Measurement of Magnetically Induced Forces on Lightweight Medical Devices in the MRI Environment

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Abstract

Scope: This protocol provides a standardized methodology to assess MRI-induced translational forces on retained or temporary epicardial pacing leads using a pendulum setup in both laboratory and MRI environments. It supports preclinical lead evaluation and translation to patient-specific MRI clearance, enabling communication between physicists and radiologists.

Objective:

Methods:

Results:

Conclusion:

INTRODUCTION

Magnetic resonance imaging (MRI) is an essential diagnostic tool, it provides superior soft tissue contrast without the safety hazzards that ionizing radiation introduces. Like every other medical imaging modality, safety is a main concern for its use in a clinical setting. In the case of MRI, the powerful static magnetic field and associated spatial gradients impose strict safety constraints on patients with implanted medical devices. Currently more than 4.5 million individuals worldwide live with cardiac implantable electronic devices (CIEDs), including pacemakers and implantable cardioverter-defibrillators (ICDs) [1, 2].

It is in our interest to study a particular subset of CIEDs, temporary epicardial pacing leads, around the MRI environment. These provisional leads are frequently placed during open-heart surgery to regulate cardiac rhythm postoperatively, then are typically cut at the skin surface leaving behind a short length of wire embedded in the tissue [3]. In general, a device labeled as MRI safe is expected to be nonconductive, non-electrical, non-magnetic, and to present no known hazards in the MRI environment. However, this classification does not apply to most epicardial leads, as they are rarely physically characterized after removal. By the time they are cut, these leads have fulfilled their clinical purpose, and systematic safety evaluations are seldom performed. Although retained leads are nonfunctional and relatively short, they are frequently classified as MRI unsafe due to concerns over radiofrequency (RF) heating, magnetically induced translational forces and torques, or inadvertent cardiac stimulation [4, 5].

The concern that has drawn the most attention among these is RF-induced heating. Previous work conducted at Creighton University evaluated the heating effects of retained leads in a tissue-simulating phantom under clinical imaging conditions. This study found that short leads (¡13 cm) posed no significant thermal hazard during MRI at a specific absorption rate (SAR) of 2 W/kg and is throughtfully described as Master Thesis in 2021 [1, 6, 7].

The next step is to asses magnetically induced translational forces. These forces are described as a function of the static field strength (B_0), its spatial gradient (∇B_0), and the magnetic susceptibility (χ) and density (ρ) of the material. A well known and expected behavior is the magnetic pull on high susceptibility materials toward regions of higher field strength, like near the bore entrance of the scanner where the spatial gradient is highest [1, 8, 9]. For instance, a nonmagnetic stainless steel wire with $\chi \approx 103$ ppm may experience a force equivalent to $\sim$30% of its weight, whereas ferromagnetic materials like pure nickel can experience forces exceeding 20,000 times their own weight. That is more than enough to become dangerous projectiles unless restrained [1, 9].

ASTM F2052-21 offers a standardized technique for assessing magnetically induced displacement force on medical equipment in order to set safety standards for such situations. This standard states that a device is MR Conditional if the deflection force it encounters in the MRI environment is less than the force of gravity upon it. This is usually verified if the deflection angle from vertical is less than 45° [10, 11].

Despite these established protocols, many retained leads have not undergone formal mechanical testing due to their temporary nature and variability in material and geometry. The primary aim of this work is to show and validate a custom-built, lab-scale, MR-compatible translational force testing platform and demonstrate its capability to produce quantitative, ASTM-aligned safety data. The device allows to precisely place a reference rod or pacing wires at clinically significant points in the MRI fringe field where translational forces are at their highest.

Measurements are interpreted in the context of magnetic susceptibility theory and compared to relevant thresholds from the literature [6, 11]. These techniques will help with more thorough evaluations of MRI safety in patients with retained temporary epicardial leads and set the stage for a future clinical adaptation of the protocol employing a 1.5 T MRI scanner. This method aids in the improvement of device classification and the creation of uniform experimental procedures for the assessment of torque and translational safety.

