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Artificial blood-flow controlling effects of inhomogeneity of twisted magnetic fields

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ABSTRACT

We developed a blood-flow controlling system using magnetic therapy for some types of nervous diseases. In our research, we utilized overlapped extremely low frequency (ELF) fields for the most effective blood-flow for the system. Results showed the possibility that the inhomogeneous region obtained by overlapping the fields at 50 Hz, namely, a desirably twisted field revealed a significant difference in induced electromotive forces at the insertion points of electrodes. In addition, ELF exposures with a high inhomogeneity of the twisted field at 50 Hz out of phase were more effective in generating an induced electromotive difference by approximately 31%, as contrasted with the difference generated by the exposure in phase. We expect that the increase of the inhomogeneity of the twisted field around a blood vessel can produce the most effective electromotive difference in the blood, and also moderately affect the excitable cells relating to the autonomic nervous system for an outstanding blood-flow control *in vivo*.

1. Introduction

Up to the present, it has been generally accepted that blood flows, as it were, in ionic flows in accordance with the bloodstream, are affected through the action of magnetohydrodynamics (MHD). Fundamentally, MHD can be regarded as the phenomenon that electromotive forces are generated in the vertical direction toward to both the directions of the fluid and the flux lines, when an electrically conductive fluid runs across the magnetic flux lines vertically. And that's why it might be considered that the effects of MHD specialized through an electromagnetic induction in a fluid, which is induced by static magnetic fields––a direct current, a permanent magnet, a geomagnetic field, and so on.

An actual blood flow *in vivo* is an exceedingly complicated phenomenon, which is deeply related to the blood viscosity [1–4] caused by various biophysical factors: hematocrit, plasma viscosity, the viscoelasticity of erythrocytes, the properties of a vessel wall, body temperature, and so on. Nevertheless, except for a few special situations, blood usually behaves as an electrically conducting Newtonian fluid as well as most other fluids. The Newtonian blood flow $\boldsymbol{F}$ is basically subject to the Hagen–Poiseuille law, which is defined as $\boldsymbol{F} = \boldsymbol{\pi r^4 \Delta P / 8 \mu L}$, where $\boldsymbol{r}$ is the radius of the blood vessel, $\boldsymbol{P}$ is the blood pressure, $\boldsymbol{\mu}$ is the blood viscosity, and $\boldsymbol{L}$ is the length of the blood vessel. On the other hand, the velocities of electrolytic solutions $\boldsymbol{v}$ can be calculated based on a fundamental equation of MHD as follows:

$$\rho \frac{\partial v}{\partial t} = -\nabla P + \mu \nabla^2 v + \rho K - \rho \nabla v^2 + iB \tag{1}$$

where $\boldsymbol{\rho}$ is the density of the fluid, $\boldsymbol{P}$ is the pressure of the fluid, $\boldsymbol{\mu}$ is the fluid viscosity, $\boldsymbol{K}$ is the external force to the fluid, $\boldsymbol{i}$ is the current density distributed in the fluid, and $\boldsymbol{B}$ is the magnetic flux density in the flow channel. Practical blood flows must be strongly dependent on the blood viscosity and the magnetic field strength; hence, the action of electric fields in a fluid is completely ignored in appearance. After all, an MHD effect for a magnetic therapy is converged to gain possible electromotive forces for the excitation of the autonomic nervous system [5–7], based on Faraday's law of electromagnetic induction, which is defined as $\boldsymbol{E} = \boldsymbol{kBlv}$, where $\boldsymbol{k}$ is the proportional constant, $\boldsymbol{B}$ is the magnetic flux density under the measuring domain in the blood vessel, $\boldsymbol{l}$ is the diameter of the blood vessel, and $\boldsymbol{v}$ is the blood-flow velocity.

Although there are several reports analyzing the effects of MHD on some different kinds of electrolytic reactions [8–13], it goes without saying that induced electromotive forces in a fluid have a powerful connection with blood flow control *in vivo*. This is because blood flows are under the control of the autonomic nervous system [14–17]. What's more, several studies have shown a possibility of extremely low-frequency (ELF) magnetic stimuli on the bioelectric activity of neuronal cells [18–20]. We also recently reported on a kind of MHD effect in ELF magnetic fields on an electromagnetic induction in a fluid, using an artificial blood-circulation system [21]. In this paper, we will report on the artificial blood-flow controlling effects of the inhomogeneity of twisted magnetic fields.

