Personalised Electrical Brain Imaging (PEBI)

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ABSTRACT

The European needs for home-based brain monitoring due to neurodegenerative diseases and cognitive dysfunctions require development of reliable, low-cost, portable imaging devices. The standard is to use electroencephalography (EEG) scalp recordings with generic software to localise brain activity. However, these software lack accuracy because they utilise standardised tissue values (instead of patient-specific ones). In this project, we used Electrical Impedance Tomography (EIT) to recover high-resolution tissue maps. We found that the developed EIT-EEG software substantially reduced the localisation errors. In Phase 2, our focus will be to design a stand-alone prototype EIT-EEG device that benefits from wearable and 3D printing technology.

Keywords: Electrical impedance tomography; electroencephalography; brain imaging; personalised medicine; neuroscience

1. INTRODUCTION

EEG is the primary technology to study the brain and monitor different brain dysfunctions in real-time [10]. Portable and low-cost EEG equipment can have significant societal and economic benefits since they allow remote supervision by the clinicians and self-administration (possibly assisted by a nurse) of a treatment at home avoiding hospitalisation. Even though the rapid progress in high-tech electronics has enabled wearable and compact EEG devices [1], the accompanied generic software do not fulfil the requirements for accurate EEG Source Imaging. The way to unlock the secrets of the brain (i.e. to determine the electric brain activity) is to build a model that connects the underlying brain activity with the EEG recordings. Because standard models have been shown to be unreliable [9, 12] and can result in misleading interpretations or diagnosis, personalised modelling is of high importance. Here, personalisation means constructing a model that includes the electrical tissue conductivities and the geometry of the person's head who undertakes the EEG measurements. Underestimation or overestimation of the tissue conductivities can have a detrimental effect on identifying accurately the brain activity. Especially the skull is of primary concern since it acts as an insulating barrier between the recordings and neuronal activity [9].

The breakthrough character of this project is to bridge the gap between the new high-end neuro-monitoring devices and highly sophisticated device-embedded software that allow the design of patient-tailored protocols for precise (focal) high spatial resolution imaging of the brain activity. To achieve this aim, we have embedded an in-line estimation procedure of the tissue conductivities via Electrical Impedance Tomography (EIT) in the EEG Source Imaging software. EIT is a type of non-invasive medical imaging that, in principal, can be used to infer electric conductivities of tissues by injecting small currents through scalp electrodes and recording the resulting voltages [5]. So far, the EIT studies of the human head have been rather limited: only few (4 or less) tissue conductivity values have been reconstructed, and their impact on mitigating EEG localization errors remains unexplored [2, 4]. The bottleneck to reach higher resolutions has been the lack of appropriate EIT imaging software.

In this project, we developed an EIT-EEG imaging software that first constructs a high-resolution conductivity map of the head, particularly the skull, and then includes this information in the EEG Source Imaging software. Our state-of-the-art algorithms can recover scalp conductivity and a detailed locally varying skull conductivity map of the head which significantly improve the accuracy of the EEG source imaging estimates when compared to previously used conductivity resolutions.

2. STATE OF THE ART

Typically, EEG Source Imaging software does not take into account individual variations in the conductivity values of tissues. Instead, bulk conductivity values from literature are used in the head models. Unfortunately, the tissue conductivities vary significantly depending on which literature is used [7], and in addition, for example the skull conductivity also has great variations within the

same subject [6]. The importance of skull conductivity and modelling for accurate EEG results is well known [9, 7].

Even though, the potential of EIT to provide personalised scalp and skull conductivities has been emphasised in literature [8], and it may seemingly appear that EIT can be easily embedded to an EEG device, since they partly share similar electronics, the reason why EIT hasn't really been properly used for this purpose so-far is its innate difficulties as a tomographic method i.e. non-linearity and sensitivity to modelling errors. So far, the EIT studies of the human head are rather limited to only very few (4 or less) tissue conductivity values while their impact on mitigating EEG localisation errors remains unexplored [2, 4].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In this project, we developed a software to estimate a high-resolution conductivity map of a patient's skull by utilising EIT measurements. This was established by dividing the skull in small pieces and treating each piece as an unknown in the resulting non-linear system which was solved by using convex optimization. For comparison, previous EIT studies typically recover only one (bulk) conductivity value for the whole skull, while we managed to recover 8860 spatially varying conductivity values across the skull. Subsequently, we combined the EIT solution with the EEG imaging software and demonstrated how this personalised conductivity map improved the EEG Source Imaging results. In the future, we envision that EIT will become an integral part of EEG devices used not only for neuroimaging but also for personal health tracking, brain-computer-interfaces and brain-to-brain communication.