METHODS

The objective of this study was to evaluate MRI-induced translational forces acting on post-surgical epicardial pacing leads using in-lab simulations based on ASTM F2052-15 standards. A secondary goal was to develop and validate apparatuses that could later be used in clinical settings to replicate these measurements under MRI field conditions. Three distinct experimental setups were involved in this study: (1) a spatial field mapping platform to characterize B_0 and ∇B_0, (2) a pendulum-based deflection apparatus to assess translational force through angular displacement, and (3) a torque measurement system for rotational

force assessments, the latter of which remains under evaluation.

Magnetic Field and Gradient Mapping Platform

Magnetic field strength (B_0) and gradient (∇B_0) measurements were performed using a commercial Hall-effect Gaussmeter (Model GM2, AlphaLab Inc., Salt Lake City, UT). The GM2 operates on the Hall effect principle, wherein a voltage is generated across a probe when exposed to a perpendicular magnetic field. This voltage is proportional to the local magnetic flux density, enabling precise spot measurements of field magnitude. The Gaussmeter used has an accuracy of 1% of the DC reading in the 16°C to 29°C range.

To ensure spatial accuracy and reproducibility, a fixture made from rigid PVC was constructed. The platform comprises a 300 mm square base and a 280 mm diameter vertical circular plate, perforated with a 5x5 grid of probe-access holes spaced at 20 mm intervals. Each access point was numerically indexed to facilitate 2D field mapping in the X-Y plane.

In clinical use, the entire fixture is intended to be shifted axially along the Z-direction of a horizontal bore MRI scanner using controlled couch increments (e.g., 10 cm). This translation allows for volumetric sampling of B_0 over several planes. The spatial magnetic field gradient∇B_0 can then be estimated numerically using finite difference calculations between adjacent measurement points. This method has previously been applied to MRI mapping in the work by Ferreira [12].

Translational Force Measurement via Angular Deflection

Experimental Setup

Laboratory Simulation with Solenoid Coil

To assess MRI-induced translational forces in a laboratory environment, we developed a pendulum-style apparatus replicating the geometry outlined in ASTM F2052-15 [**?**]. The vertical post includes a screw clamp mechanism that enables height adjustment; however, a default suspension height of 1 meter was used for consistency across trials.

The experimental frame was constructed entirely from **PVC** components (Figure **??**), including a vertical post of 1.5 meters and a rigid base for stabilization. The sample—a **solid ferromagnetic cylinder** (length = 6 mm, diameter = 3 mm, mass = 0.3648 g, density = 8.6 g/cm^3)—was suspended by a **955 mm-long sewing thread**, tied via a simple knot at its top. For clinical applications, a **0.25 mm nylon monofilament** is recommended for improved reproducibility and safety. Additionally a frame for lead configuration must be

added, which design is discussed briefly in the next section. The bottom of the sample was free to swing, forming a pendulum under gravity. A horizontal ruler, fixed along the Z-axis, served as the visual reference to quantify lateral displacements as shown in Figure **??** b .

Lead Holder Frame Design

To accommodate epicardial lead positioning while maintaining MRI compatibility, we propose the use of a lightweight, non-magnetic frame fabricated from Polyvinyl Chloride (PVC) and equipped with nylon screws used to secure the epicardial lead at discrete positions. The suggested frame dimensions are 70 mm wide by 100 mm tall, with a thickness of 3 mm. A series of 3 mm diameter holes for screws placed along the vertical centerline at 10 mm intervals should allow reproducible placement of leads at known lengths (6–13 cm). As shown in figure [smth]

The frame needs to be suspended such that the lead axis was aligned approximately parallel to the magnetic field gradient (Z-axis). While the frame's lightweight design aimed to minimize its contribution to the total magnetic force, its mass may not be explicitly subtracted from the translational force calculations.

Magnetic Field Generation

Magnetic fields were generated using a **custom-built air-core solenoid**, approximately 15 cm in length and 10 cm in outer diameter. The solenoid was densely wound with **copper wire (∼1 mm diameter)**, forming an inner core of approximately 5 cm. A **Pasco Scientific SF-9584 DC power supply** was used to deliver currents in the range of **0–4 A**, corresponding to magnetic field strengths from **1 to 18.9 Gauss**. The system operated in a continuous mode; no rest periods were applied between trials due to the time required to stabilize the pendulum after each adjustment. as shown in the experimental setup.