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2. Experimental methods

2.1. Exposure coil

The theoretical calculation of the magnetic flux density of an exposure coil was leaded according to the previous method [21]. On the calculation of the flux density $\boldsymbol{B(r,0,z)}$ at a cylindrical coordinates system, the density $\boldsymbol{B_z}$ in the $\boldsymbol{z}$-axis direction from an air-cored coil with $\boldsymbol{n{*}m}$ windings is given by

$$Bz = \frac{\mu_0 I}{\pi}\sum_{i=1}^{n}\sum_{j=1}^{m}\frac{s_i}{r}\frac{s_i^2 - r^2 + z_j^2}{\{(s_i + r)^2 + z_j^2\}^{3/2}}\left\{\frac{(2 - k_{i,j}^2)E(k_{i,j}) - 2(1 - k_{i,j}^2)K(k_{i,j})}{2k_{i,j}^2(1 - k_{i,j}^2)}\right\}$$

$$+ \frac{\mu_0 I}{2\pi r}\sum_{i=1}^{n}\sum_{j=1}^{m}\sqrt{\frac{s_i}{r}}\frac{1}{k_{i,j}}\left\{\left(1 - \frac{k_{i,j}^2}{2}\right)K(k_{i,j}) - E(k_{i,j})\right\} \tag{2}$$

where $\boldsymbol{\mu_o}$ is the magnetic permeability of a vacuum, $\boldsymbol{I}$ is the electric current running through the coil, $\boldsymbol{s_i}$ is the distance in a horizontal direction from the center of the coil surface, $\boldsymbol{K(k_{i,j})}$ is the complete elliptic integral of the first kind, $\boldsymbol{E(k_{i,j})}$ is the complete elliptic integral of the second kind, and $\boldsymbol{k_{i,j}}^{\mathbf{2}}$ is the square coefficient related to a multilayer coil. The coefficient $\boldsymbol{k_{i,j}}^{\mathbf{2}}$ is defined as $\boldsymbol{k_{i,j}}^{\mathbf{2}} = 4\boldsymbol{s_i r}/(\boldsymbol{s_i} + \boldsymbol{r})^2 + \boldsymbol{z_j}^2$, where $\boldsymbol{s_i} = \boldsymbol{a} + (2\boldsymbol{i} - 1)\boldsymbol{d}/2$, $\boldsymbol{z_j} = \boldsymbol{z} + (2\boldsymbol{j} - 1)\boldsymbol{d}/2$, $\boldsymbol{a}$ is the radius of the iron core, and $\boldsymbol{d}$ is the diameter of the electric wire.

The detailed account of an ELF-exposure coil system (Coil A and B) was given in our previous report [22]. The magnetic flux density (B_{eff}) was measured with a gauss meter (Yokogawa, Type3251). As shown in Fig. 1, we were able to obtain an alternating B_{eff} of 21.6 mT (theoretical: 27.4 mT) on the coil surface, under a constant current of 2.37 A. In this paper, two newly designed coils were used for producing a desirably twisted magnetic field under the measuring domain in the flow channel. For the preparation of the new coil, a hard plastic air core (ø50×70 mm) was wound tightly with 5000 turns of polyester-copper wire (Furukawa, PEW 0.5, S = 0.2 mm^2). These two coils (Coil C and D) were arranged surrounding the flow channel near two measurement points with test equipment electrodes (see Fig. 2). The field frequencies of all the coils were fixed at 50 Hz, and the waveform signals from the three coils (Coil A, B and D) were synchronized in phase in the direction of the measuring domain, that is, only the signal from Coil C was in absolutely reverse phase in the direction.

