Measurement of the conductivity of the skull, temporarily removed during epilepsy surgery

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Introduction

For EEG source localization of brain activity, exact knowledge of the conductivity of the skull is essential, because it is low as compared to the other conductivities in the head. Simulation studies have shown that the depth of a source as determined while assuming a wrong skull conductivity may differ from its actual position by up to two centimeters[1]. A conductivity ratio between skin, skull, and brain of 1:1/80:1 is usually used, where the skull conductivity is 0.0048 S/m. This value has been reported by Rush and Driscoll in 1968[2] and has been questioned recently[3]. In that paper, the conductivity of *post mortem* skull material was measured and, additionally, an estimate was made based on a whole-head electrical impedance tomography (EIT) type of measurements.

All data on human skull conductivity currently available is either based on *post mortem* material or on indirect EIT measurements. The drawback of using the first approach is that the bone is not in its natural condition. EIT measurements are performed *in vivo*, but accurate knowledge of skull geometry is needed, since in a model skull thickness and conductivity are interchangeable to some extent (although this may not be a problem if the identical model is used in the inverse problem[4]).

During epilepsy surgery, a part of the skull is removed to gain access to the brain. This provides a unique opportunity to directly measure the skull conductivity, *in vitro*, but on a fresh skull part at body temperature, still saturated with its natural contents. We present a method to estimate the conductivity of this skull part, using an electrical impedance tomography approach.

Methods

A freshly removed skull part was placed in a specially constructed measurement device, consisting of two matrices of 4 × 4 electrodes, placed on either side of the skull part (figure 1). The electrodes were 1 cm apart. The measurement set-up was placed in an incubator, that was set at 37° C and at a relative humidity of 95%, to prevent the skull part from cooling and drying. A 1 μA 10 Hz current was sent through two electrodes and the resulting potentials on all other electrodes was measured. Thus, an extended four point measurement was made . Twenty-eight symmetrical current electrode pairs, with an inter-electrode distance of 3 cm or more, were used sequentially. In the postprocessing the measured data was bandpass filtered around 10 Hz using FFT.

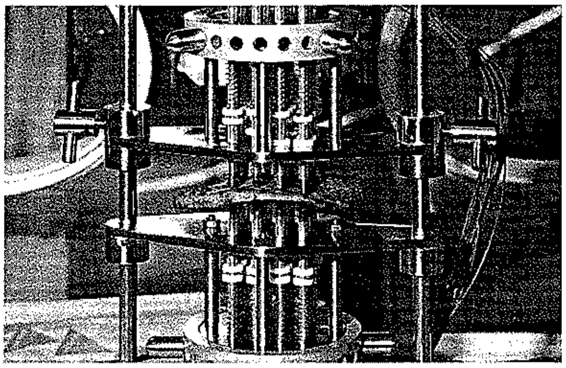

Figure 1: The measurement set-up.

At the end of the measurement the electrodes were fixed in a vertical direction, thus obtaining the skull profile. A sterile pencil was used to mark some electrode positions at which small holes were subsequently drilled. The skull part was replaced in the patient at the end of the surgical procedure. A low-dose CT of the patient's head was made a few days after surgery. From this CT, the geometry of the skull part was reconstructed (figure 2). A finite difference model (FDM) was constructed, using the geometry of the skull part and the electrode locations (figure 3).

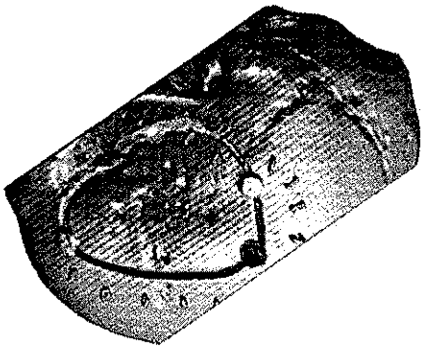

Figure 2: The geometry as reconstructed from the CT.

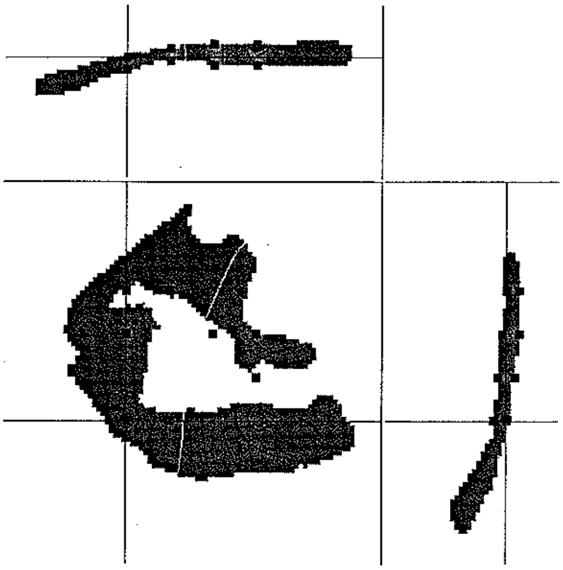

Figure 3: The finite difference model.

The model contained typically 96 × 80 × 48 vertices. The potential distribution in the model, due to the current injected in the skull part, was computed using a multigrid method. Thus, the measurement was mimicked, and the skull conductivity value was estimated by tuning the conductivity values in the model in such a way, that the computed potential distribution matched the measured potentials. In the model, a different conductivity value can be assigned to dense and trabecular bone (the geometry of each can be determined from the CT images), but in this study a homogeneous skull conductivity was assumed.

