

Finite Element Study of Skin and Fat Delineation in an Obese Subject for Transcranial Direct Current Stimulation

Dennis Q. Truong, Greta Magerowski, Alvaro Pascual-Leone, Miguel Alonso-Alonso, and Marom Bikson

Abstract— Because of pilot data suggesting the efficacy of transcranial Direct Current Stimulation (tDCS) in treating a range of neuropsychiatric disorders as well as in controlling cravings, there is interest to apply to obese subjects. The abnormal thickness of fat that exist in obese subjects may influence current delivery from scalp electrodes to the brain. MRI-derived Finite Element (FE) models of a morbidly obese subject were created with and without fat delineated. The inclusion of fat to the FE model reduced the effective volume of the relatively conductive skin. This led to greater current penetration to the cortical surface. Electric field was substantially greater (60%) in magnitude and a difference in the spatial profile was noted in the model with fat. Additional models testing the effect of varying fat conductivity revealed an inflection in current penetration as fat conductivity is varied. It was postulated that this may be due to a shunting effect both when the shell of fat surrounding the skull is too resistive for penetration and when the fat is so conductive as to lead current around rather than through the head. Precise FE tDCS model of obese patients requires the precise inclusion of fat.

I. INTRODUCTION

Transcranial Direct Current Stimulation (tDCS) has been proposed for many different uses for many different people. Its underlying principal remains the same. Low-intensity electric current is passed non-invasively through the head to induce changes in cortical excitability [1]–[3]. Disorders such as depression and chronic pain have been ameliorated by tDCS in a clinical setting [4], [5]. Studies have suggested the cravings associated with smoking and alcohol can be reduced [6], [7]. There is additional evidence that tDCS reduced the cravings for certain foods [8]. There is thus rationale for exploring tDCS in obese subjects.

However, a specific complication exists in treating obese subjects with tDCS. As a noninvasive technique, current delivery to the brain during tDCS is subject to the conductivities of all tissues that surround the brain. This includes the relatively low conductivity of fat. Electrical penetration into the brain – current flow through the skin, fat,

and skull – may thus be an issue. Finite Element (FE) models are standard tools to predict brain current flow during electrical stimulation (“forward” model) but must be parameterized accurately.

Magnetic Resonance Imaging (MRI) derived FE models have been utilized in the past to predict the flow of current in the brain [9], [10]. An individualized patient specific model has also been created in the case of stroke [11]. The effect of fat in a normal head has been modeled [10], [12]. In particular, one of these papers found profound differences in the current density of skin and skull with the addition of fat [12]. The cortical current density was altered as well, but to a lesser extent (Relative Difference Measured: 5.0 %). This, however, was modeled in a normal head.

The efficacy of tDCS has been demonstrated in a range of individuals [4]–[8], but efficacy in an obese individual remains unknown. This modeling study is intended to serve as a preliminary analysis that will lead to an optimized FE model of obese heads undergoing tDCS. In the future this model can be applied to optimize tDCS electrode montage to deliver current to specific brain targets, such as those associated with appetite suppression.

II. METHODS

Anatomical MRI scans were produced from a 3T Philips Achieva scanner for a thirty-five year old female with a Body Mass Index (BMI) of 53.5. The MRI scans were T1 weighted using an MP-RAGE (magnetization-prepared rapid acquisition with gradient echo) sequence, which produced high resolution scans with a spatial resolution of 1x1x1.2mm. From this data, tissues of interest were segmented. Large 5x7 cm sponge pads and electrodes were modeled and added to the segmentation, the segmentation was meshed, and the mesh was solved.

A. Segmentation and Mesh Generation

There were 7 tissues of interest to be segmented from the MRI scan: skin, fat, bone, cerebral spinal fluid (CSF), gray matter, white matter, and air. This was initially accomplished using an automated segmentation algorithm contained in Statistical Parametric Mapping (SPM8) software. Additional post-processing was applied via an in-house algorithm programmed in MATLAB (2010b, The MathWorks, MA) to correct for errors in continuity. Additional detail, however, remained to be segmented. The gyri and sulci needed to be resolved in greater detail, and fat was not included at all in

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D.Q. Truong and M. Bikson are with the Department of Biomedical Engineering, The City College of the City University of New York, New York, NY 10031 USA (phone: 212-650-8876; fax: 212-650-6727; e-mail: dtruong01@ccny.cuny.edu).

G. Magerowski is with the Center for the Study of Nutrition Medicine and Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA 02215 USA. (e-mail: gmagerow@bidmc.harvard.edu).