4. PROJECT RESULTS

4.1 EIT conductivity imaging

Our main result is the EIT-EEG software pipeline that allows estimation of personalised conductivities and their use in EEG source reconstructions. To test the pipeline, we built a 3D head model by adapting a geometry from [15] and assigning tissue conductivities. Our test head consisted of scalp, skull, cerebro-spinal-fluid (CSF) and brain. The 'true' skull conductivity map was set-up based on conductivity values measured from 20 bone samples that were removed from a *post mortem* skull [6], and the remaining tissues had the following conductivities: 0.43 S/m, 1.79 S/m and 0.33 S/m for scalp, CSF and brain, respectively [3,11]. The 'true' skull conductivity map is visualised in Fig. 1 (top row). The EIT measurements were simulated by using Finite Element Method [16] and a set of 32 electrodes around the scalp. 5% of random white noise was added in the measurements.

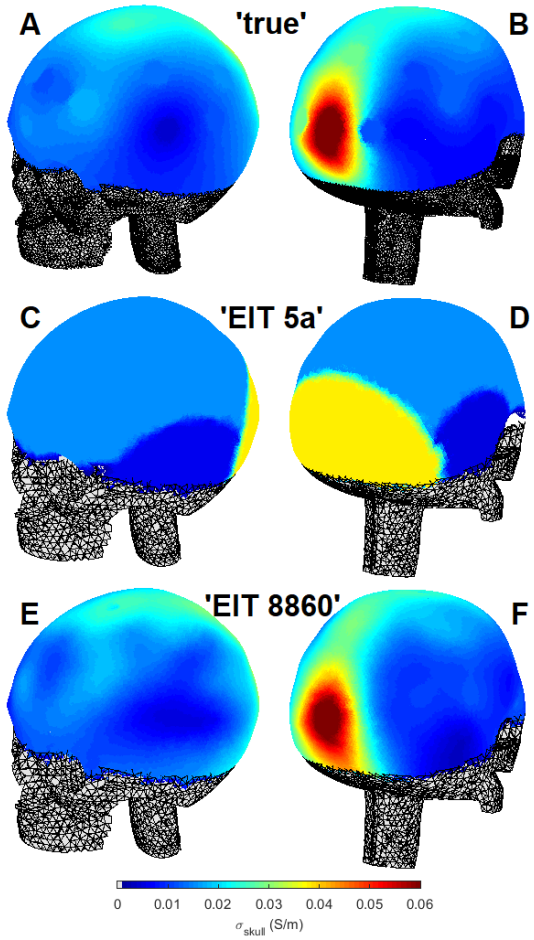


Fig. 1. *A and B: The 'true' skull conductivity distribution that was used in the test case. C and D: The reconstructed skull conductivities for the 5 anatomically defined skull bones. E and F: The reconstructed high-resolution skull conductivity map for 8860 skull segments.*

For comparison, we first used the pipeline to reconstruct only one bulk conductivity value for the scalp and skull, resulting in 0.383 S/m and 0.016 S/m, respectively. It is worth noting that this bulk skull conductivity value is close to the average of the skull conductivity map, and scalp conductivity is lower than the 'true' value (0.43 S/m). Subsequently, we refined the model and reconstructed one conductivity value for each of the bones in the head (frontal, left/right temporal, parietal and occipital bone) in addition to the scalp conductivity. The skull conductivities that were solved are visualised in Fig. 1 (middle row), and the found scalp conductivity was 0.385 S/m, again, lower than the 'true'. The skull conductivity for the frontal and parietal bones are very close to each other, and therefore are difficult to distinguish from each other in Fig. 1. These two tests were to showcase what kind of conductivity values one can get

when using too low conductivity resolution in EIT imaging.

By studying the computational performance and stability of the develop EIT solver as the resolution of the conductivity map increased, we verified that the software was able to construct high-resolution maps with 8860 separate skull segments that were sufficient for the pipeline. The resulting non-linear EIT imaging problem was solved by imposing restrictions to the solution (see, [13] for details). This resulted in 0.430 S/m scalp conductivity that is very close to the 'true' value, and a skull conductivity map very similar to the 'true' one (see, bottom row of Fig. 1). Our solver achieved to find the low skull conductivity values around the temporal bones and the high values in the occipital bone.

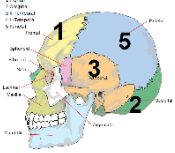
4.2 EEG source imaging

As mentioned, the personalised conductivities of the human head were envisioned to improve the EEG source imaging results. Here, we demonstrated that this was indeed the case by performing EEG source reconstructions with the help of the personalised head conductivities reconstructed in the previous section. For comparison, we also performed the same EEG reconstructions by using a head model with standard conductivity values for scalp 0.465 S/m [17] and skull 0.01 S/m [3].