2.2. Circulation system and signal detection

A saline solution (*e.g.*, 10 L of 0.9% NaCl) in a water tank was circulated in a ceramic tube (inside, ø12 mm; outside, ø16 mm) by a general-purpose pump with flow-rate controls (Nisso, PP-51). Exposures to ELF fields were performed using the above-mentioned four air-cored coils (Coil A–D). The rectangular signal obtained from an optional-waveform function-generator (Leader, LG-1301) was amplified with a power amplifier (Behringer, iNUKE NU3000DSP) in the dual-mono mode. Signal detections of electromotive forces were carried out the same as in our previous report [21]. In brief, the signal was amplified differentially with an original differential amplifier containing built-in triple operational amplifiers (Burr-Blown, INA103) and sampled and amplified differentially with an original sampling circuit. The circuit consists of two monolithic sample-and-hold circuits (Texas, LF398NE), a CMOS output microcontroller (Microchip, PIC12F675), a three-terminal positive regulator (Texas, LM78L15ACZ/NOPB), a direct current (dc)/dc-converter (Recom, RSO-1205DZ), and a built-in high common-mode amplifier (Burr-Blown, INA117).

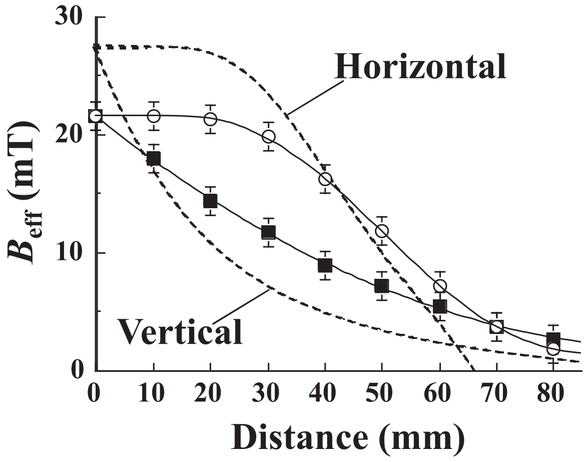

Fig. 1. Magnetic flux distributions generated using exposure coil. The flux density (B_{eff}) was measured every 10 mm vertically and horizontally from the center of the coil surface. Dashed lines: theoretically expected values.

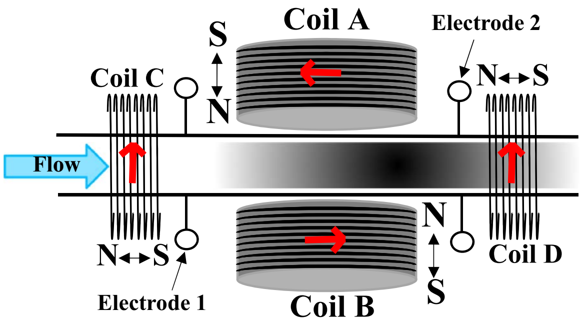

Fig. 2. Arrangements of ELF-exposure coils and electrodes. The shading shows the inhomogeneity of the twisted magnetic field. White is low and black is high. Only the waveform signal from Coil C was in absolutely reverse phase toward the measuring domain.

2.3. Prototype diverted from an existing AMTA

Diverting the use of a commercial alternating magnetic therapy apparatus (AMTA), we prepared a prototype equipped with two additional coils stated above (Coil C and D) for twisting the magnetic field of the machine and reversing the phase of the alternating field in both of the additional coils. The commercial AMTA (Biobeam 21) was kindly supplied by the NIKKEN Corporation (Fukuoka, Japan). The maximum B_{eff} was revealed as 60 mT at each center of the air core. Fig. 3 shows the partial view on the positions of all the exposure coils and three electrode pairs. The field frequencies of all the coils were fixed at 50 Hz, and the rectangular waveform signals from the additional coils were synchronized in (Fig. 3A) or out (Fig. 3B) of phase in accordance with the axis of the flow channel. For evaluating electromotive forces generated by static magnetic fields of the prototype, we actuated dc electric currents equal to the native current alternating the currents through all the coils in every direction of the flow of the dc currents, using a regulated dc power supply (Kikusui, PAB32-1.2).

3. Results and discussion

The induced electromotive difference generated by the overlapped ELF magnetic fields in a fluid is shown in Fig. 4. From this result, it is quite probable that the inhomogeneous region obtained by overlapping the alternating fields, namely, a desirably twisted magnetic field revealed a significant difference in the induced electromotive forces at the insertion points of the electrodes. Needless to say, the induced electromotive forces are ordinarily destined to convert into an ionic current "polarization current" within the fluid. The process of the electromagnetic induction in a fluid is also closely connected with a loop current "eddy current" caused by ELF exposures. From the point of view of a MHD effect, it is considered that an ELF-induced