A. Pascual-Leone and M. Alonso-Alonso are with the Berenson-Allen Center for Noninvasive Brain Stimulation and the Division of Cognitive Neurology, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA 02215 USA (e-mail: malonso@bidmc.harvard.edu).

the automated segmentation algorithms. Additional manual segmentation of the brain was necessary to complete the model. This was accomplished using ScanIP+FE (SIMPLEWARE LTD., UK). An initial segmentation of fat was generated through use of a thresholding flood fill algorithm. The segmentation data, which was originally sampled like the MRI scan at 1x1x1.2mm per voxel, was resampled to 1x1x1mm per voxel and smoothed. Additional close filters were applied to repair rough patches of fat at the base of head and neck.

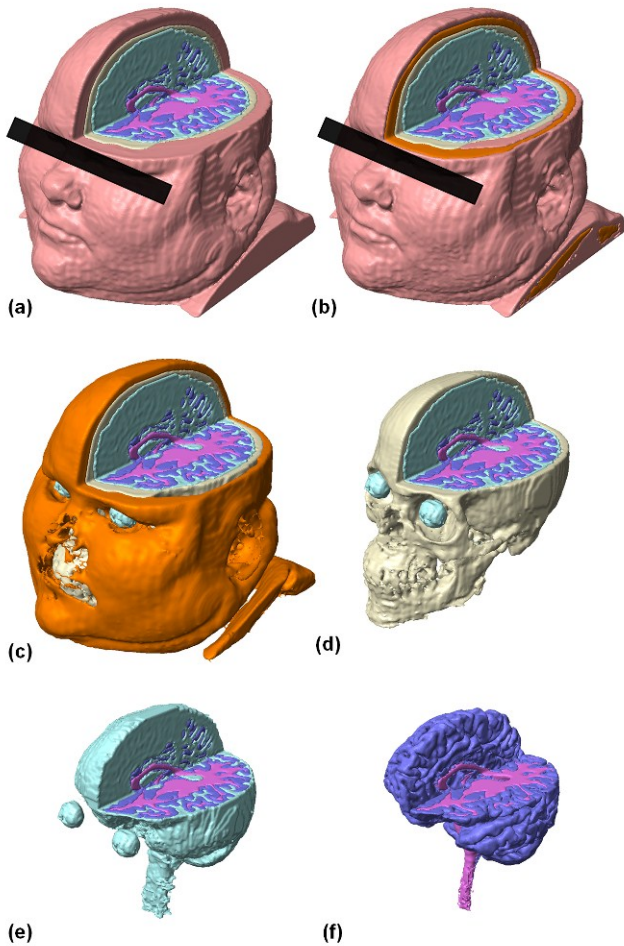


Figure 1: The segmentation of homogenous skin and heterogeneous skin are contrasted in (a) and (b). A quarter of the model was cut away for visualization purposes only. Images of the fat, skull, CSF, and gray matter segmentation are shown in (c-f) respectively.

Large 5x7 sponge pads and electrodes were created in a computer aided design (CAD) program (SOLIDWORKS, DS SolidWorks, MA). A rectangle with a slight curve was sketched to approximate the cross-sectional dimensions of a sponge pad roughly 10mm thick. This slight curvature was drawn to reflect the curvature of the scalp at the placement site. Another curve was sketched in an orthogonal plane along which the cross-sectional profile of the pad was swept. This process was repeated for the corresponding electrode and was repeated for a second set of pads and electrodes with curvatures that matched the second placement site.

The pad and electrode pairs were then imported into ScanCAD (SIMPLEWARE LTD., UK) alongside the segmentation model as a Standard Tessellation Language (STL) file. The pads were then placed according to a possible montage, F8 active with the return over the contralateral supraorbital [13]. Once these CAD models were in place, the models were converted to segmentation masks and exported back into ScanIP+FE for meshing.

An adaptive tetrahedral meshing algorithm within ScanIP+FE was used to mesh the models. The initial model with fat segmented had 7 tissue masks in addition to the electrodes and pads. This model meshed at approximately 11 million quadratic elements with about 15 million degrees of freedom. The second model with the fat mask merged into the skin managed to mesh at approximately 6 million quadratic elements and about 8 million degrees of freedom.

