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Correlation between Live and Post Mortem Skull Conductivity Measurements

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***Abstract*— The skull is a tissue with a widely controversial range of conductivity values. This article correlates live skull conductivity measurements with post mortem conductivity measurements with a scaling factor ranging between 2.5 and 4. The scaling factor is validated by a mathematical model that determines the skull conductivity using saline and CSF conductivities and correlated with published physical live and post mortem skull conductivity measurements which show support for this live-to-post mortem scale factor.**

I. INTRODUCTION

Analyzing and estimating neuroelectric sources from electroencephalograms (EEGs) is an area of interest in the field of neurology. Modeling the head as a volume conductor is a common approach to study these source potentials, solving either the forward or inverse problem. These models critically rely upon the accuracy of the head tissue conductivities as well as the model geometries. Using the correct conductivities and dimensions enables the model to more accurately locate internal electrical sources and to more correctly model current densities, lead fields, and sensitivity distributions. When inaccurate tissue conductivities or model dimensions are used, the results contain error. Lead field distortions and localization errors influence researchers to draw incorrect conclusions. The literature on head tissue conductivities is quite limited in experimental findings but shows that several studies repeatedly refer to the same data [1].

The cornerstone model by Rush and Driscoll [2] established head conductivity values that are still used in models over three decades later. They used a brain-to-skull conductivity ratio $\sigma_{Br} : \sigma_{Sk}$ of 80:1 and defined the conductivity of the scalp σ_{Sc} equal to the brain σ_{Br}. As a result of a wide range of conductivity values in the literature, the following sections review, analyze, and discuss appropriate conductivity values for the skull conductivity and brain-to-skull conductivity ratio. In order to propose revised values, a way of assessing live tissue versus post mortem tissue measurements versus numerically estimated conductivities is addressed.

The key to selecting an appropriate skull conductivity is evaluating the experimental setup of reported measurement results. Without assessing the significance of the corresponding measurement procedures, undue weight would be given to several post mortem tissue samples. In the early 1980s, research by Kosterich et al. [3], [4] determined that bone conductivity is primarily dependent on the conductivity of the fluid perfusing the bone tissue, supporting the hypothesis of Rush and Driscoll [2]. Their research comparing the effect of natural cellular fluids against saline solutions perfusing bone tissue has been overlooked [3]. Furthermore, their research was performed on rat femurs within 90 minutes after the animal was sacrificed, then again within 50 hours post mortem, and once more one week post mortem. Their findings report that bone conductivity decreases by a factor of 2.5 to 3 in the DC conductivity range over the live-to-50 hour post mortem time and no change between 50 hours and the one week post mortem measurements. There should only be insignificant changes in the specimen because the living cellular components would have died and the natural fluids washed away prior to the 50 hour measurements with no significant change after the tissue fixation. Consequently, this overlooked factor is crucial to evaluating live tissue samples with natural fluids against moistened and saline immersed post mortem samples.

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II. METHODS

A simple mathematical model used along with the live-to-post mortem conductivity ratio further supports the live conductivity measurements. The formula introduced by Rush and Driscoll [2] and verified by Kosterich et al. [4]

$$\sigma_{Sk} = \sigma_{fluid}/80 \tag{1}$$

states that the skull conductivity σ_{Sk} is dependent on the fluid permeating the skull σ_{fluid}. Since the model by Rush and Driscoll [2] was based on a post mortem skull sample, (2) scales the post mortem skull conductivity value $\sigma_{Sk_{PM}}$ with the live-to-post mortem conductivity factor f to approximate a living skull sample conductivity value $\sigma_{Sk_{Live}}$.

$$\sigma_{Sk_{Live}} = f \times \sigma_{Sk_{PM}} \tag{2}$$

III. RESULTS

Applying the commonly modeled saline and cerebrospinal fluid (CSF) conductivity values 1.3 S/m [5], [6] and 1.79 S/m [1], respectively, to (1) yielded the unadjusted skull conductivities of 0.016 S/m and 0.022 S/m, respectively. The values of 2.5 and 3 were used for the live-to-post mortem conductivity factor f [3], and then inserted into (2) with the values from (1) to produce the lower and higher live-adjusted skull conductivity values. The saline-live-adjusted skull conductivities ranged from 0.041 S/m to 0.049 S/m,

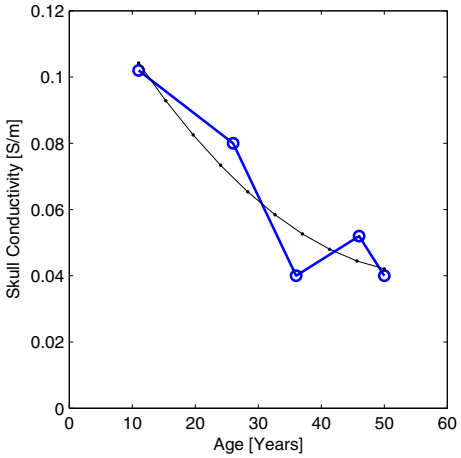


Fig. 1. Reported conductivity values of live skull samples temporarily removed during epileptic surgery plotted against patient age. The blue trend with circles graphs raw data, and the gray trend with dots graphs the least squares fit [7].

whereas, the CSF-live-adjusted skull conductivities ranged from 0.056 S/m to 0.067 S/m.

