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Innovative anisotropic phantoms for calibration of diffusion tensor imaging sequences

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ABSTRACT

The paper describes a novel type of anisotropic phantoms designed for b-matrix spatial distribution diffusion tensor imaging (BSD-DTI). Cubic plate anisotropic phantom, cylinder capillary phantom and water reference phantom are described as a complete set necessary for calibration, validation and normalization of BSD-DTI.
An innovative design of the phantoms basing on enclosing the anisotropic cores in glass balls filled with liquid made for the first time possible BSD calibration with usage of echo planar imaging (EPI) sequence. Susceptibility artifacts prone to occur in EPI sequences were visibly reduced in the central region of the phantoms.
The phantoms were designed for usage in a clinical scanner's head coil, but can be scaled for other coil or scanner types. The phantoms can be also used for a pre-calibration of imaging of other types of phantoms having more specific applications.

1. Introduction

Diffusion tensor imaging (DTI) provides precise measurements of diffusional properties of the examined samples [1–3]. However, the precision of DTI can be significantly impaired due to poor calibration. Thus choice of a proper calibration phantom is crucial for the quality of DTI results.

Several approaches to the construction of diffusion phantoms have been noted in the literature. Most of them focus on obtaining a phantom with maximized fractional anisotropy (FA), at least in one of its regions. High FA volumes have a well-defined anisotropy which should be easily distinguished by means of DTI, and also can mimic neuronal tissue, which can achieve FA values in order of 0.8 [4].

1.1. Applications of anisotropic phantoms

A simple fiber phantom can be constructed from tiny hydrophobic fibers held tightly with a shrinking tube [5]. The fiber density (FD), and thus also FA, of the phantom depends on how tightly the fibers are kept together. Unfortunately, diffusion properties such as diffusivity or diffusion kurtosis, are contingent not only on FD, but also on the fiber packing geometry [5], which is somewhat unpredictable in such a simple phantom.

More realistic model must take into consideration a possibility of fiber crossings. Alternately wounded fibers on a Plexiglas support can mimic the crossings of e.g. white matter fibers in brain [6]. Sections of the phantom of various FD come also in useful for proper calibration of DTI sequences.

Diffusion parameters highly depend on temperature, as well. An attempt to manufacture thermally controlled phantom with crossing fibers was also taken [7]. However, an effort put into stabilization of the phantom's temperature may be more of a hindrance than help in everyday practice, because of the mismatch of the imaging conditions for a patient or a sample and the calibration phantom. Even perfect control of the temperature of the latter will not prevent the first two from heating during the imaging sequence.

High angular resolution diffusion imaging (HARDI) can also benefit from calibration with proper phantoms dedicated to those techniques. In this case crucial are precisely defined crossings of the fibers, which can be a good test for the robustness of the reconstruction techniques like Q-ball [8–10].

However, precisely defined structure of a phantom in a scale smaller than the spatial resolution of the measurement is likely to exacerbate the quality of the results, due to partial volume effect (PVE) [11].

All of the aforementioned diffusion phantoms are very specific in terms of their applications. They can be used to improve a particular sequence or a reconstruction method or to reduce some artifact effects. What we present here is a more general vision of phantoms for diffusion MRI. The idea is based on b-matrix spatial distribution DTI (BSD-DTI) [12,13].

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1.2. BSD-DTI

In principle, BSD-DTI is a calibration method for all kind of diffusion sequences and reconstruction methods. It focuses on a precise measurement of magnetic gradient fields inhomogeneity induced mostly by the diffusion sensitizing gradients. Once the spatial distribution of the effective diffusion gradients is known it can be eliminated as a systematic error [13].

The process of calibration by means of BSD-DTI needs anisotropic phantoms whose diffusional properties are stable during the measurements. If geometry of the phantom is precisely defined and the phantom has a uniform diffusion properties along each direction, the calibration procedure simplifies and requires determination only of N diffusion tensors in order to derive spatial b-matrices for given volume of interest (VOI), where N is the number of diffusion sensitizing gradients. Otherwise, the number of diffusion tensors necessary to derive is multiplied by the number of phantom voxels inside the VOI. Rotations of the phantom during the calibration process must be than performed carefully [14].

2. Material and methods

Two types of anisotropic phantoms – cubic plate (CP) and cylinder capillary (CC) phantom – and an isotropic one – water reference (WR) phantom – were developed. Those three types create a complete set necessary to both calibrate and validate quality of the calibration by means of BSD-DTI.

b-Matrix spatial distribution can be derived basing on measurements of CP phantom in at least six different positions. Then a normalization of the b-matrices to WR phantom is done. Eventually, CC phantom is used to validate the quality of calibration and to assess the improvement factors, i.e. the ratios of standard deviation (SD) of eigenvalues, fractional anisotropy or volume ratio (VR) for BSD-DTI calculation and standard DTI, respectively.

