Predicting Pileup Artifacts Around Magnetized Spheres in SWIFT Images

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Introduction: Magnetic objects cause T_2^* shortening and frequency shifts in MRI. Zhou et al [1] showed that with conventional MRI techniques, titanium balls (TiB) cause a signal void[2][3], whereas with SWIFT [4] a signal void exists that is surrounded by a 'pileup' artifact with a distinct shape. The pileup artifact arises from off-resonance spins located in the vicinity of the metallic object. By knowing how the signals from these spins are displaced in the reconstructed image, it should be possible to return them to their correct positions in the image, and thus, correct image distortions created by the magnetic objects. The purpose of this work is to develop a predictive equation for the pileup artifact created by spherical magnetic objects when using SWIFT. Here, the theory is validated for TiB, although it is applicable to any spherical object.

Theory: The T_2^* shortening and frequency shifts are caused by the inhomogeneous field from the TiB, which acts as a dipole. The pileup is clearly visible in SWIFT images but not in conventional images because SWIFT does not lose the signal due to T_2^* shortening. The effect of the dipole field in MRI is a "secular dipole field" where only the component parallel to the main B0 causes first order frequency shift, and is given by equation 1: $\omega_z = \frac{\gamma M}{3}\left(\frac{r_s}{r}\right)^3\left(3\cos^2(\theta)-1\right)$, where M is the sphere's magnetization, r_s is the radius of the sphere, r is the distance from the center of the sphere, and θ is the angle from the z-axis. In a SWIFT image, this inhomogeneous field causes signal displacements in space that are predicted by equation 2: $x_f = x_o + \frac{M}{3G}\left(\frac{r_s}{|x_o|}\right)^3\left(3\cos^2\theta-1\right)$, where x_o is the object's physical position, x_f is its apparent position in image space, and G is the gradient magnitude used for encoding projections with SWIFT. The pileup artifact can be predicted by taking the derivative of equation 2 with respect to x_o, setting it equal to zero, solving for x_o, and then using equation 2 to solve for x_f. The result is given by equation 3: $x_{pileup} = \frac{4}{3}\left(\frac{M}{G}r_s^3\left(3\cos^2\theta-1\right)\right)^{1/4}$

Methodology: Simulations were done in one and two dimensions. Signal values were designated to discrete locations and were then relocated based on equation 2 for a range of values for M/G and r_s. The 2D images were constructed using the same radial technique and reconstruction program that is used in SWIFT experiments.

Experiments were done using a 4T MRI machine on TiB suspended in 1% agar gel with Teflon mesh. M/G was adjusted by changing the pulse bandwidth for values between 16.7 and 125 kHz. The flip angle was adjusted to maintain a constant peak power per unit time. The magnetization of the TiB was measured using a SQUID.

Results and Discussion: Figure 1 shows an image of the measured Ti balls of 3/64, 1/16, 5/64, and 3/32 inch radii. Figure 2 shows an image of a 2D simulation result. Table 1 lists the constants (a, b) obtained from plots of $1/G$ versus x_{pileup} (from the center of the particle) for the farthest pileup artifact and fitting to the equation, $x = a(1/G)^b$. These results indicate that the analytical equation agrees very well with the simulations and experiments. In simulation, the multiplier values are within 0.3% of the theoretical value and the power value is exactly equal to the theoretical value of 0.25. In experiment, the calculated (from measured r_s and M of a TiB) a value is within 6% of the measured value.

Conclusion: The pileup artifact from a magnetized sphere can be predicted by equation 3. Conversely, if the pileup artifact and the type of metal are known then the magnetization and particle radius can be calculated. This technique can be extended to magnetized objects of other shapes, such as metal implants and screws and thus can be used as an image based method to correct distorted images acquired with SWIFT.

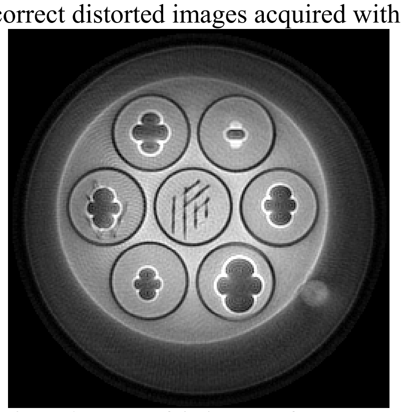

Figure 1: Image of 6 TiB and teflon mesh in 7 tubes embedded in agar gel

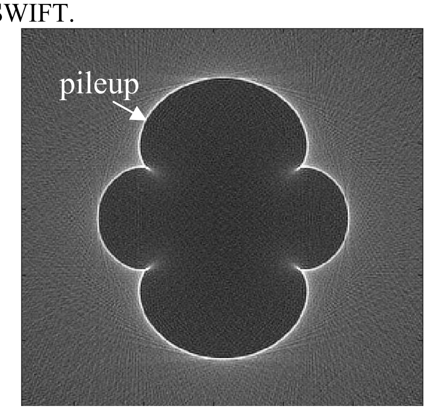

Figure 2: Simulation of a magnetized sphere pileup artifact

$x = a(1/G)^b$	a	b
Theory (r_s=1, θ=0)	1.586	0.25
1-D simulation (r_s=1, θ=0)	1.583	0.25
2-D simulation (r_s=1, θ=0)	1.582	0.25
Experiment (r_s=1/16 inches)	0.00221	0.25
Calc. from r_s and M	0.00208	0.25

Table 1: Comparison of theory, simulation, and experiment of TiB when fit with $x = a(1/G)^b$

References: [1] Rong, et al. MRM (2010) [2] Posse, Aue. JMR (1990) [3] Burkhardt, et al. Med. Image Analysis (2003) [4] Idiyatullin, et al. JMR (2006)
Grants: We gratefully acknowledge support from NIH P41RR008079, R21 CA139688, S10 RR023730, and S10 RR027290.