In the EEG tests, we reconstructed brain sources that located under different skull bones and calculated the localisation errors between the reconstructed and the 'true' source. The results are summarised in Tab. 1. As can be seen, the high-resolution personalised skull conductivity map results in the most accurate source localisation in all cases when compared to the other conductivity resolutions. The improvements in the source localisation accuracy are the most evident close to the lowest (temporal) and highest (occipital) skull conductivity regions.

Tab. 1. Average localisation error (in millimetres) of the brain sources when a particular conductivity resolution was used in the EEG source reconstruction. The numbers 1 to 5 refer to source locations in the brain that locate under a certain skull bone: frontal (1), occipital (2), right-hand-side temporal (3), left-hand-side temporal (4) and parietal (5) bone (see, image on the right, by Wikimedia Commons).

Conductivities used in the EEG source imaging	Average error under bone 1 (mm)	Average error under bone 2 (mm)	Average error under bone 3 (mm)	Average error under bone 4 (mm)	Average error under bone 5 (mm)
Literature conductivity values for σ_{scalp} = 0.465 S/m and σ_{skull} = 0.01 S/m	3.5	7.5	3.8	3.4	4.7
EIT determined bulk conductivity value for σ_{scalp} and σ_{skull}	3.1	6.5	10.0	8.2	3.2
EIT determined bulk σ_{scalp} and 5 σ_{skull} values (one for each major skull bone)	2.6	7.8	5.7	4.7	3.0
EIT determined bulk σ_{scalp} and 8860 locally varying σ_{skull} values	1.4	2.9	2.4	2.5	1.1



5. FUTURE PROJECT VISION

In the future, we envision that wearable, highly personalised EEG-based instruments will enable remote and home-based brain monitoring and communication, and can become as common in personal health tracking as smart watches nowadays.

5.1. Technology Scaling

During the ATTRACT Phase 1, we have achieved Technology Readiness Level 3 (TRL), i.e. we have shown with numerical experiments that the proposed EIT-EEG imaging pipeline produces high-resolution conductivity maps of the human head which subsequently improve EEG source localisations.

During the ATTRACT Phase 2 (see Fig. 2), we'll conduct EIT laboratory measurements with human head phantoms that are built with 3D-printing technology (TRL 4). These tests will help us in designing appropriate measurement set-ups (e.g. no. of electrodes, electrode locations, optimal currents). To reach TRL 5, we'll develop a prototype with wearable electronics that combine both EIT and EEG technology. To reach TRL 6, the prototype will be tested with a head phantom. After successful testing, we'll conduct the first pre-clinical human experiments in a controlled environment.

1.1. Project Synergies and Outreach

For the ATTRACT Phase 2, we are looking for reinforcing our consortium with partners who have (i) experience in clinical use of standard EIT, (ii) facilities to build a prototype EIT-EEG device, and (iii) expertise in wearable technologies. Here, we also see an opportunity to cluster with other Phase 1 projects that concentrate on neuroimaging and diagnostic tools.

Based on our experience in Phase 1, we understand that we need to engage with dissemination from the very beginning of Phase 2. Our aims are to engage with the relevant stakeholders, to articulate in a very easy way

what the project is about and what it can offer to our target audiences, and receive feedback and consultation that we'll use in the subsequent stages of the project.

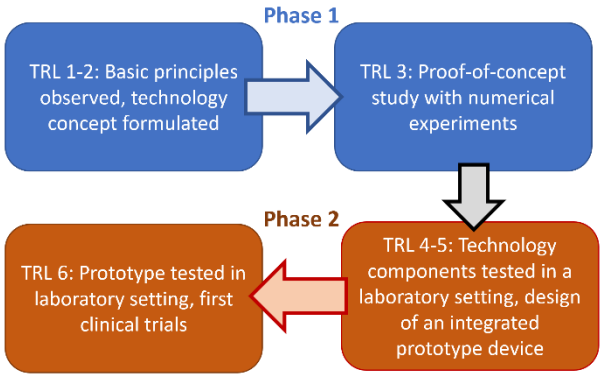


Fig. 2. *The Technology Readiness Levels achieved during ATTRACT Phase 1 and the projected TRLs for the Phase 2.*

The ATTRACT Consortium will be facilitated for connecting with potential stakeholders (e.g. EC, medical and wearables industry, neuroscientists, researchers in brain imaging, medical personnel) and for public dissemination. We'll disseminate our progress and research outcomes through ATTRACT's media platforms, social media channels and in Consortium meetings & conferences. Our plan is to provide regular briefings on the progress of the project, newsletters, videos with interviews and presentations.