B. Finite Element Model

A FE model based on electrostatic volume conductor physics was created in COMSOL Multiphysics 3.5a (COMSOL, Inc., MA). Each mesh was imported into this FE solver and isotropic conductivities (in S/m) were assigned as follows: skin: 0.465, fat: 0.025, skull: 0.01, csf: 1.65, gray matter: 0.276, white matter: 0.126, air: 1e-15, sponge pad: 1.4, gel: 0.3, electrode: 5.99e7 [9]–[12], [14]. Additional models were run using a range of conductivities for fat. These values (in S/m) are 0.0125, 0.07, 0.125, and 0.250.

Boundary conditions were applied as electrically insulated to all exterior boundaries and continuous to all interior boundaries. The exterior boundaries of the electrodes were altered to be 1A/m² of inward current injection for the active electrode and ground (V=0) for the return electrode. For the active electrode, 1A/m² corresponded to an inward current injection of about 4.38mA in the homogeneous skin model and 4.43mA in the heterogeneous skin (skin and fat) model. The model was then solved to a relative tolerance of 1e-6.

After solving, boundary plots of the cortical surface (gray matter) were plotted with a false color map and scaled to a visible range. This scale was then normalized to be per 1 mA of current injection. Additional lighting was used in some images to better visualize brain morphology and the spatial distribution of electric field.

III. RESULTS & DISCUSSION

Fat represented a large proportion of what would normally be modeled as skin. As seen in Fig. 1 (a-c), the addition of fat thins the skin greatly – to just a few millimeters in some areas such as the forehead. The other tissue masks were segmented in the same manner as a non-obese head. This generated fairly typical looking skull, CSF, gray matter, and white matter tissue mask as seen in Fig. 1 (d-f).

The results of the homogeneous skin condition were contrasted to the heterogeneous skin condition. In Fig. 2 (A.1-A.3), peak electric field is plotted on the same scale. An

