Biomedical comparison of magnetometers for non-ferromagnetic metallic foreign body detection

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Abstract. The location and surgical removal of foreign bodies in patients is still challenging, especially for firearm projectiles, which are small and non-ferromagnetic. Conventional location techniques use ionizing radiation, posing health risks while the procedures often last several hours and end unsuccessfully. The use of high sensitivity magnetometers provides a non-invasive and innocuous alternative for metallic foreign body location. The developed technique consists of a primary AC magnetic field generator (a solenoid) inducing eddy currents in non-ferromagnetic metallic foreign bodies, which results in an ultra-low secondary magnetic field that can be measured. This work compares the initially developed theoretical technique using Superconducting Quantum Interference Device (SQUID) magnetometers with the developed prototypes using lower cost alternatives, namely Giant Magnetoresistance (GMR) and Giant Magnetoimpedance (GMI). The comparison is based on biomedical device requirements for widespread clinical application. The proposed GMI location system is deemed the most qualified for clinical use.

1. Introduction
The need for surgical removal of firearm projectiles from patients is commonplace and continues to present challenges for physicians [1]. The only widely available location techniques use ionizing radiation, posing health risks to both patients and staff. Furthermore, these methods are often ineffective, with surgical procedures lasting several hours and typically ending unsuccessfully, especially when dealing with small objects.

The Laboratory of Biometrology (LaBioMet) at Pontifical Catholic University of Rio de Janeiro (PUC-Rio) performs research in the field of non-invasive clinical diagnosis [1-6]. The success in detecting ferromagnetic needles using a Superconducting Quantum Interference Device (SQUID) [2-3] prompted the development of a technique to locate non-ferromagnetic foreign bodies, in particular lead projectiles, which are diamagnetic [1]. This technique was adapted in the development of biomedical devices to locate such bodies while respecting project goals such as low cost for clinical application, innocuousness, non-invasiveness, safety, portability, ease of use and capacity to operate at room temperature [7-11]. In order to comply with such requirements, magnetometers based on the Giant Magnetoresistance (GMR) and Giant Magnetoimpedance (GMI) effects were used as lower cost alternatives to SQUID sensors, which require liquid Helium cooling [12-13].
This work introduces a fundamental comparison between the proposed location systems based on SQUID [1], GMR and GMI sensor elements regarding compliance with project requirements for the clinical application of biomedical devices.

2. Methods
The essential detection technique consists of using a time-varying primary magnetic flux density to induce eddy current loops in the foreign body, which consequently produce a secondary magnetic flux density to be measured by a gradiometric (differential) reading system, composed by two sensor elements [1,8,10]. The gradiometric configuration increases the signal-to-noise ratio (SNR) by minimizing the effect of the environmental and primary magnetic flux densities [1]. Figure 1 is a simplified illustration of this detection concept [10] when using a solenoid as a primary magnetic flux density generator and placing its axis aligned with the centre of the spherical foreign body. This axis is defined as the z-axis, over which the distance or depth values are measured.

Figure 1. Simplified diagram of the detection procedure. The solenoid generates a time-varying primary magnetic flux density $B_s$ (dashed line) towards the spherical foreign body that induces the also time-varying eddy current loop $I_{eddy}$ (dotted line), in return producing the secondary magnetic flux density $B_t$ (dash-dot line). The result of a gradiometric (differential) reading by sensor elements S1 and S2 is mostly composed by the secondary magnetic flux density [10].

Mathematical work on theoretical models of eddy currents in spherical conductors when applied to this configuration result in equation (1) [1,10,14].

$$B_{s_{\text{max}}}(h, a, f_0) = B_o V(a, f_0) \left( \frac{1}{h^3} - \frac{1}{(h + l_o)^3} \right)$$

(1)

Where $B_{s_{\text{max}}}$ is the peak secondary magnetic flux density, $B_o$ is the primary magnetic flux density, $h$ is the depth distance between the foreign body and the sensor element S1, $l_o$ is the baseline (distance between the centres of S1 and S2) and $V(a, f_0)$ is a phasor variable given by equation (2).

$$V(a, f_0) = a^3 \left[ (2\mu_r + 1) - (2\mu_r + v^2 + 1) \frac{\tanh \nu}{\nu} \right] \left( \mu_r - 1 - (\mu_r - v^2 + 1) \frac{\tanh \nu}{\nu} \right)^{-1}$$

(2)

Where $\mu_r$ is the relative permeability of the conducting sphere, $a$ is its radius and $\nu$ is a factor related to the skin depth in the material, calculated by equation (3).

$$\nu = a(1 + i)(\pi \mu_r \mu_0 \sigma f_0)^{-1/2}$$

(3)

Where $\mu_0$ is the permeability of free space, $\sigma$ is the conductivity of the conducting sphere and $f_0$ is the frequency of the primary magnetic flux density.

