Magnetic Forces on Medical Implants

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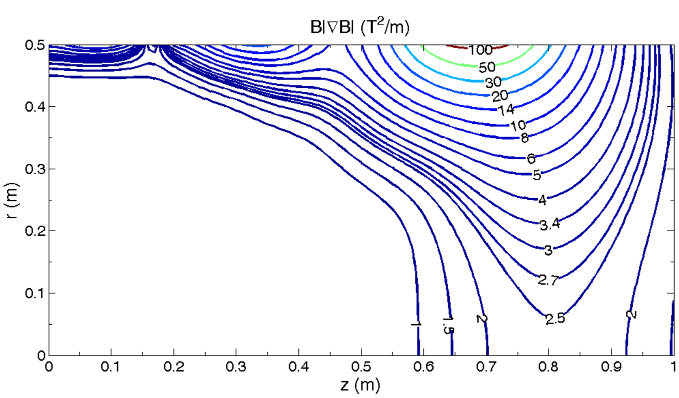
INTRODUCTION: Medical implants raise important safety concerns for patients receiving MRI due to the forces and torques acting on these metallic implants while a patient is receiving a scan or being loaded into the scanner. The implant can be deemed MRI safe if the magnetic forces and torques acting on the implant are less than the forces due to gravity.[1,2] In this work we give a method for calculating the magnetic forces and torques and apply this to implants made of titanium and 304 stainless steel. MRI manufacturers provide magnetic field maps (B, $|\nabla B|$, and $B|\nabla B|$, where $B=|\vec{B}|$) for their machines which can be used to calculate these forces. For a paramagnetic or diamagnetic object the force is $\vec{F}_m = \vec{m}\cdot\nabla\vec{B} = (\chi_V V/\mu_0)\vec{B}\cdot\nabla\vec{B} = (\chi_V V/\mu_0)B\nabla B$, where $\vec{m}$ is the magnetic moment, V is the volume, μ_0 is the vacuum permeability, and χ_V is the volume magnetic susceptibility ($|\chi_V| \ll 1$). The relationship $\vec{B}\cdot\nabla\vec{B} = B\nabla B$ is derived from $\nabla(\vec{u}\cdot\vec{v}) = (\vec{u}\cdot\nabla)\vec{v} + (\vec{v}\cdot\nabla)\vec{u} + \vec{u}\times(\nabla\times\vec{v}) + \vec{v}\times(\nabla\times\vec{u})$, with $\vec{u}=\vec{v}=\vec{B}$ and approximating $\nabla\times\vec{B}$ as zero. The ratio of the magnetic to gravitational force is then given by $F_m/F_g = (\chi_{mass}/\mu_0 g)B|\nabla B|$, where $\chi_{mass} = \chi_V/\rho$ is the mass susceptibility, $\rho = M/V$ is the density, and M is the mass. If $F_m/F_g \le 1$ for all possible locations of the implant during entry or scanning then the implant is deemed safe for static forces. In this abstract we show a representative contour plot of $B|\nabla B|$ for a 1.5T MgB_2 MRI magnet design, which shows the safe region depending on the susceptibility. We also show that if the implant is safe for forces, it is also safe for torques resulting from magnetic field inhomogeneities. In addition, we do a calculation verifying that torques in a homogeneous field for an isotropic material are indeed very small, as pointed out in Shellock.[1]

METHODS: To calculate the torque resulting from field inhomogeneities we look at the worst case scenario corresponding to all the mass lying at one end. Any actual implant will have torques less than this. The maximum torque will be $\tau_m = F_m L$, where L is the length. Subsituting for the magnetic forces gives $\tau_m = (\chi_V V L/\mu_0)B|\nabla B|$. Dividing this quantity by MgL gives $(\chi_{mass}/\mu_0 g)B|\nabla B|$, which is the same as the force ratio. Therefore if the implant is safe for forces, it is also safe for torques resulting from field inhomogeneities. In a homogeneous field the torque for an isotropic material is $\tau_h = (\chi_V^2/8\pi\mu_0)VB^2(N_2 - N_1)\sin(2\theta)$, where the shape is approximated as an ellipse, N_1 and N_2 are the demagnetizing factors for the ellipse oriented such that the major and minor axes, respectively, are in the direction of the magnetic field.[3] The worst case scenario corresponds to $N_1 = 0$, $N_2 = 2\pi$, and $\theta = \pi/4$, corresponding to a long thin ellipse aligned at 45° to the magnetic field. Using these values and dividing by MgL gives $\tau_h = \chi_V^2 B^2/4\mu_0\rho g L$. An important point is that this quantity is proportional to χ_V^2, and $|\chi_V| \ll 1$. Therefore, this torque is normally very small.

RESULTS: The figure shows a contour plot of $B|\nabla B|$ for a 1.5T magnet design with a bore of 1m. As seen from this plot, the largest forces will occur near the entrance to the bore. Noting that $F_m/F_g = 1$ when $B|\nabla B| = \mu_0 g/\chi_{mass}$, the safe region can be determined for a given susceptibility. For example, titanium[2], which has $\chi_{mass} = 4.04\times10^{-8}\,\mathrm{m^3/kg}$, is safe for regions with $B|\nabla B| < 304\,\mathrm{T^2/m}$. Therefore, a titanium implant is safe for all locations in the bore. Stainless steel 304,[2] which has $\chi_{mass} = 4.46\times10^{-7}\,\mathrm{m^3/kg}$, is safe for all regions with $B|\nabla B| < 27.6\,\mathrm{T^2/m}$. Therefore, this stainless steel is safe out to a radius of about 0.43 m at $z \approx 0.7$ m. For a uniform 1.5T field, $\tau_h / MgL = 7.16\times10^{-3}$, which is negligible.

CONCLUSION: We have shown a contour plot of $B|\nabla B|$ for a 1.5T magnetic design. These contours are related to the susceptibility for safe forces. Calculations are done for titanium and stainless steel 304. Such contours have value for assessing patient safety for a given MRI scanner.



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