addresses the second problem, and consequently tries to optimize their physical and NMR characteristics (T2, FA, exact control of the geometry, SNR). It is now possible to investigate existing diffusion models and benchmark them (angular resolution, accuracy, noise robustness) with a perfect knowledge of the true anisotropy of the fibers. This work can be done together with simulation, help developing and validating diffusion simulators.

References

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