Magnetic field measurements were performed using an **AlphaLab Inc. Gaussmeter**. To characterize local field gradients, measurements were taken at three positions: at the pendulum's equilibrium position, 5 mm below, and 5 mm above, yielding values of B_{-5}, B_0, B_{+5}, respectively. Each position was sampled **nine times per current level**, and gradients were computed using the finite difference method:

$$\frac{dB}{dz} \approx \frac{B_{+5} - B_{-5}}{10mm} \tag{1}$$

Measurement Protocol

Once the pendulum reached equilibrium under each magnetic condition, the horizontal displacement x was recorded visually using the ruler as a reference. With known suspension length L, the **deflection angle** α was calculated as:

$$\alpha = \tan^{-1}\left(\frac{x}{L}\right) \tag{2}$$

Following ASTM F2052-15, the ratio of magnetic to gravitational force is:

$$\tan\alpha = \frac{F_m}{mg} \tag{3}$$

where m is the mass of the test object and g is gravitational acceleration. The translational force F_m is then:

$$F_m = mg\tan\alpha \tag{4}$$

This relation also enabled the **estimation of volumetric magnetic susceptibility** χ under the assumption of a linear force model:

$$F_m = \frac{\chi V}{\mu_0} B_0 \frac{dB_0}{dz} \quad \Rightarrow \quad \chi = \frac{\mu_0 F_m}{V B_0 \frac{dB_0}{dz}} \tag{5}$$

where μ_0 is the permeability of free space and V is the object volume. Values of χ were inferred from the slope of $\tan\alpha$ versus $B_0\frac{dB_0}{dz}$, based on the Newtonian framework.

Data Collection and Analysis

All measurements were logged in **Microsoft Excel**, and photos/videos were casually captured via smartphone to document behavior. A minimum of **three trials** were performed for each current level; however, only the final (most consistent) dataset was retained for analysis. Data were plotted to evaluate $\tan\alpha$ vs. field gradient force. Propagated uncertainties in α and dB_0/dz were computed using standard error propagation formulas. Estimated measurement errors were:

- Gaussmeter resolution: ± 0.001 G
- Ruler displacement: ± 1 mm

A summary schematic of the apparatus is included in **Figure ??**, with additional engineering drawings available in **Appendix A**.

Torque Measurement Apparatus (In Progress)

A torque measurement system based on ASTM F2213 is under development. While a prototype was fabricated under the supervision of Dr. Nichols and prior students, detailed calibration, operational workflow, and data acquisition methods are still being finalized. The system is expected to allow both qualitative torque threshold assessments and quantitative torque calculation by assessing rotational displacement under a known static field.

RESULTS

DISCUSSION

EVALUATION PLAN Device Fabrication and Protocol Development. After we have fabricated the devices described in Aims 1 and 2 and established their utility, we will prepare publications providing appropriate schematics and materials as well as protocols for their effective use. This will also be disseminated through presentations at local, regional, and national conferences.

Data Analysis. The successful completion of the project requires establishing the measurement accuracy for the static B0 field, the field gradient, translational forces, and torques (by two techniques). For each of 10 Z-axis locations, approximately 60 measurements of B0 will be made and repeated on at least three separate occasions to verify consistency. Each of the translational force and torque measurements will be repeated approximately 3-5 times at each location within the MRI scanner tested (up to 10 axial measurement sites with 5 positions within the plane (left, middle, right, top, bottom). The mean and the standard error will be reported and results for each epicardial lead will be compared to the established safety standards.

Expected Outcomes, Benchmarks for Success, and Projecting Future Directions. By completing Aims 1 and 2, we will develop the apparatus and methodology to 1) characterize the spatial distribution of the magnetic field in a clinical MRI scanner, 2) measure the maximum translational forces and torques on a representative subset of temporary, post-surgical epicardial pacing leadings, and 3) assess the safety of the leads regarding static B0 magnetic field interactions according to established standards. These results will be interpreted along with our prior measurements of potential hazards of RF heating to provide a more complete assessment. The techniques and the collaboration strengthened through this study will also pave the way for a future study of the potential for electrical stimulation by retained, post-surgical epicardial pacing leads during MRI. We plan to publish these results within respected medical physics and radiology journals, and will disseminate the results at

national meetings, including the American Association of Physicists in Medicine (AAPM) annual meeting. Progress made through this work will enable applications for future funding such as NIH R15 and R21 proposals through NIGMS and NIBIB.

CONCLUSION

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