A total of two phantoms and five patients were included in this study. The first phantom, an disk-shaped agar-agar jelly, was measured using the described set-up and by using a straightforward four-point method. The second phantom was a *post-mortem* skull piece, soaked in saline and formaline. On all five patients epilepsy surgery on the temporal lobe was performed. The temporarily removed skull parts were similar. The age of the patients ranged from 11 to 50.

Results

In figure 4, on the left, the upper 16 electrode locations as extracted from the set-up (circles) and from the CT (crosses) are shown. On the right the upper and lower 16 locations from the set-up (circles) and as implemented in the FDM model (crosses) are shown. The average difference was 0.5 mm.

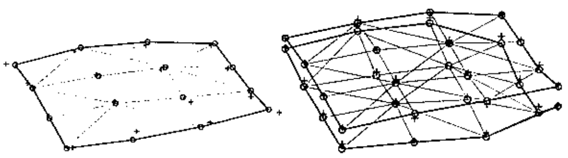

Figure 4: Measured electrode geometry.

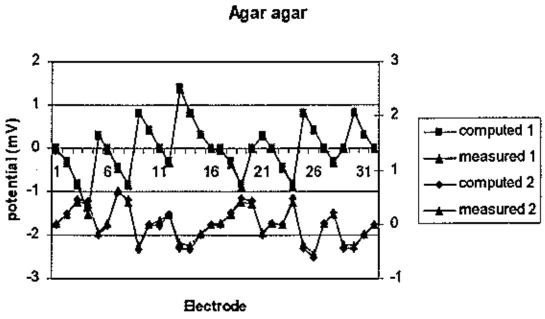

Figure 5: Result for the agar-agar phantom.

In figure 5 the results for the agar-agar phantom using the measurement set-up are given. Shown are, for two different pairs of current injecting electrodes, the measured and computed potentials in all electrodes. The fitted conductivity value was 0.040 S/m. The same value was found using the four point method.

Potential measurements and simulations for one pair of current injecting electrodes for the *post-mortem skull* are shown in figure 6. The conductivity value fitted was 0.040 S/m. Figure 7 shows the results for patient#1 (0.102 S/m). All results are summarized in table 1.

Discussion

The results for the agar-agar phantom show that the EIT approach using a finite difference model with realistic geometry leads to a conductivity value that is identical to the one obtained using the four point method. Moreover, the potential profile, as simulated in the model, is almost identical

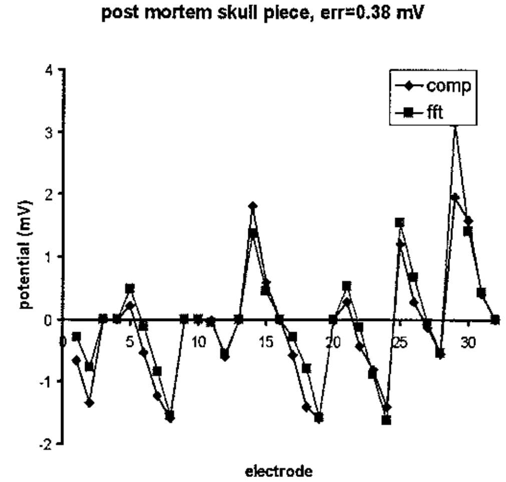

Figure 6: Results for the post-mortem skull phantom.

Table 1. Summary of results

measurement	age	cond.(S/m)
agar - agar	–	0.040
post mortem	–	0.026
patient 1	11	0.102
patient 2	26	0.080
patient 3	36	0.040
patient 4	46	0.052
patient 5	50	0.040

to the measured one (figure 5). This gives confidence that the modeling of the physics is accurate. Of course, the geometry for this cylindrically shaped phantom is relatively simple, but as is shown in figure 4 the geometry information that is extracted from a real skull piece is accurate, and for this more complex shape potential patterns as simulated in the model are very simular to the ones measured (figures 6 and 7). The conductivity value found for the *post-mortem* skull piece (0.026 S/m) is twice as high as the one reported in [3] (0.013 S/m). The fact that the skull is soaked in saline and formaline can explain this.

The realization that measurement of *in vitro post-mortem* skull will not lead to accurate measurement of the conductivity, because the skull is not in its natural state, led us to the *semi in-vivo* approach of measuring bone temporarily removed during epilepsy surgery. In a carefully chosen procedure, in which sterility, a stable temperature and relative humidity were assured, we measured skull conductivities that are about10 times higher than those reported by others (table 1). We found that conductivity was even higher for the younger patients.

It may be that saline, applied during the opening of the skull for cooling purposes, may have left a thin conductive layer on the skull piece. In the homogeneous geometrically realistic model, however, the measured and simulated potential patterns were very similar. This suggests that if this layer exists, it must be present completely around the piece. The presence and effect of such a layer should be studied in a more controlled situation. This will be the subject of further study. A non-homogeous model, with different conductivity values for dense and trabecular bone, will then be tested as well.

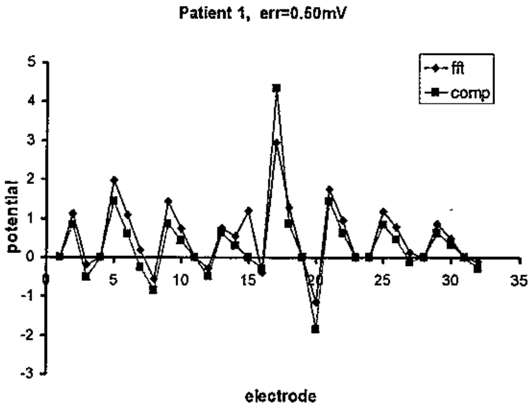

Figure 7: Results for patient #1.

Acknowledgements

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