A Structured MRI Phantom with the Magnetic Susceptibility of Air

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Motivation: Magnetic resonance techniques depend crucially on the homogeneity of the static magnetic field. Especially for MRI sequences with long readouts (e.g. echo-planar imaging EPI), B_0-inhomogeneities can lead to impairments ranging from slight geometrical distortions to complete failure of the image encoding, depending on the degree of the disturbance and the sequence parameters. In MR spectroscopy field distortions are a major challenge, since they lead to undesirable peak broadening and overlapping. Magnetic field inhomogeneities are mainly caused by the presence of magnetically susceptible material in the scanner bore. In human applications the dominating source is often the subject itself, with additional contributions from RF coils and other equipment. Whereas distortions of low spatial orders – as for example originating in distant sources – can often be corrected satisfactorily by shimming, distortions caused by magnetized material close to the field of view are of higher spatial order and remain uncompensated. Therefore, the enforcement of field homogeneity puts strong limitations on susceptibility and geometry of objects allowed in the magnet bore.

We here report the development of a novel solid material, whose susceptibility can be adjusted over a vast range while keeping excellent mechanical properties. Furthermore it is nonconductive, resistant to most chemicals and transparent. With such a material it is possible to construct objects with the susceptibility of air, rendering them "invisible" within the magnetic field. As an illustration, the construction and a few applications of a field distortion free MRI phantom are presented.

Methods: Some duroplasts can take up ionic substances to form stable solid solutions. This property can be exploited to adjust the magnetic susceptibility of the polymer over a large range. Using acetone as a solvent shuttle we added $Dy(NO_3)_3$ to a commercially available epoxy resin (Epoxy L from Swiss Composite, Fraubrunnen, Switzerland), giving a versatile solid material with the susceptibility of air (+0.34 ppm) [1,2]. The exact dopant concentration was determined using an MRI-based susceptometry method [3]. The sensitivity of the measurement and the reproducibility of the doping process allows the bulk susceptibility adjustment to better than 0.01 ppm.

A square phantom of 180x180x25 mm^3 size was cast from this air-matched epoxy (fig. 3). The lower part of the lumen contains a square grid of 1.5 cm edge length (wall thickness 1.5 mm), as well as four solid characters (R, A, L, P). The seal of the phantom is realized with a threaded (M8) filler neck and a corresponding screw, located in one corner of the phantom. All these parts are equally made from air-matched epoxy. The phantom is filled with a 16.3 mM aqueous solution of $Dy(NO_3)_3$, which has again the susceptibility of air [4,5] and relaxation times allowing for efficient MR imaging ($T_1 \approx T_2 \approx 100$ ms @ 3 T and 22° C). For comparison, a phantom with the same geometry was constructed from conventional materials (PMMA and ABS filled with an 8 mM $CuSO_4$ solution). All the MR images shown were acquired with a 3 T Achieva whole body scanner (Philips Healthcare, Best, Netherlands) using the quadrature body coil to prevent field inhomogeneities created by receive coils (cf. Fig. 2).

Results: Figs. 1a and 1b show B_0-maps of the phantoms (a: matched, b: unmatched) after pencil-beam shimming (2^{nd} order). As expected the susceptibility-mismatch of the lumen of the conventional phantom and the surrounding air introduces strong inhomogeneities that can only partly be compensated by shimming. In the case of the air-matched phantom the remaining frequency spread had a RMS of 3.8 Hz with outliers up to ±18 Hz in some regions of the phantom. They have been identified as higher order inhomogeneities of the background field (spatial field pattern was flat up to 2^{nd} spatial order and remained unaffected under translation and rotation of the phantom). As an ultimate challenge to test the quality of the field homogeneity, a single-shot EPI scan with an unusually long acquisition duration of 185 ms was acquired (FOV: 220x220 mm, 1.1 mm resolution). Whereas the matched phantom gives a near-perfect image (fig. 1c), the image of the unmatched phantom (fig. 1d) is severely distorted. The small artifacts in c) e.g. in the upper left quadrant (they can also be detected in fig. 2), were identified (under the microscope) as impurities introduced most likely during the casting process. They could probably be prevented when working in a dustless setting. Fig. 2 shows the effect of surface coils of two sizes, a multi-channel head coil and MR headphones on the field homogeneity when brought close to the phantom as shown in the photographs (fig 3, note the different scaling of the individual maps).

