3D-printed phantom for diffusion MRI model validation

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Introduction

Diffusion weighted imaging [5] (DWI) has proven to be a viable tool with many scientific and diagnostic applications in the brain and the whole body. Analysis typically makes heavy use of modelling and all these models as well as novel diffusion-weighted MR sequences need to be rigorously tested and validated, effectively requiring the availability of specific diffusion phantoms with known properties. Here we present a novel diffusion phantom manufactured with high-resolution 3D-printing technology that is capable of producing precise, arbritarily-oriented structures.

Methods

Two diffusion phantoms were prepared using multi-photon lithography (MPL) [4]. Femtosecond laser pulses were used to induce localised cross-linking of ethoxylated trimethylolpropane (ETA) and trimethylolpropane triacrylate (TTA) in a ratio of 75:25 via multi-photon absorption [8] using M2CMK (5 mmol/g) as photoinitiator. Objects with arbitrary, axon like networks of channels with high-definition spatial features down to 100 nm can be constructed in this way. Two MPL upscaling techniques [1,2] were combined in order to overcome constraints in fabrication time and size.

Both phantoms contained 12x12 μm² fibre-like channels with 12 μm and 5 μm in vertical and horizontal spacing repsectively. The phantoms comprised 42 966 and 51 000 channels respectively in different channel configurations (see Figure 1). The channels were filled with copper(II)sulfate (20 mmol/l) and PBS and the phantoms were embedded in 7% porcine gelatine.

MR measurements were acquired at 7T (Magnetom Siemens Healthineers, Erlangen, Germany) using a microimaging system (gradient strength: 750 mT/m) and a 39 mm proton NRM volume coil (Rapid Biomedical, Wuerzburg, Germany). DWIs were acquired using a single shot, diffusion-prepared EPI imaging sequence (CMRR multiband sequence [3]). A multi-shell protocol with b-values up to 2500 s/mm², 64 diffusion directions and either 322μm or 156μm in-plane resolution was employed.

The data were analysed using DSI Studio (http://dsi-studio.labsolver.org) using a generalised q-sampling imaging (GQI) model [6] and a deterministic fibre tracking algorithm [7] after correcting for field inhomogeneities using FSL's topup.

Results

The reconstructed fibre tracts, representing the directions of the channels, of both phantoms can be seen in Figure 2 and scanning electron microscope images in Figure 3.

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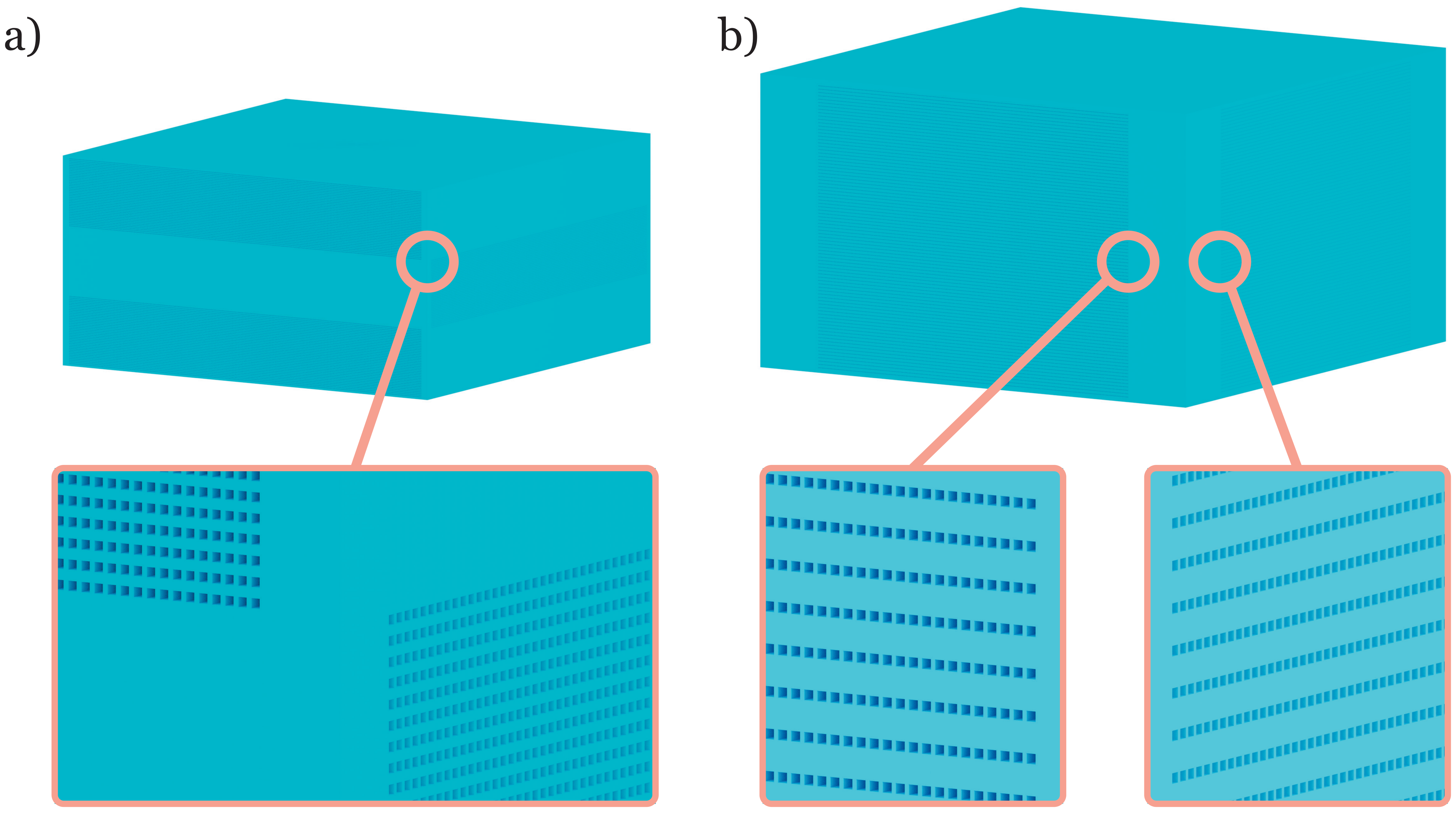

