Peripheral Nerve Stimulation Considerations in the Presence of the Metallic Objects

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Introduction: In order to achieve higher image quality and speed, it is preferred to use high-strength, high-slew-rate gradient coils in imaging applications[1]. The peripheral nerve stimulation (PNS), however, limits this fast gradient switching where it may result in a mild to intolerable discomfort for the patient. IEC standards put limits on the gradient output to operate in the normal safe mode. For biological tissues, the IEC standard for safe gradient switching is given by the following formula as the upper limit: $dB/dt = .8 \times 20(T/s)(1 + 360(\mu s)/t\,(\mu s))$. Here dB/dt, which is a hyperbolic function of the duration of stimuli(t), is the allowed intensity of the gradient pulse for the normal safe mode[2]. According to[3], the required intensity for reaching a discomfortable state is 50% above the mild threshold and the intolerable state requires the dB/dt to be twice as much as the mild threshold. PNS may happen at lower gradients because of eddy currents in the vicinity of metallic foreign objects, adjacent to sensitive locations. Such objects can intensify and concentrate the induced current by the gradient switching. In this study we evaluate the effect of eddy current on defining the safe mode to prevent the PNS.

Theory and Methods: Eddy currents, although oppose the increase of the magnetic flux along the metallic object, in coplanar points outside of the object further intensifies the magnetic field. The effect of eddy current is highest, when a conductor with a coin-geometry is placed perpendicular to the time-varying magnetic field. It will result in the maximum induced current in the conductor and the maximum resultant dipole moment. Considering a coin with a radius *"a"* and thickness *"d"*, placed in the transverse plane during the rise time of a gradient pulse, the induced current density can be calculated, by combining Faraday's and Ohm's laws as in (Eq.1). Applying the dipole-approximation (Eq.2) (Eq.3), the overall magnetic field is approximated for coplanar points (Eq.4) and its time variations expressed as Eq.5.

$$j_\emptyset = \frac{-dr\sigma}{2}\frac{dB_0}{dt} \quad (Eq.1 \qquad m = \int_0^a \pi r^2 j_\emptyset dr = -\frac{\sigma\pi d a^4}{8}\frac{dB_0}{dt}a_z \quad (Eq.2 \qquad B(r) = \frac{\mu_0}{4\pi}\left(\frac{3r(m.r)}{r^5} - \frac{m}{r^3}\right) = \frac{1}{4\pi}\left(-\frac{m}{r^3}\right) \quad (Eq.3$$

$$B_t = \left(\frac{\sigma\mu_0\pi d a^4}{32\pi r^3}\frac{dB_0(t)}{dt} + B_0(t)\right)a_z \quad (Eq.4 \qquad \frac{dB_t}{dt} \approx \frac{B_{t(t=t_r)} - B_{t(t=0)}}{t_r} = \frac{dB_0}{dt}\left(1 + \frac{2\pi\sigma\mu_0 d a^4}{32\pi r^3 t_r}\right) \quad (Eq.5$$

Result: To consider the maximum possible adverse effect of eddy current, we assumed a large diameter of about 30 mm with a thickness of d=1.5 mm for a metallic foreign object made from a highly conductive material with $\sigma = 10^8 S$. The maximum value for the dB_t/dt was then estimated through Eq.5 for common rise-times. The variation of normalized dB_t/dt in $t_r = 200\mu s$ versus the radial distance from the coin origin (in and out of the coin plane) is shown in Fig.1. The new safe mode values for applicable dB_0/dt, are calculated and shown in figure.2 under the aforementioned circumstances.

Discussion and conclusion: According to Eq.5 the applied gradient intensity reaches its maximum value in the coin plane where $= a$. According to Fig.1 which denotes the $((dB_t/dt)/(dB_0/dt))$ $(t = 200\mu s)$ versus r, this extra gradient drops fast with a $1/r^3$ factor such that at radial distance $r = 2a$, the external metallic object intensifies the applied dB_0/dt **only** by a factor of 1.10. So if the external objects located far enough from the sensible location; there is no major threat and discomfort for the patient. Fig.2 shows that for $tr = 100\mu_s, 200\mu_s, 300\mu_s$, the $dB_t/dt\,(\boldsymbol{max})$ can respectively reach 2.76,1.88,1.58 times greater values and therefore may change the comfort zone with painful or even intolerable situation for the patients. The interesting outcome of the study is that the new limit for dB_0/dt (considering the metal induced eddy current) is much less sensitive to gradient rise time compared to original limit set by the IEC standard (Fig.2). The current analysis is valid not only for non-magnetic metals but also for most ferromagnetic objects as they are saturated in the static magnetic field.

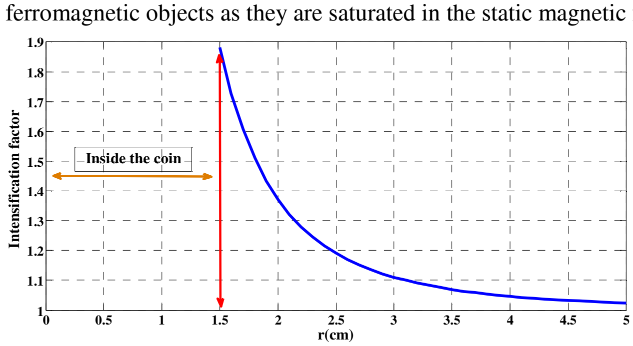

Figure 1. Amplification factor for the applied intensity of the gradient pulse (with $t = 200\mu s$) versus r for coplanar points outside of a coin.

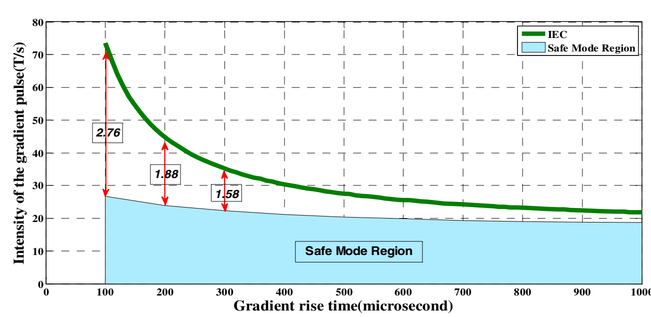

Figure 2. Modified limit for gradient pulse intensity as a function of the gradient rise time.

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