2.1. Preliminary phantoms

The development of the anisotropic diffusion phantoms (ADP) was a long process including many trials with variety of the prototypes. The first attempt led us to construction of a small CP phantom consisting of several layers of very thin (100 μm) glass plates separated with water. The homogeneity of the diffusional properties in the entire phantom volume was more than satisfying, however, high cost and low durability forced us to trials with thicker plates and placing the phantom in thick glass housing. As a result the phantoms diffusional properties lasted longer in an acceptable range, and thanks to the external layer of glass and thus better susceptibility match, reduction of the imaging artifacts was noticeable.

Along with the CP phantoms, we made an attempt to develop CC type phantoms, trying various materials (glass, PMMA), sizes, geometries, getting gradually better results [15]. Basing on the results, but still not being fully satisfied, we decided to somewhat reinvent the whole idea.

2.2. Geometry and design

The two geometries of the considered anisotropic diffusion phantoms (ADP), enable to restrict diffusion in only one direction (across plates plane) for CP phantoms, as well as, to allow for free diffusion in only one direction (along the capillaries) for CC phantoms [15]. We decided to keep the developed ADP as cores of the novel phantoms.

The CP phantom core consists of square glass plates separated with thin water layers, together forming a cube. The distance between neighboring plates is set by four tiny glass cylinders placed in the four corners of the plate. The height and diameter of the cylinders is 20 μm. After some trials and errors plate thickness of 180 μm turned out to be a reasonable compromise between phantom's spatial resolution and durability. The core, is placed in a PMMA housing, which was enclosed in spherical glass ball filled with liquid.

The CC phantom core is a cylinder containing tightly packed photonic-crystal fibers (PCF) consisting of array of capillaries. The core, similarly to CP phantom, is placed in a PMMA housing and immersed in liquid inside a glass ball.

The water reference phantom is just a glass ball of the same dimensions as in case of ADP, filled with adequate liquid. Photos of the phantoms are collected in Fig. 1. The external dimensions were adjusted to fit a particular tomograph and receiver coil (head coil of the 3.0 T Siemens Skyra scanner). The exact dimensions of recently manufactured head coil phantoms are collected in Tables 1 and 2.

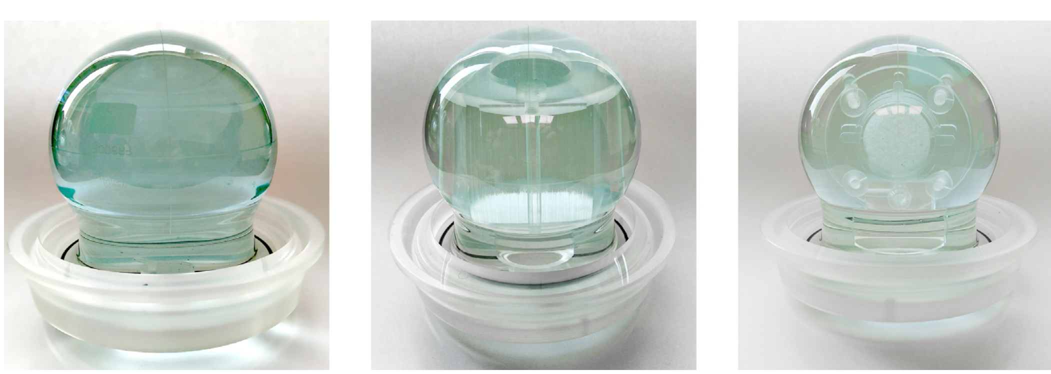
All the three phantoms can be combined with dedicated goniometer enabling precise positioning and rotating of the phantom before an experiment (Figs. 2 and 3.)

2.3. Susceptibility match

A susceptibility mismatch of adjacent phantom's elements can cause severe artifacts, especially in the case of EPI imaging in higher fields [16]. In order to avoid the artifacts the susceptibility of the liquid filling the phantom must be matched with the susceptibility of the phantom core. Water doped with copper sulfate is a liquid with susceptibility precisely controlled by the amount of $CuSO_4$ added.

A percent volume fraction of $CuSO_4$ in water solution of susceptibility matched to the susceptibility of core material can be derived as:

$$1 - V_{WF}, \tag{1}$$



a) Isotropic water reference phantom (WR).
b) Anisotropic cubic plate phantom (CP).
c) Anisotropic cylinder capilary phantom (CC).

Fig. 1. Complete set of glass ball phantoms enabling calibration normalization and validation of BSD-DTI measurements.