Introducing results from living skull fragments by Hoekema et al. [7] enables graphical comparisons testing our live-to-post mortem scaling factor. Using their results, we defined the average adult skull conductivity as 0.053 S/m by averaging tissue samples from patients aged 26 to 50 years old. Including the tissue sample of the eleven year old increased the average skull conductivity from 0.053 S/m to 0.063 S/m (Fig. 1). Their measurements came from skull fragments temporarily removed during epileptic surgery. Using the average adult-live skull conductivity measurement and the all-ages-averaged live skull conductivity measurement, these live measurements are plotted against commonly reported brain conductivities [2], [6], [8], [9], [10], to depict plausible brain-to-skull conductivity ratios (Fig. 2). Additionally, Fig. 2(a) includes both the scaled live-modeled trends and unscaled post mortem trends according to (1) and (2), while Fig. 2(b) tests the scale factor on published post mortem results against the live measurements.

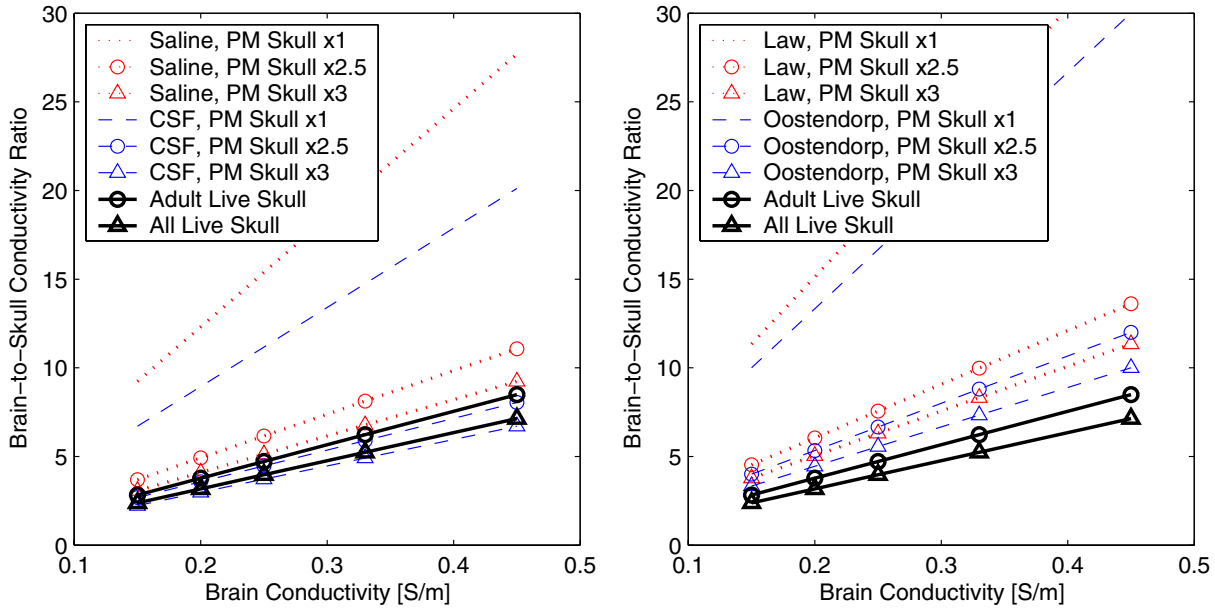
IV. DISCUSSION

The live-to-post mortem conductivity scaling factor f closely correlates modeled data with live physical skull conductivity measurements. The modeled skull conductivity value using the CSF scaled by 2.5 (0.056 S/m) nearly matches the skull conductivity value of the adult live skull tissue, using 0.053 S/m as the average live skull conductivity; therefore, the CSF-calculated skull conductivity scaled by 2.5 nearly reflects the average adult-live trend in Fig. 2(a). Also, the CSF-modeled skull conductivity scaled by a factor of 3 (0.067 S/m) closely resembles the all-ages-averaged live trend. These nearly correlated trends lend support to the live-to-post mortem scaling factor according to the mathematical model based upon natural skull-perfusing fluids; however, the live-to-post mortem scaling factor falls short of scaling the saline-modeled skull conductivity to the average adult-live skull conductivity. A more appropriate scaling factor for converting a saline model into a live CSF model would require a slightly higher factor in the range of 3 to 4, which estimates 0.049 S/m and 0.065 S/m respectively. It makes sense that a higher scaling factor is required when converting a lower conducting saline-solution-based model to an approximated realistically live skull conductivity.

