COMPARISON OF CURRENT DISTRIBUTIONS IN THE HEAD IN ELECTROCONVULSIVE THERAPY AND TRANSCRANIAL MAGNETIC STIMULATION

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INTRODUCTION

Electroconvulsive therapy (ECT), in which electric currents are applied to the brain, improves severe mental illnesses such as depression [1]. Transcranial magnetic stimulation (TMS) is a method to stimulate neurons using eddy currents generated by pulsed magnetic fields [2,3]. Because TMS has a potential to give a comparable therapeutic effect to ECT with less invasiveness, TMS has been used for treatments of depression in numerous studies. However, these trials have not necessarily given beneficial results. Because the mechanisms of ECT largely remain to be understood, the optimum stimulus intensity and the desirable current distribution in ECT are still not clear. In many cases, however, ECT with a commonly used voltage (100 V) and an electrode position (a pair of electrodes attached to the tempora) has produced an improvement of depression. Thus, an appropriate approach for the initial attempt of TMS therapy is to find a stimulus condition which gives a similar current distribution in the brain to ECT. In a previous study, we calculated current distributions in ECT and TMS using the finite element method (FEM) [4]. As a result of this calculation, TMS could generate eddy currents of comparable intensity to ECT. Nadeem et al. performed an impedance method simulation for the same purpose, and found that the current densities and electric fields in the ECT case were stronger and deeper penetrating than the corresponding TMS quantities [5]. However, these studies obtained results for only one condition of TMS. In the present study, we investigated dependences of the current distribution in TMS on coil current intensity, coil diameter, and coil position. Current distributions in ECT and TMS were compared under various conditions to find optimum conditions of TMS as an alternative to ECT.

MATERIALS AND METHODS

Calculations were performed on a three-dimensional human head model [6]. As a typical condition of ECT, a voltage of 100 V was applied between a pair of electrodes place on the tempora. Current distributions in TMS were simulated for the following coil shapes and diameters: circular coils of 50 mm, 75 mm, 100 mm, 125 mm, and 150 mm, and figure-eight coils of 50 mm, 75 mm, 100 mm, and 125 mm. To investigate the dependence of eddy current distributions on the coil position, the coil was rotated around the center of the head, O, at angle θ, from the vertex toward the forehead. The difference in current distributions between ECT and TMS was evaluated using a performance function,

$$F = \frac{1}{V_0} \int_{\text{cortex}} \left(\left| \mathbf{j}_E \right| - \left| \mathbf{j}_T \right| \right)^2 dV \tag{1}$$

where V_0 is the volume of the cerebrum, $\mathbf{j}_E$ is the current density in ECT, and $\mathbf{j}_T$ is the current density in TMS. Because this function increases with the difference in current distributions between ECT and TMS, the optimum condition of TMS gives a minimum value of the function.

RESULTS

Figures 1(a)(b) show current distributions in ECT on a transversal slice and the brain surface (the gray matter, the white matter, and the cerebellum). The time for calculation was 30 seconds in the case of PC with a 2.2-GHz processor and a 1.0-GB RAM. The scalp under the electrodes located on the temora exhibited the maximum current density 876 A/m^2. Because the skull had a relatively low conductivity, a significant amount of the current flowed along the scalp and did not penetrate the skull. While a voltage of 100 V was applied between the electrodes on the scalp, the potential difference was 70 V between the maximum and the minimum values within the brain. Because the electrodes were located on the opposite sides of the brain, the injected currents distributed among the brain and did not significantly attenuate at the deeper regions. The white matter tissues at the center of the brain exhibited current densities of approximately 20 A/m^2. The frontal cortex exhibited higher current densities. The maximum current density within the brain was 69 A/m^2.

