Electrostimulation by time-varying magnetic fields

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Despite several investigations and publications on possible effects due to time-varying magnetic fields, the question remains as to the magnitude of the field, or its derivative with respect to time, that is capable of stimulating the human heart. It is quite surprising how little information on cardiac stimulation has entered the discussion to date. If the law of induction and the fundamental law of stimulation, both in their field forms, are combined, the result is quite different from what has been published: (1) It is the amplitude of the gradient field that is responsible for stimulation and not $\frac{dB}{dt}$. (2) The shape of the time-varying pulse has no influence on stimulation but only its mean value. (3) Owing to different rheobase and chronaxie values for cardiac tissue and peripheral nerves, the threshold for magnetostimulation of the myocardium is up to 200-fold higher than that for nerves. These results allow for the determination of safety limits that are certainly above those proposed to date. Based on these limits, technological advancement can be achieved without neglecting the patient safety requirement.

Keywords: electrostimulation, magnetostimulation, neurostimulation, cardiac stimulation, electrical safety, magnetic field, electric field.

INTRODUCTION

Although there have been several investigations and publications on possible effects due to time-varying magnetic fields in the last decade [1–7], the question remains open as to the strength of the magnetic field required to excite the heart during NMR imaging. Is a possible hazard associated with the rate of change $\frac{dB}{dt}$ of the magnetic field, or is the peak value of rectangular stimulus fields responsible for excitation of nerves or cardiac muscle? What is the threshold value for cardiac excitation in relation to peripheral nerve thresholds? The IRPA/INIRC Guideline on MRI [4] warns that electric field strengths exceeding 5 V/m may cause ventricular fibrillation, suggesting that the thresholds for nerve and cardiac muscle stimulation are very close.

Reading the articles discussing magnetic stimulation, it is surprising to note how little information on cardiac pacing has entered the discussion so far, and, furthermore, that discrepancies between the levels of proposed and measured electric fields obviously require further investigation [6]. It is the intent of this article to apply the enormous knowledge of cardiac pacing compiled during the last three decades to the special problem of magnetic stimulation of the heart.

INDUCTION OF ELECTRIC FIELDS BY TIME-VARYING MAGNETIC FIELDS

According to Maxwell’s laws, a time-varying magnetic field produces an electric field, which can be calculated by the integral equation

$$\oint E \cdot ds = \frac{d}{dt} \int B \cdot dA$$

(1)

which is simple to solve for a uniform magnetic field and a circular cross section perpendicular to the direction of the magnetic field

$$2\pi r [E(r)] = \pi r^2 \frac{dB}{dt}$$

(2)

$$E(r) = \frac{r}{2} \frac{dB}{dt}$$
Silny [7] found that the induced electric field in elliptic bodies, with uniform magnetic fields applied, depends on the field orientation, either longitudinal or transversal, yielding a coefficient of orientation $c$:

$$E(r) = cr \frac{dB}{dt}$$  \hspace{1cm} (3)

with $c = 0.5$ for longitudinal orientation and $c = 1$ for transversal orientation:

$$0.5 \leq c \leq 1$$  \hspace{1cm} (4)

Under magnetic resonance imaging (MRI) conditions the magnetic field is not uniform. The gradient fields produce only layers of constant magnetic fields with zero levels at the symmetry line and increasing (absolute) values as the distance increases. Although the calculation of the electric field with such inhomogeneous magnetic fields seems to be possible with finite element techniques, one can simplify the problem by the following assumption:

$$E_{\text{nonuniform}} \leq E_{\text{uniform}} \quad \text{(with } B = B_{\text{max}})$$  \hspace{1cm} (5)

An electric field induced by a nonuniform magnetic field is equal to, or smaller than, the corresponding electric field produced by a uniform magnetic field with a magnitude of the maximum amplitude of the nonuniform field $B_{\text{max}}$. In other words, the assumption of a uniform magnetic field with maximum amplitude yields a worst-case estimation of the induced electric field.

Keeping this in mind, we can state that a 100 T/s change in magnetic flux density during MRI can cause, in a “large man,” a maximum electric field of 14.4 V/m in sagittal orientation, 16.0 V/m in frontal orientation, and 9.9 V/m in longitudinal orientation [8]. The heart would be exposed to maximum fields of 12.2 V/m, 8.6 V/m, and 8.7 V/m, respectively, in the three directions. These field strengths have led to the suspicion that such $dB/dt$ values could be hazardous for MRI patients.

THE FUNDAMENTAL LAW FOR ELECTROSTIMULATION

The best formula for describing electrostimulation is given by

$$\int^t E \, dt \geq E_{\text{theo}} \frac{t_{\text{chron}}}{t_{\text{chron}}} \left(1 + \frac{\tau}{t_{\text{chron}}}\right)$$  \hspace{1cm} (6)

where $\tau$ is the duration of the electric field $E$, $E_{\text{theo}}$ is the rheobase of the electric field, and $t_{\text{chron}}$ is the chronaxie time of the physiologic system.

Figure 1 explains the chronaxie $t_{\text{chron}}$ as it was introduced by Lapicque in 1909 [9]. Throughout the text chronaxie is exclusively used as one of the determining parameters of the hyperbolic strength-duration function and not as a time constant of an exponential expression, often called “membrane time constant.” Equation 6 which has been used by us since 1973 [10], but is rarely utilized elsewhere, has the following advantages:

(1) It is (nearly) independent of the coupling mechanism. For reduced electrode size the chronaxie time is nonlinearly reduced [11].

(2) The primary parameter responsible for stimulation, the electric field, is addressed [3, 8, 10, 12–15]. The electric field is least influenced by changes in conductivity [14, 16, 17].

(3) The time integral over the electric field guarantees that the average value and not any other specific value (peak, root mean square value) is considered as being exclusively effective, as was already stated by Weiss in 1901 [18] and others over the last 80 years [14, 19–21].

(4) The linear approach is not only the simplest and best fit for experimental results [22] but can be justified theoretically by the assumption of a mechanical impulse necessary for opening the sodium channels within the membrane during electrostimulation [14]. Moreover, the calculations of Reilly with his SENN model [23] reveal that the calculated charge curves represent excellent straight lines, with a correlation coefficient of better 0.99, which cannot be reached with the so-called “exponential approach,” especially for long pulse durations.