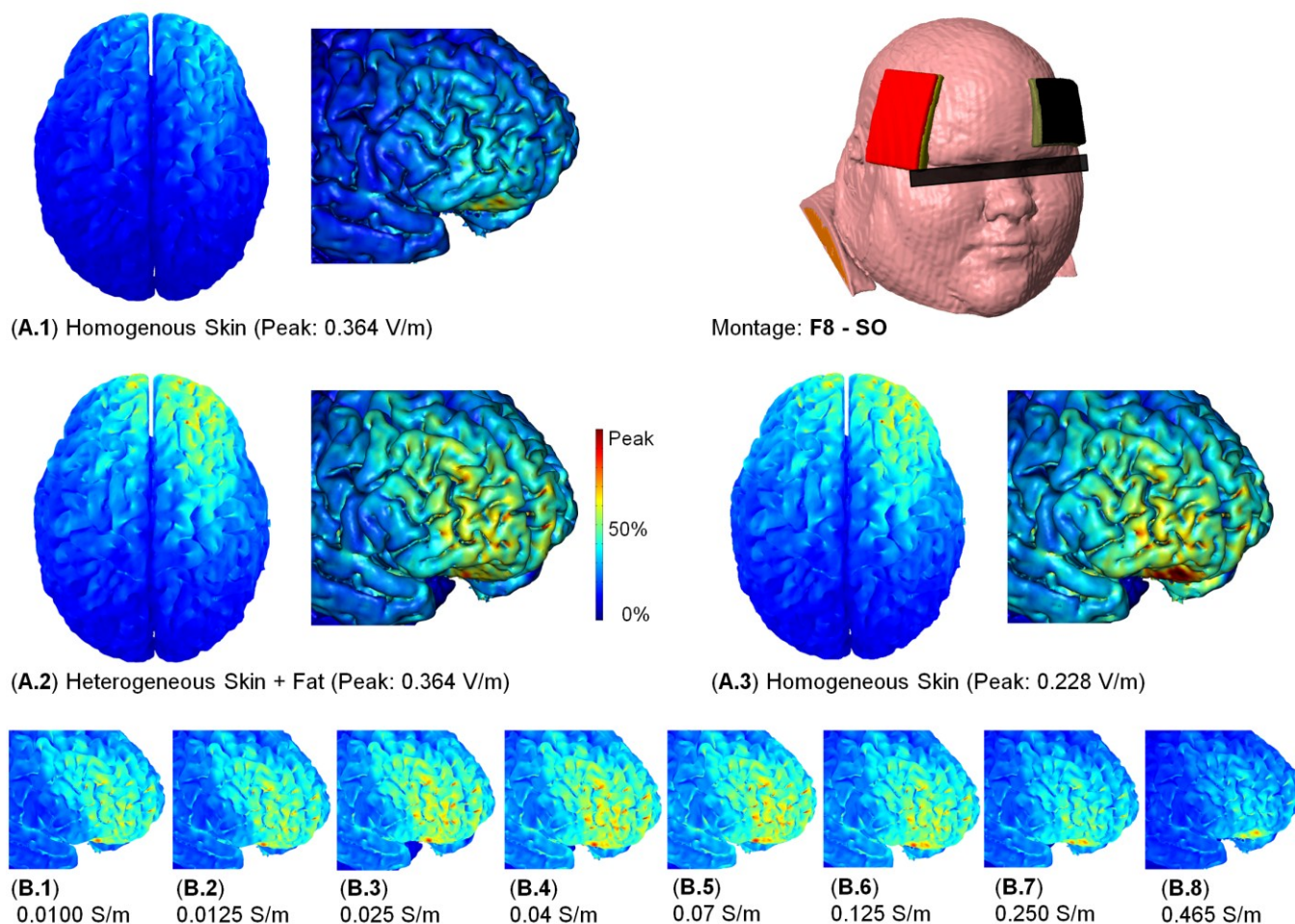


Figure 2: Predicted Electric field on the cortical surface due to F8 - SO stimulation via 5"x7" pads. The simulated montage appears at the top right. Two conditions, homogenous skin (A.1) and heterogeneous skin (A.2), are contrasted on the same scale of 0.364 V/m per mA maximum. The homogeneous skin condition is re-plotted (A.3) at a lowered scale of 0.228 V/m per mA maximum to better compare the spatial distribution to the heterogeneous condition (A.2). The effect due to a range of varying fat conductivities (B.1 - B.8) is compared on a fixed scale of 0.364 V/m per mA maximum. The values tested range from the conductivity of skull (B.1), to the nominal value for fat (B.3), to the conductivity of homogenous skin (B.8).

apparent difference can be seen between the two conditions. The inclusion of fat leads to greater electric field peaks than in the model without fat. The scale for Fig. 2 (A.3) is adjusted to show electric field peaks in the homogenous condition. While the locations of the peaks are similar, the magnitudes differ greatly. The maximum peaks plotted in the heterogeneous condition are at 0.36 V/m per mA, while the maximum peaks in the homogeneous condition are only 0.23 V/m per mA. This is an increase of close to 60%. Significant shifts in spatial targeting are also apparent, including electric field peaks in the medial orbitofrontal cortex (OFC).

In Fig. 2 (B.1-B.8) the results of the cortical electric field due to varying fat conductivity are displayed from left to right in order of increasing fat conductivity. A surprising trend is seen in which cortical electric field intensity increases from (B.1) to (B.3) before the intensity again diminishes in (B.8). Coincidentally, the most commonly used value for fat conductivity (0.025 S/m; as reported in literature) may be near the optimal range for current

penetration in this particular model. A possible explanation for this inflection in cortical electric field intensity may be a shunting effect through the skin. At the low extreme in (B.1), the shell of fat that surrounds the skull is too resistive for much current to penetrate into the brain. As the conductivity is increased there is an "optimum" at which current can pass into the brain. But if the conductivity is increased further as in (B.8), current again shunts around the skull.

This concept of current shunting through soft tissue can be used to explain the results in parts (A.1-A.3). The increased current penetration in the heterogeneous model could be explained by a reduction in skin volume. In the homogeneous model, more current may shunt through the scalp instead of penetrating the more resistive skull. The soft tissue commonly modeled with the conductivity of skin is essentially wedged between the surrounding air and the skull – both of which are extremely low in conductivity. Skin is relatively conductive compared to skull, air, and fat. It is modeled with a value of 0.465 S/m in contrast to 0.01, 1e-15, and 0.025 S/m for skull, air, and fat respectively. Replacing

much of the skin for fat may lead to a dramatic reduction in the conduction through the skin. Indeed, this concept of a “preferential pathway” through skin was postulated by Shahid [12] after a similar effect was observed in a normal head model with fat. The effect, however, appears to be magnified in an obese model in which the inclusion of fat leads to an increase of nearly 60% in peak electric field. From these results, fat should not be neglected and should be precisely parameterized in an accurate model of an obese head.

IV. CONCLUSION

This modeling study provides the first indication of current flow through the head of an obese subject during tDCS and considers general modeling methodology for such cases. As with any modeling effort, additional details (e.g. muscle mask, DTI) can be further considered, but our results indicate that precise consideration of fat anatomy and properties is essential for accurate predictions.

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