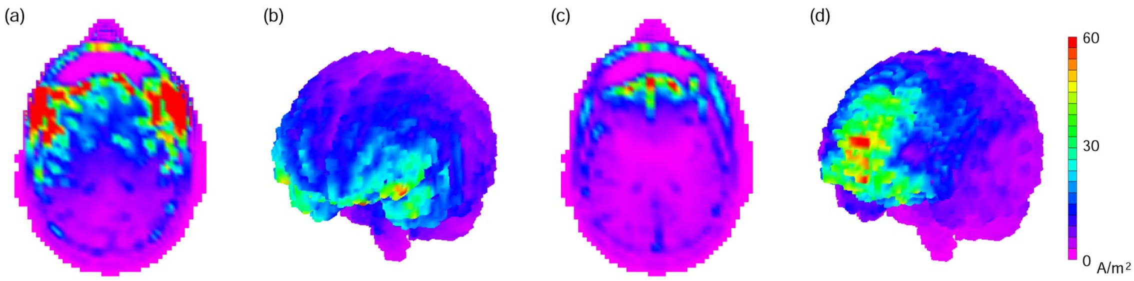

Figure 1: (a)(b) Current distributions in electroconvulsive therapy (ECT) represented in a transversal slices and the brain surface. (c)(d) Current distributions in transcranial magnetic stimulation (TMS) represented in a transversal slices and the brain surface.

Figure 1(c) shows current distribution in TMS on a transversal slice calculated for coil position of $\theta = 30^o$, coil diameter of 75 mm, and coil current of 150 kA. The calculation times were 6 minutes for magnetic fields and 26 minutes for eddy currents. Figure 1(d) shows current distribution on the surface of the brain. Because the two coil elements induces eddy currents in the same direction under the intersection of the figure-eight coil, the eddy currents converged at this point. Brain surface under the intersection of the coil exhibited high current density values. The maximum current density within the brain was 82 A/m^2, which was comparable to that of ECT. Because the model had a homogeneous magnetic permeability, the magnetic fields were not disturbed by tissues and efficiently induced eddy currents in the brain. Relatively weak currents flowed in the scalp. Because the pain during stimulation is perceived mainly on the scalp, TMS causes weaker pain than ECT. This is one of the main advantages of TMS. The scalp under the coil exhibited the maximum current density 158 A/m^2, which was much smaller compared to the case of ECT. Magnetic field generated by the coil attenuated with an increase of distance from the coil. Eddy current density exhibited higher values on the surface and gradually decreased with depth from the surface. This result was consistent with the previous studies [4,5]. Current densities at the center of the brain was below 10 A/m^2, which was much smaller compared to the case of ECT. Coils with smaller diameters induced more localized eddy currents and exhibited more significant attenuation in deep regions. A certain amount of current flowed in the side of the brain because the two coil elements were positioned in a horizontal orientation.

Because the eddy current $\mathbf{j}_T$ induced by TMS was proportional to the coil current, the performance function defined by (1) exhibited parabolic dependences on the coil current. The maximum value of F decreased with an increase of the coil angle. At larger coil angles, the coil approached to the electrode positions in ECT, and generated currents in the forehead. In our previous calculation, a coil was placed on the vertex ($\theta = 0$), however, the results above suggested that a larger coil angle could give a better result. The coil angle was limited to 60^o in order to avoid interference between the coil and the nose. In the case of $\theta = 60^o$, the performance function had a minimum value of 55 A^2/m^4 at a coil current of 130 kA which corresponded to a magnetic flux density of 2.2 T at the center of each coil element. The coil current giving a minimum value of F decreased with an increase in θ. This was because eddy currents induced in the vertex at small θ values resulted in an increase in the performance function.

The minimum value of F decreased with an increase in the coil diameter. This was because eddy currents induced by larger coils distributed in larger and deeper areas. Thus, the use of larger coils is desired to obtain similar current distributions to ECT. In the case of 100 mm diameter, the performance function had a minimum value of 53 A^2/m^4 at a coil current of 87 kA which corresponded to a magnetic flux density of 1.1 T. In the case of 50 mm diameter, the performance function had a minimum value of 75 A^2/m^4 at a coil current of 257 kA. The coil current corresponding to the minimum value of F is more significantly affected by the coil diameter. Thus, the coil current should be carefully determined for coils with different diameters. The coil current giving a minimum value of F decreased with an increase in the coil diameter. This was because large coils produced higher current densities in the side of the brain.

In this study, stimulus conditions of TMS were optimized based on numerical simulations. In conclusion, a coil position on the forehead and the use of a large coil gave better results. These results provide useful information for choosing stimulus conditions in therapeutic applications of TMS.

ACKNOWLEDGMENT

This study was supported by a Grant-in-Aid for Scientific Research (S) (No. 17100006) from the Japan Society for the Promotion of Science (JSPS).

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