Figure 1 3D renderings of the phantoms. **a)** The „slab" phantom, consisting of three distinct, orthognal regions. **b)** The crossing-fibres phantom, consisting of alternating layers of orthogonal channels.

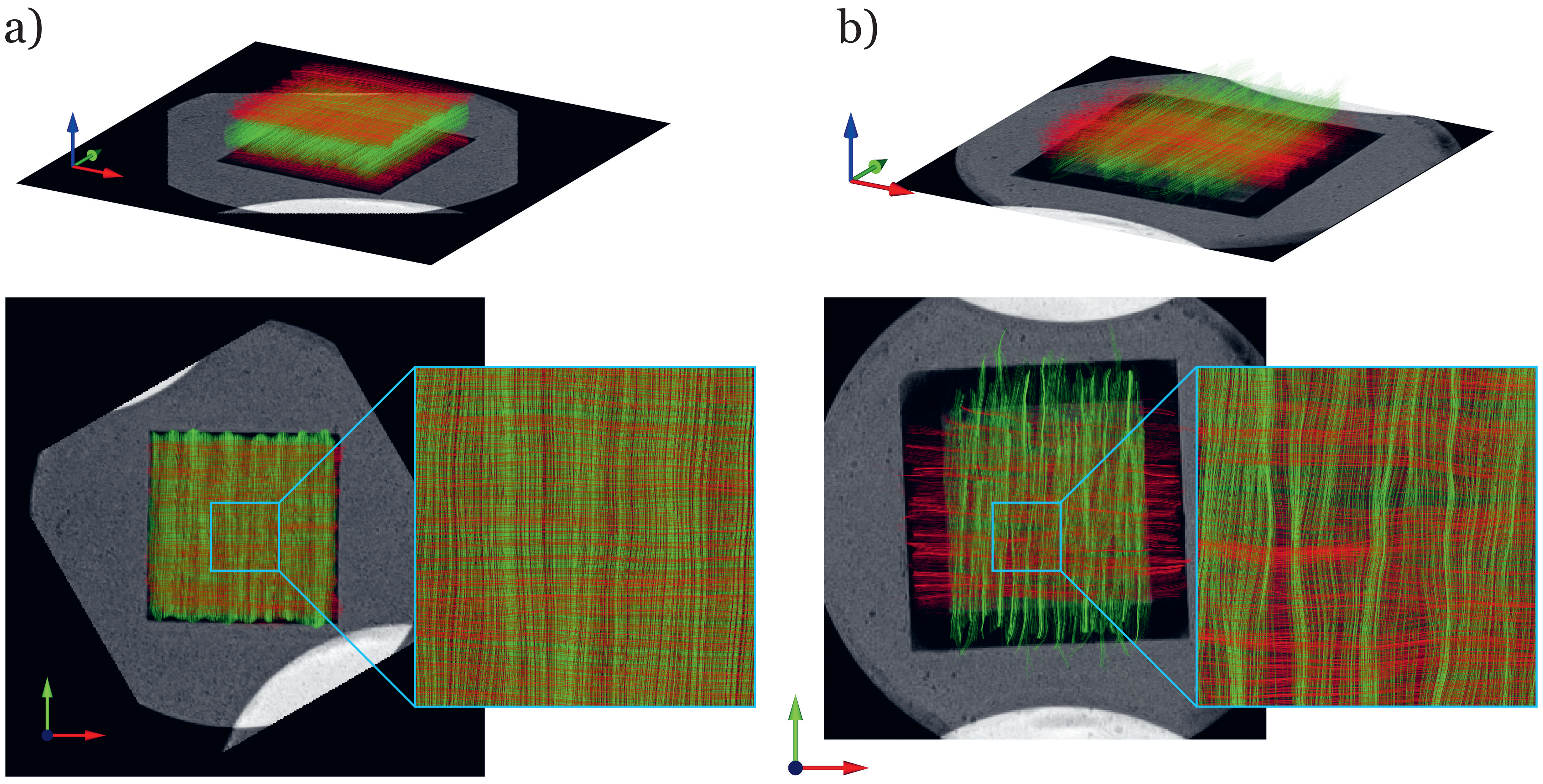

Figure 2 Estimated diffusion tracts using the generalised q-sampling model and a deterministic fibre tracking algorithm. **a)** Tracts from the „slab" phantom. The individual slabs can be easily distinguished from the orientation of the fibres. **b)** Tracts from the crossing-fibres phantom. The estimated fibres cross inside the overlapping region and are cleary orthogonal in the non-overlapping regions.

Conclusion

We have successfully created a novel phantom for diffusion MRI by using advanced, high-resolution 3D-printing technologies. Diffusion is acchieved by creating liquid-filled channels in