Magnetohydrodynamic Design of Radiofrequency Powered Microscopic Endocapsules in 3T MRI

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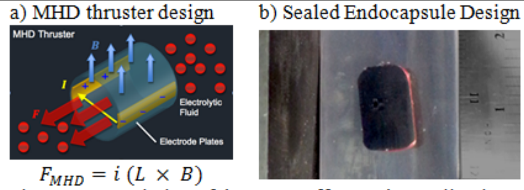
Target Audience: This research is intended for investigators pursuing drug delivery and vascular micro surgical techniques in MRI.

Purpose: Microscopic medical robots capable of translating in a bloodstream or similar liquid represent a new type of therapeutic technology for vascular interventions. With physical dimensions less than a cubic millimeter, these endocapsules may easily travel to body regions inaccessible by conventional surgical practice to perform strategic interventions or local drug delivery of diagnostic and therapeutic agents. Several outlets have been explored for wireless control of endocapsule intra-MRI, although complications in MRI-compatibility and design result in the inability to maneuver during MRI scan sequences [1-3]. Motivated by the large magnetic field within the MRI bore, we developed a Magnetohydrodynamic (MHD) propulsion method derived from conductive fluids exposed to strong magnetic fields (Fig. 1). We hypothesized that a wireless MHD-driven thruster could be developed for the application of controlling microscopic endocapsules within the MRI strong magnetic field.

Methods: An endocapsule prototype was constructed using an inductive coil and a rectifying circuit mounted upon a 3D-printed capsule (Fig. 1). Through a half-bridge amplifier circuit, a 1.1 MHz signal was used to drive the on-board rectifier to produce a driving current for the MHD thruster (Fig. 2). Using a coil with multiple taps, multiple rectification and tuning circuits may be cascaded to allow for multi-directional control using several independent resonant frequencies. Before testing the capsule in 3T MRI, it was first calibrated using a controllable field ranging from 0T to 0.4T.

The plastic raft was positioned in a saline bath (0.9% w/v) above the magnet and the device was filmed above a grid at various field strengths to verify the model's performance (Fig. 3). Subsequently, the capsule was also tested in a sealed vasculature surrogate (1.3cm diameter tubing) to evaluate performance while submerged. Power and resultant velocity were tracked and recorded. MRI compatibility was determined using ASTM Standards [4].

a) MHD thruster design b) Sealed Endocapsule Design



$F_{MHD} = i\,(L \times B)$

Figure 1: Translation of the MHD effect to the application of a MHD-based thruster

a) Principle of Wireless Energy Transfer b) S-parameter Tx / Rx Coil Characterization

c) System Block Diagram

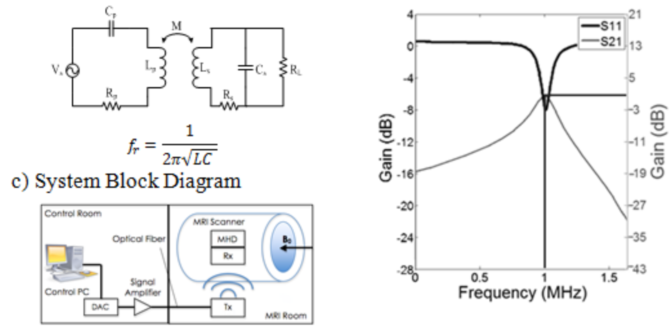


Figure 2: Utilization of the MHD effect for the design of a thrusting mechanism to be used in the presence of the strong magnetic field of the MRI.

a) Velocity as a Function of Varying Power in the Secondary Coil b) MHD Force as a Function of Varying Power Levels in the Secondary Coil

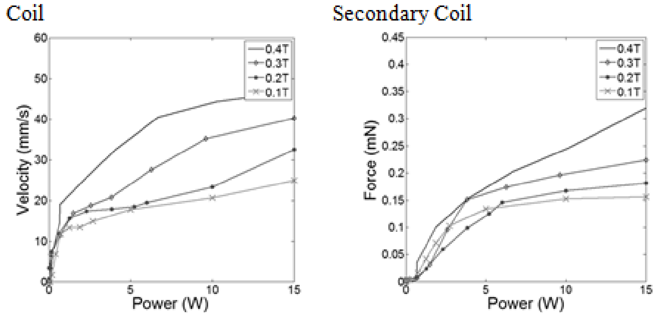


Figure 3: Quantification of system dynamic performance using the preliminary raft design. Power is scaled to required 3T levels based on data acquired at lower field strengths: (a) peak velocities under varying power levels, (b) and MHD force.

Results: S-parameter characterization of the primary coil and the capsule were recorded, estimating a wireless transfer efficiency of 94% based on the forward voltage gain (S21) (Fig. 2b). In the test setup, a peak velocity of 46.6 mm/s and a peak force of 0.31mN (calculated using average acceleration, F=ma) were observed, typically accelerating to max velocity within 0.40 seconds (Fig. 3). Using the vasculature surrogate, peak velocity was observed to be 33.1 mm/s, a 28% decrease relative to the original test configuration due to the increased drag resistance, calculated using $F_{drag} = C_{drag}v$. A SNR reduction of 5.67% was observed when the endocapsule was introduced into the scanner isocenter, which is within an acceptable range of SNR reduction (Fig. 4) [4].

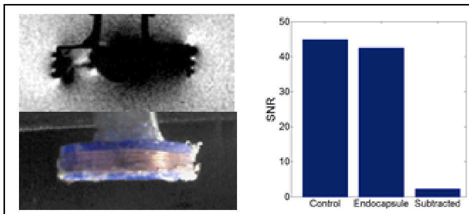


Figure 4: Measurement of endocapsule MRI compatibility and evaluation of induced image artifact and signal SNR

Discussion and Conclusion: In this study, a MHD drive was designed and evaluated in an MRI-environment, demonstrating the ability to propel a scaled endocapsule in a magnetic field. The measured resultant forces on the endocapsule were shown to be an order of magnitude greater than similar designs [3]. MRI-compatibility testing at 3T suggests that the capsule produces a negligible effect on the image SNR when operating during MR scanning. This leads to the conclusion that the device is MRI-conditional in its current configuration. Limitations to the current model include limited applied field strength. Future work will involve parameter and circuit optimization, and model miniaturization.

References: [1] Mathieu, BiomedMicroDev., 2007. [2] Vartholomeos, IEEERSJ., 2011. [3] Kosa, IEEERobotics, 2007. [4] ASTM, F2119, 2013.