MRI Gradient Field-Induced Heating and its Frequency Dependency for Different Materials

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Introduction:

Switched gradient magnetic fields are necessary in Magnetic Resonance Imaging (MRI) for spatial encoding of the received signals. The rapid switching of these gradient fields (usually in the order of the kilohertz) creates induced currents in the conductive structures exposed to that electromagnetic environment. Some studies have already confirmed that gradient fields can increase the temperature of metallic objects in a significant way. For example, an increase of more than 10 °C in a copper plate of 50 x 50 mm has been reported in [1]. According to the recently published technical specification ISO/TS 10974:2012 [2] devices should be exposed to a time-varying field with a constant dB/dt of 100 T/s and a frequency of 2.5 kHz for a time of 900 seconds. However, it is still not clear whether those conditions cover the worst clinically relevant sequences or not, and especially if a worst-case field condition can be defined (independently of the device under test). This study evaluated the gradient-induced heating of a pair of metallic plates (dimensions similar to commercial medical implantable pulse generators IPGs) made of different materials in order to determine a suitable test procedure for the test of gradient induced heating.

Devices and Measurement Setup:

The devices used during this study are shown in Fig. 1, and are basically a circular plate made of copper (Ø = 46.1 mm, h = 0.5 mm) and titanium (Ø = 46.8 mm, h = 0.6 mm).
A dB/dt-Pulsed Magnetic Field Generator (MR:comp GmbH, Germany) including a split solenoid coil has been used for generating a uniform magnetic field in the measurement volume. Induced heating has been measured while immersing the devices under test in a cylindrical phantom filled with a gel emulating the thermal properties of human tissue. The conductivity of the gel was 460 [mS/m] with thermal conductivity of 0.54 [W·K/m].
Temperature was recorded in three different points of the devices (one in the center and two points of the circumference edge) with a commercial available fiber optic thermometer (OPTOCON, Dresden, Germany), 4 channel, 4 temperature probes, probe tip diameter < 1 mm, resolution 0.1°C, probe accuracy ±0.1°C close to point of calibration (23°C).
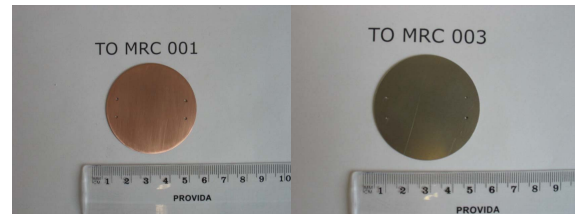

Figure 1. Metallic devices used during the heating measurements. The one made of copper is shown on the left, and on the right it can be seen the titanium one.

Methodology:

The increase in temperature of a given metallic object exposed to electromagnetic fields is proportional to the deposited power (assuming that the surface of the device is small enough to ignore the heat loss due to radiation) [3]. The deposited power on a metallic object is dependent on many factors (including shape and material), and therefore it can be very difficult to predict for complex shapes or multi-component objects. However, it is known that deposited power is proportional to the square of the magnitude of the time varying magnetic field. Therefore, the heating of a given object can be modeled as follows:

$$P \propto \Delta T = B_G^2 \cdot \gamma(f) \cdot L$$

where B_G is the peak amplitude of the gradient magnetic field, f is the frequency, $\gamma(f)$ is the characteristic response of the device under test and L is the loading factor between the field generator and the device (which tends to 1 if the metallic device is much smaller than the field generator).

The temperature increase on the two metallic plates was measured while exposed to a time-varying sinusoidal magnetic field of 6 mT amplitude, and for a range of frequencies between 1 and 5 kHz. Exposition time was 300 s. From those results, it is calculated the characteristic response of the devices $\gamma(f)$ (assuming L=1). The experiment was then repeated, changing the field amplitude (setting now as constant the relation $B_G^2/\sqrt{f}$). With the characteristic response of the devices obtained previously, it is also possible to calculate the heating predicted by the proposed model.

Results:

The maximum temperature increase (vs. frequency) during the first experiment is shown in Fig. 2 for the two objects. With the results of this experiment, it can be calculated $\gamma(f)$ for each device. Fig 3. shows the results of the second experiment (constant $B_G^2/\sqrt{f}$), with both measured (bold lines) and predicted (dotted lines) results. Predicted values were calculated using the $\gamma(f)$ for each device (obtained from the first experiment), the amplitude of the varying field, and assuming L=1.

Discussion:

The results obtained show that heating is proportional to the square of the field amplitude and to a characteristic frequency response $\gamma(f)$ that depends on the particular object. Once that the characteristic response has been obtained for a given object, it is possible to predict the heating for different field amplitudes with good accuracy (as shown in Fig. 3). Moreover, the frequency response found for the 2 measured objects is not similar between them, neither linear with frequency. This makes it very difficult to predict the characteristic frequency response of a given object a priori.
Therefore, in order to guarantee the safety of patients with metallic objects during an MRI scan, the frequency response of the gradient-induced heating interaction should be studied in advance.

Conclusion:

The worst-case exposure cannot be concluded only by a particular set of gradient field conditions for all different implants. A relative design and therefore frequency dependence is expected and need further investigation on real IPGs when studying the gradient-induced heating.

References:

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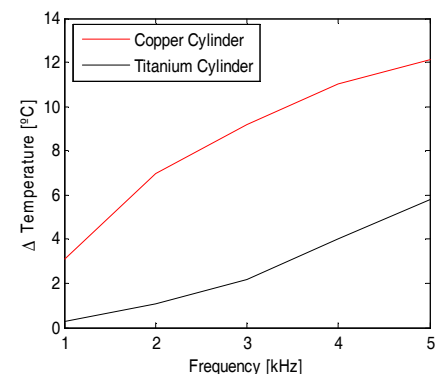
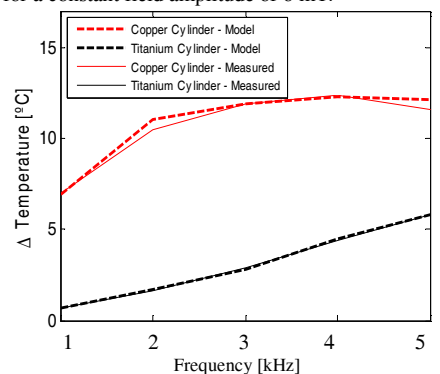Figure 2. Measured temperature increase vs. frequency for a constant field amplitude of 6 mT.

Figure 3. Measured (and predicted) temperature increase vs. frequency when the relation $B_G^2/\sqrt{f}$ is set constant.