a 3D-printed surrounding in any arbitrary configuration. Here we presented two simple configurations with orthogonal directions and crossing channels respectively. The employed diffusion model and tracking algorithm was able to accurately capture both configurations, demonstrating the phantom's utility for diffusion imaging studies.

Our contribution is the first 3D-printed DWI phantom with micrometer resolution and channels approaching pysiological sizes. Due the phantoms versatility, we envision it being useful in translating imaging methods from basic research to clinical applications because with the ground-truth known, diffusion imaging methods can be more reliably tested against.

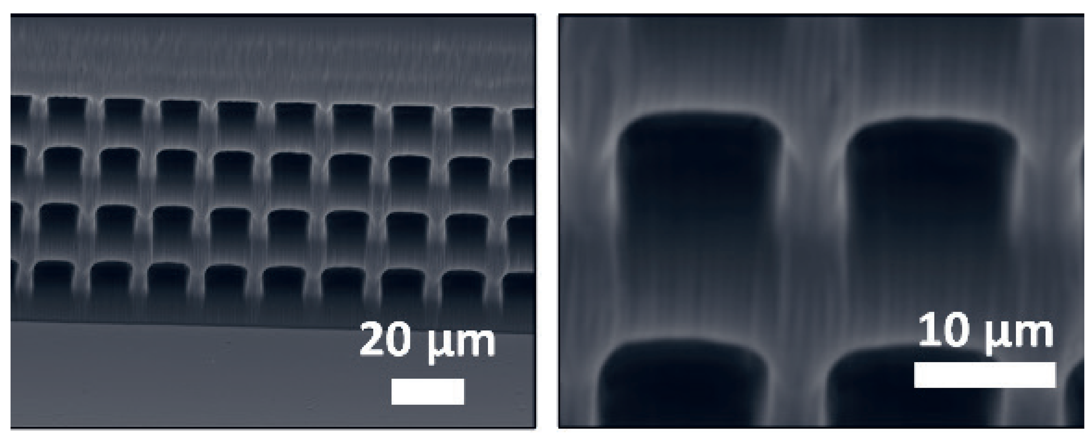

Figure 3 Scanning electron microscope images of sample channels.

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