These theoretical models were used to estimate secondary magnetic flux density levels for varying distances and foreign body radii [1,10]. These results were associated with sensor specifications in order to design signal processing circuits and conduct complete system simulations and experiments [10]. The GMR sensors used were NVE AA-005-002 and the GMI sensors were Aichi MI-CB-1DJ-M-B commercially available prototypes.
The technical specifications of each sensor element and certain parameters utilized in each system were used for comparison regarding project requirements [7]. Innocuousness was evaluated according to the exposure limits established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) to electromagnetic fields [15-17] and primary magnetic flux density levels of each detection system. Assuming measurement at the edge of the solenoid, the SQUID system in [1] uses 5.15 mT (rms) at 1 kHz, the GMR system uses a DC component of 4 mT and an AC component of 1.77 mT (rms) at 123 kHz while the GMI system uses 468 nT (rms) at 8 kHz [10]. The magnetic field density decreases rapidly with the distance from the solenoid; therefore a minimum distance to reach the reference levels can be calculated. This analysis, exhibited in Table 1, considers the different reference levels established by ICNIRP for occupational and for public exposure.

Table 1. Innocuousness analysis of the location systems using ICNIRP reference levels [10].

| System | Frequency | Primary Magnetic Flux Density (rms) | Occupational Reference Level | General Public Reference Level | Safe Distance Occupational | Safe Distance Public |
|--------|-----------|-----------------------------------|------------------------------|--------------------------------|---------------------------|---------------------|
| GMR    | DC        | 4 mT                              | 2 T [15]                     | 400 mT [15]                    | Compliant                | Compliant           |
|        | 123 kHz   | 1.77 mT                           | 16.3 µT [17]                 | 6.25 µT [17]                   |                           |                     |
| GMI    | 8 kHz     | 468 nT                            | 100 µT [16]                  | 27 µT [16]                     | Compliant                | Compliant           |
| SQUID  | 1 kHz     | 5.15 mT                           | 0.3 mT [16]                  | 80 µT [16]                     | 7.86 cm                  | 14.1 cm             |

Non-invasiveness is determined by the principle of detection used by the location systems while criteria such as portability, ease of use and room temperature operation depend mostly on the sensor element characteristics and the complexity of the electronics involved, in particular the primary magnetic field generator and the signal processing requirements. The main component impacting cost, in this case, is the sensor element. Safety evaluation can be manifold; however, a few critical concerns can be established for each system, including the basic requirements for medical electrical equipment safety.

3. Results

Regarding the innocuousness criteria, the GMI system is the only candidate that uses primary magnetic flux densities below the safety reference levels recommended by ICNIRP at the edge of the solenoid. The other systems require small distances in order to be compliant. Non-invasiveness is satisfied by any magnetic measurement technique, being a common advantage of the three detection systems. The SQUID necessity for cryogenics affects the other requirements, imposing high operational costs and safety concerns, as well as reducing portability, adding complexity of use and preventing room temperature operation. Meanwhile, the GMR and GMI sensors comply with these requirements. The GMR system possesses the lowest cost, however there are some safety concerns due to the high solenoid excitation currents. The low cost of the GMI system should become even more competitive when nanotesla GMI sensors enter mass production. Comparison results are summarized in Table 2.
Table 2. Analysis of the major biomedical device requirements for the considered magnetometers and their respective location systems [10].

| Biomedical Device Requirements | SQUID [1] | GMI (Aichi MI-CB-1DJ-M-B) | GMR (NVE AA-005-002) | Most Suitable Magnetometer |
|-------------------------------|-----------|---------------------------|----------------------|---------------------------|
| **Innocuousness**<br>(distance for reference levels) | 7.86 cm (occ.)<br>14.1 cm (public) | No limitation | 9.6 cm (occ.)<br>14.0 cm (public) | GMI |
| **Non-Invasiveness** | Yes | Yes | Yes | Any |
| **Low Cost** | No | Yes | Very | GMR |
| **Safety**<br>(main concern) | Cryogenics<br>MEES<sup>a</sup> | MEES<sup>a</sup> | High excitation current<br>MEES<sup>a</sup> | GMI |
| **Portability** | No<br>(Dewar and Cryogenics) | Yes | Yes | GMI and GMR |
| **Ease of Use** | No<br>(Requires Cryogenics) | Yes | Yes | GMI and GMR |
| **Room Temperature Operation** | No<br>(lower than 77 K required) | Yes | Yes | GMI and GMR |

<sup>a</sup> MEES - Medical Electrical Equipment Safety

4. Conclusions
Although SQUID sensors are currently a benchmark for magnetic measurements by possessing the lowest noise levels, the need for cryogenic temperatures does not comply with several major requirements for clinical use. The analytical comparison between the three proposed non-ferromagnetic metallic foreign body location systems indicates the GMI system as the most suitable for this biomedical application. It is capable of complying with the major biomedical device requirements that enable widespread clinical use, in particular the detection system based on the GMI sensor is the only inherently innocuous according to exposure limits established by ICNIRP guidelines. The GMR system comes at close second with an advantage of even lower cost. These results evidence the potential of introducing new techniques based on magnetic measurements for clinical use, providing innocuous and non-invasive alternatives to traditional techniques and maintaining low costs.

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