In order to validate a mathematical model, the live-to-post mortem scaling factor should be weighed against physical measurements. Comparing the live measurements of Hoekema et al. [7] with the post mortem skull sample of Oostendorp et. al [6] yields a ratio average of slightly over 3, and Law [11] yields a ratio range of 4 ± 1.8 based on the overall skull average, thus supporting the need for a live-to-post mortem scale factor (Fig. 2(b)); however, the ratio range of 3 to 4 more appropriately fits the conversion of these saline-immersed post mortem skull conductivity values. The skull sample measured by Oostendorp et al. [6] was a frozen post mortem skull rewarmed to body temperature performed in a saline environment rather than in natural CSF. Measurements of the frozen and thawed tibia by Saha and Williams [12] are even lower because they were performed in a 100% humidity chamber without fluid perfusion at 27 °C. Measuring the specimens ten degrees below natural body temperature lowers the resultant conductivity values due to a decrease in diffusion and ionic motion [1]. By more accurately categorizing and assessing the physical experimental setup of previously measured post mortem samples, we can better utilize post mortem tissue findings to apply towards living tissue sample conductivities.

The live-to-post mortem scaling factor appears to be a plausible way to convert fluid perfused post mortem conductivities into the conductivity range of the state of living tissue. The results from the mathematical models supported the physical experimental scaled results. Taking the ratio of CSF to saline solution yielded a ratio of 1.4. Since the CSF-live-adjusted-adult scaling factor nearly approximated 2.5 when scaling a CSF solution into a CSF-based-skull conductivity, we scaled the ratio of 2.5 by 1.4 yielding 3.5 to compare it against the saline-converted-post mortem physcial measurements. It is evident that the results of the mathematical models support the scaled physical setups of the 100% fluid perfusion experiments at natural body temperature.

Finally, it is relevant to address electrical impedance tomography (EIT) estimated conductivities that support post mortem findings. EIT estimates the skull conductivity by solving the inverse problem, which has an un-unique solution. Oostendorp et al. [6] supports their physical post mortem skull conductivity measurements by a volume conductor that fixes the scalp conductivity equivalent to the brain conductivity. Other groups, Lai et al. [13] and Clerc et al. [14], also recently fixed the scalp to the same brain conductivity, whereas, Ferree et al. [15] cited brain to scalp conductivity ratios slightly less than two in their models. Furthermore, Lai et al. [13] derived their brain-to-skull con-



(a) Mathematical model vs. Live measurements

(b) Post Mortem vs. Live measurements

Fig. 2. Brain-to-skull conductivity ratios plotted against common brain conductivities. All of the red dotted and blue dashed trend lines in (a) and (b) identify the post mortem (PM) skull conductivity trends by a factor of 1 and scale the PM skull conductivity to the live-adjusted conductivity by 2.5 (circles) and 3 (triangles). The black trends with circles in (a) and (b) use the average adult live skull conductivity 0.053 S/m [7], and the black trends with triangles in (a) and (b) use all-ages-averaged live skull conductivity 0.063 S/m [7]. (a) The red dotted trends represent the conductivity ratio using the conductivity of saline solution, 1.3 S/m, in (1) and (2). The blue dashed trends in (a) use the CSF conductivity, 1.79 S/m. (b) The red dotted trends use the average skull conductivity 0.013 S/m reported by Law [11], and the blue dashed trends in (b) use the average skull conductivity 0.015 S/m reported by Oostendorp et al. [6].

ductivity ratios correlating pediatric scalp recordings from patients aged 8 to 12 years old using an adult sized volume conductor. Considering these discrepancies, it is plausible that solutions to the un-unique inverse problem correlated to the measured post mortem tissue findings.

V. CONCLUSION

After evaluating live and post mortem skull conductivity data along with a supporting mathematical model of the skull conductivity, a recommendation of 0.053 S/m for the skull conductivity reflects this discussion. This report proposed and evaluated a live-to-post mortem scaling factor that depends on fluid conductivity, percent of fluid perfusion, and temperature of the post mortem conductivity measurements. Finally, the brain-to-skull conductivity ratio is in the vicinity of 5, not 80 as reported by Rush and Driscoll [2](Fig. 2); however, the brain-to-skull conductivity ratio ranging from 5 to 10 should be investigated. Focusing subsequent investigations on a slightly broader range will possibly accommodate for variations in skull thickness and perhaps the higher conducting diploe encased between possibly lower conducting bone material. A three layer bone model would better represent the skull by including the porous diploe that possibly has a higher conductivity since more higher-conducting fluid plausibly perfuses this region than the denser outer and inner skull surfaces [16]; however, only isotropic homogeneous skull conductivities have been published to date.

Furthermore, this report concludes that there is a further need for live tissue measurements to confirm a live-to-post mortem scale factor correlating measurement types. The subject's age needs to be recorded along with the conductivity measurements to validate the decrease in skull conductivity with age [7], [17]. Also, the skull measurement recording locations should be included to address decreases in conductivity near sutures [11] and conductivity variations due to localized skull thickness variations [11], [16].

Suggesting a brain-to-skull conductivity ratio ranging from 5 to 10 impacts forward and inverse EEG problems. This conclusion implies that the spatial resolution of the EEG half sensitivity volume (HSV) is much smaller than the magnetoencephalogram (MEG) HSV as calculated by Malmivuo and Suihko [18].

VI. ACKNOWLEDGMENTS

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