Figure 1 | Single Shot EPI's and B0-maps of the two Phantoms

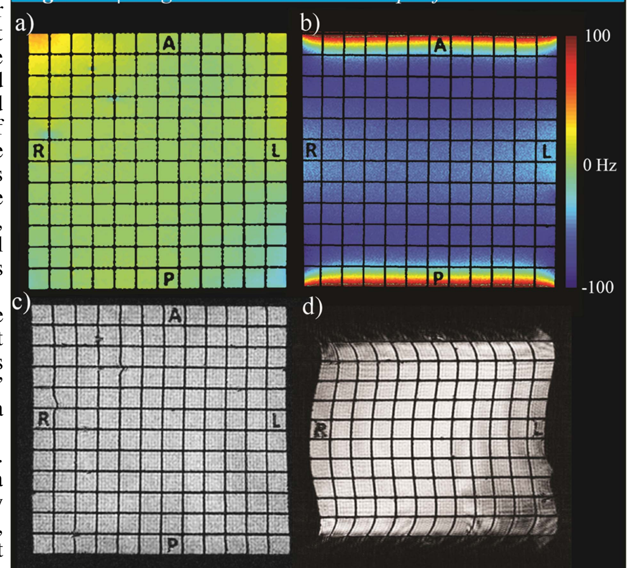


Figure 2 | Field Patterns from RF Coils & Head Phones

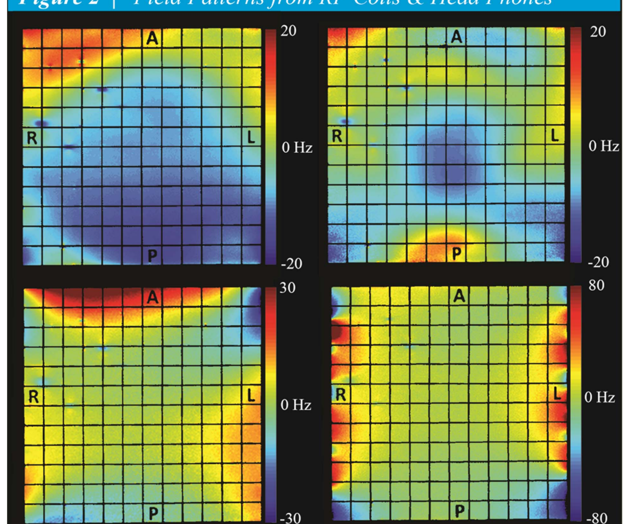
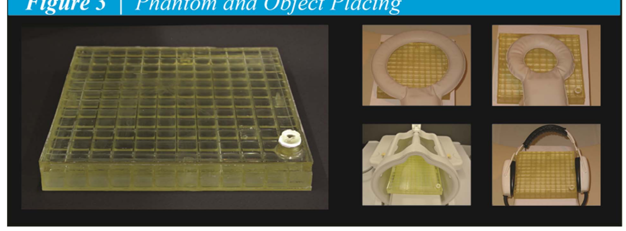


Figure 3 | Phantom and Object Placing



Discussion and Outlook: Whereas susceptibility matching of liquids [4] and the construction of well shimmed imaging phantoms using spherical (or ellipsoidal) geometries is routinely done, the possibility to simultaneously match the susceptibilities of a solid, a liquid and a gaseous compound, allows the construction of a new class of imaging phantoms, which can be of arbitrary shape with or without inner and outer structure. Such phantoms can be of great value as a sequence development tool and in quality assurance for example for the measurement of B_0-footprints of objects (coils, supports) or to disentangle sources of image distortions (B_0-inhomogeneities vs. gradient imperfections), especially for fast imaging techniques.Yet the application of a solid material with widely adjustable magnetic susceptibility is not restricted to the construction of phantoms. The mechanical properties of the matched epoxy are ideal for most mechanical machining techniques (milling, lathing, drilling, grinding, etc.). This makes it possible to construct sophisticated structures and objects, which can be brought close to the field of interest without affecting the field homogeneity. This is otherwise becoming ever more challenging with the trend towards higher field strengths. Besides applications in human and animal MRI (headphones, stereotactic frames, supports, and other equipment), probable fields of application are high resolution NMR spectroscopy [6,7], high throughput screening NMR spectroscopy [8], MR/MRI of granular systems [4] and structures for microfluidic NMR spectroscopy [9].

References: [1] Prüssmann et al., Patent WO2007118715 A1 (2007-10-25). Pr. 2006-04-19. **[2]** De Zanche et al. MRM 60 (2008). **[3]** Barmet et al., Proc. ISMRM 15 (2007). **[4]** Stoll et al., JMR, 46 (1982). **[5]** Tayler et al., JMR 211 (2011). **[6]** Mansfield et al., Patent US005416414A (1995-05-16). Pr. 1994-02-28. **[7]** Peck et al., Patent USOO568440lA (1997-11-04). Pr. 1996-02-01. **[8]** Fishbein K., Patent WO2007047149 A2 (2007-04-26). Pr. 2005-10-12. **[9]** Ryan et al., MicroTAS 16 (2012).