1.2. Technology application and demonstration cases

Our main technology demonstration cases in Phase 2 will be (i) applying the EIT-EEG technology to a 3D head phantom, (ii) building a prototype EIT-EEG device with the developed software, and (iii) conducting the first pre-clinical human experiments.

The new EIT-EEG device will improve the accuracy of brain imaging, thus enable better diagnostics and shed light on the brain research. It is expected that especially infants and children whose skull conductivities exhibit very large individual and inter-personal variations will benefit from the personalised conductivity models constructed using the EIT part.

Furthermore, as the population of Europe is becoming older, it can be expected that neurological dysfunctions (such as Alzheimer's and Parkinson's disease) will become more common, and since potential pandemics can inhibit hospital-based treatments, having reliable home-based brain monitoring & treatment technologies can become increasingly important. Therefore, the proposed EIT-EEG technology can become a new standard in safe smart systems that rely on relatively cheap, portable and robust features when high-end modalities (e.g. MRI, MEG, CT) are not accessible. Notably, it could enable real-time monitoring of brain (dys)functions (e.g. epileptic seizures) and possibly combined with instant response treatment (either automatically or remotely), for example with targeted transcranial electrical (or magnetic) stimulation (TES/TMS) treatment of the brain. We remark that the current dosage estimates received during TES suffer from the same sensitivity to inaccurate conductivities [8,14] (as the standard EEG brain imaging) which the personalised EIT conductivity maps can mitigate.

Finally, we envision that personalised EIT-EEG technologies can boost the industry in the development of Brain-Computer-Interfaces (BCI) and Brain-2-Brain-Communications not only in terms of personal (mental) health tracking but also safety, entertainment and lifestyle.

Our plan is to contribute to the European Research Infrastructure for Imaging Technologies in Biological and Biomedical Sciences (Euro-BioImaging) by providing data and algorithms in their open-access services. In later stages, we are aiming in partnering with the European Advanced Translational Research Infrastructure in Medicine (EATRIS) for early Health Technology Assessment support.

1.3. Technology commercialisation

During Phase 1, we received feedback from industry that the personalised conductivity modelling of the head is of high importance. We envisage that the following basic commercialisation steps will take place after the demonstration of our prototype device:

- First stage: secure funding, assemble team/key partners, regulatory plan based on product classification, cost structure
- Development phase: design, supplier using high fidelity materials, verification by performing tests and updates when required, regulatory submission
- Product launch: device registration, distribution network, revenue streams

In Phase 2, we'll include a company in our consortium to provide insight and experience regarding commercialisation which will hasten the development process from lab to market.

1.4. Envisioned risks

Technical: The possible risks of the project are related to the outcomes of the laboratory tests: for example, the prototype device may suffer from sensitivity to noise (thus require use of denoising techniques), the choice of electrodes may be critical (here we'll rely on expert knowledge), the measurement set-up may require alternative ways of validation (e.g. extra tests in simulated environments) or the computational effort for high-resolution EIT imaging may be demanding (thus

requires compressed sensing techniques). Naturally, the transition from a phantom experiment to a pre-clinical experiment may raise risks, especially for the validation (cross validation with different modalities or with standardised tests for which the neural patterns are well documented).

Organisational: There can be unexpected organisational issues (related to permissions, resources or logistics) within or between some of the participating institutes that may cause delays. We intend to mitigate these circumstances by re-arranging the sequence of tasks to achieve the milestones on time.

Management: Management and communication of a multinational and interdisciplinary consortium can become inefficient if proper management practices are not used. This can lead to asynchronous progress of work. Here we expect to benefit from such management frameworks as Scrum or Agile.

1.5. Liaison with Student Teams and Socio-Economic Study

We had a fruitful collaboration with one Bath-based student team in Phase 1 during which two students finished their Final Year Projects.

In Phase 2, one experienced researcher will be nominated to facilitate MSc. Level explanation materials related to the project. We'll collaborate with MSc. Student teams both with hands-on and brainstorming projects. These projects will be related to designing and 3D-printing of head phantoms, testing simple wearable circuits, and inventing novel BCI applications (in health tracking & monitoring, entertainment) for example.

We shall take part in the socio-economic study of Phase 2 by sharing information and evidence, particularly regarding the projected societal impacts of the developed technologies, e.g. how personalised home-based monitoring technologies can improve people's lives.

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