Material- and B_0-dependent scaling of torque effects

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Introduction:

The upper limit for the main magnetic field strength of clinical and research MR scanners increased from 1.5T over 3T to 7T and higher. For implants and implanted devices, the strong magnetic fields may impose a safety risk, as they may align with or be attracted by the strong magnetic field. Consequently, the resulting force and torque effects have to be evaluated for all field strengths. The magnetic forces scale mainly with the gradient of the main magnetic field (dB_0/dz). For torque, it is less known how it will change with the increased field strength. Linear and even quadratic increase of the torque is partly assumed as $\vec{M} = \vec{m} \times \vec{B}_0$ (m: magnetization of the material, B_0: main magnetic field). In contrast, the appendix of ASTM F2213-06, a calculation based on a publication from Wittenauer et al.[1], shows that the maximal torque on saturated ferromagnetic parts should not change with the field strength. The purpose of this abstract was to evaluate the scaling of the torque effect with different kinds of magnetic materials.

Methods:

Different samples were used for the torque measurements: a small NdFeB magnet ($5x5x5mm^3$, remanence ~1,2T), a nickel plate ($1x4x50mm^3$), a test tube (11cm long, 1cm diameter) filled with dysprosium sulfate (μ_r>15'000), and a loop recorder (Reveal XT, Medtronic Inc). The samples included magnetic, ferromagnetic, and paramagnetic material respectively. In addition, a device with ferromagnetic components has been chosen. Torque effects were measured with a low friction floating platform connected with a thin string to a force meter as mentioned by the ASTM F2213-06 as alternative measurement setup. Torque effects have been measured in a whole body 1.5T, 3.0T and 7.0T scanner (Achieva 1.5T, 3.0T, and 7.0T, Philips Medical Systems, Best, the Netherlands). With the 7T magnet, not only at 7T, but also at 3T, 1.5T, 1T, 0.5T, and 0.15T torque effects have measured, by positioning the measurement setup out of the isocenter, but not leaving the central z-axis.

Results:

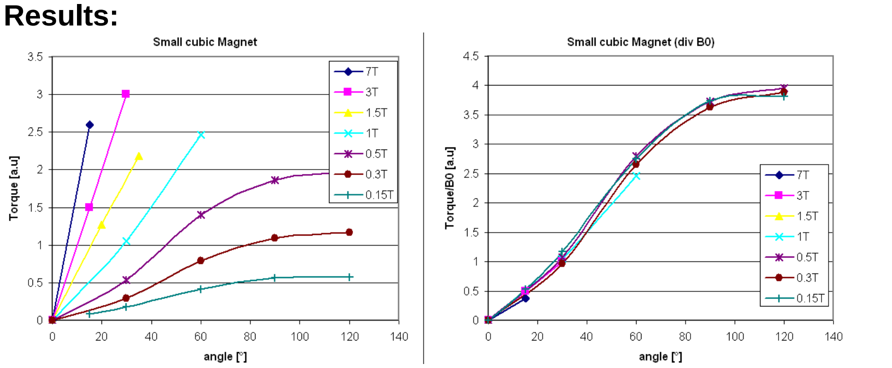

Figure 1: *Small NdFeB magnet. The torque effects scale linearly with the main magnetic field strength. All measurements except the values for 1.5T and 3T have been performed in the 7T scanner. Left: the torque effects, right: torque effects divided by B_0.*

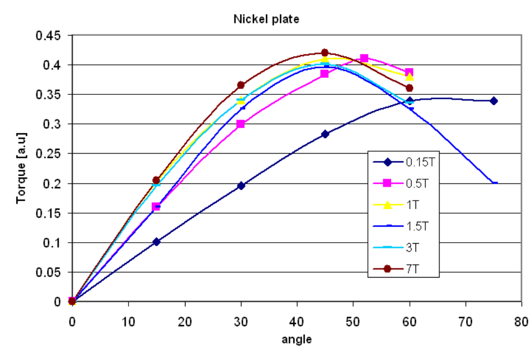

Figure 2: *Nickel plate. The maximal torque effects are independent of the field strength. However, they reach the maximal torque effects at a lower angle. At a field strength <0.5T nickel was not magnetically saturated, and therefore, lower torque values could be measured.*

The results for the small NdFeB magnet are shown in fig. 1, for the nickel plate in fig. 2 and for the Reveal XT device in fig. 3. The test tube filled with dysprosium sulfate did not show enough torque effects to provide reliable values especially below 7T. Measuring the torque effects in the stray field of the 7T works well as seen in fig. 1. Only the torque values between ~1.5-4T will be overestimated due to additional force effects in the spatial field gradient of the stray field. At 1.5T and 3T this overestimation of torque was about 20% for the small NdFeB magnet. Due to the fast drop of the field gradient outside the magnet the overestimation will be strongly reduced for torque measurements at field strength <1T.

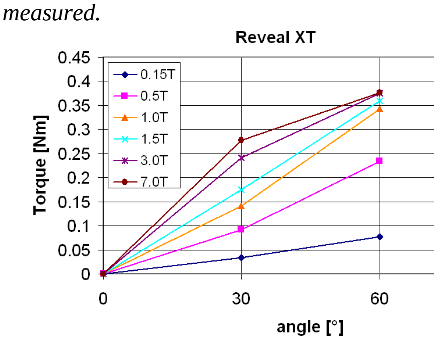

Figure 3: *Reveal XT (Medtonic Inc.). The torque effects showed similar behavior as the nickel plate (ferromagnetic material). However, the ferromagnetic material in the device seems to be saturated between 0.5 and 1T, which is above the value from nickel.*

Discussion:

The torque effects can be calculated using the formula $\vec{M} = \vec{m} \times \vec{B}_0$. However, the magnetic property of the sample is now defined by the magnetization m. In case of the small NdFeB, m is fixed and therefore, the torque will scale linearly with B_0. In case of ferromagnetic materials the energy needed to change the magnetization will limit the maximal torque if the material is saturated, which is the case for most materials in the range of 0.1-1T. With increasing field strength this energy requirement will be reached earlier as seen in fig. 2. The highest torque effects are around 90° for magnets but around 40-70° in case of a ferromagnetic material. In case of para- and diamagnetic materials the magnetization m will scale linearly with B_0, and therefore, the torque should scale quadratically with the field strength. However, since para- and diamagnetic effects in materials are much lower than ferromagnetic effects ,it will not be important for safety evaluations.

For medical implants and devices without any magnets embedded, torque effects will not scale with the main magnetic field of the MR scanner for field strength above 0.5T. If there are magnets embedded, torque will increase with higher magnetic field.

References:

[1] Wittenauer, M. A., Nyenhuis, J. A., et. al. "Growth and Characterization of High Purity Single Crystals of Barium Ferrite," Journal of Crystal Growth, Vol 130, 1993, pp.533-542.