Optimization of Electroencephalography Reference Layer

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Abstract
Simultaneous Electroencephalography & Functional Magnetic Resonance Imaging (EEG-fMRI) is a brain imaging technique that combines the high spatial resolution of fMRI with the high temporal resolution of EEG. However, the usage of magnets in fMRI induces electrical currents which are picked up by the EEG scalp electrodes, this is an effect of Faraday's Law which creates electrical noise. Inside the magnetic field the cardiovascular system of the human skull also creates artifacts known as Ballistocardiogram (BCG) noise and this reduces the clarity of EEG data. Researchers try to remove these artifacts by designing and producing reference layers which consist of insulating and conductive pieces of fabric that collect BCG noise signals, allowing for the reduction of artifacts in post-hoc analysis. These Reference Layers tend to be crudely made to fit researchers' specific needs. In the Lewis Lab, we've created a standardized design for a double-sided Reference Cap, consisting of a single fabric that has holes cut out for EEG Scalp Electrodes. This fabric layer has an insulating spandex side that makes contact with the scalp and a nylon side that makes contact with EEG Reference Electrodes. This nylon side is coated in poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), an electrically conductive polymer that is safe for usage in MRI machines. With this design, we are able to provide a reference layer that is easy to replicate and assemble in any lab. This design functions well as a reference layer, allowing researchers to attenuate unwanted signals found during EEG-fMRI imaging.

Introduction & Background

Simultaneous acquisition of electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI) has become an important technique for non-invasive brain imaging. EEG is a brain imaging method that collects electrical signals from the scalp, this electrical data is produced from pyramidal neurons found at the surface level of the brain cortex and provides a high temporal resolution of macroscopic brain activity.[4] Functional Magnetic Resonance Imaging collects information about neuronal activity indirectly through the measurement of the Blood Oxygen Level Dependent (BOLD) signal of brain blood dynamics.[1] FMRI excels at providing high spatial resolution of activity in the brain.[1]

While simultaneous EEG-fMRI has the advantages of combining the high temporal and spatial resolution of EEG & fMRI respectively, this technique is not without its challenges, however, as combining fMRI and EEG produces several artifacts in the data collected by EEG scalp electrodes. These include Gradient Artifacts (GA), Ballistocardiogram (BCG) artifacts, and some minor artifacts produced by interference from environmental factors.[2,3] These artifacts are produced by the effects of Faraday's Law, where the strong electromagnets used in MRI machines induce electrical currents particularly in the cardiovascular system of the human skull, which is where BCG artifacts come from. Therefore, there is an area of research within neuroscience dedicated to reducing noise during EEG-fMRI measurements by developing methods for artifact removal.

One such method is to use an insulating and conductive reference layer in conjunction with an EEG cap. The reference layer consists of an inner electrically insulating layer, which blocks some of the EEG electrodes from reaching the scalp, and an outer conductive layer, which allows the blocked channels to collect reference signals. This reference layer will directly measure artifactual signals, which can then be subtracted from the total EEG signal in post-hoc analysis. Reference layers are commonly used in EEG-fMRI research to solve this common problem. However, there is a severe lack of commercially available equipment for this technique, with there currently being no reference layers in the market. As a result, research labs that use EEG-fMRI to collect data will produce their own custom-made solutions for reference layers, which often leads to crude implementations of designs that depend on a researcher's specific needs, as is seen in the Lewis lab.

The reference layer seen in the Lewis lab consists of the following design seen in Figure 1. The inner insulating layer is a shower cap that will go on the subject's head. The conductive layer is a white cloth that is attached by glue to the outside of the shower cap. To make it conductive, the cloth layer is soaked in an electrically conductive saline solution containing potassium chloride. The EEG cap is then placed on top of the entire reference layer. Both the inner insulating shower cap layer and the conductive cloth layer have holes and grommets placed through them which allow the EEG scalp electrodes from the EEG cap to make contact with the scalp. The EEG cap electrodes that do not go through to the scalp are instead making contact with the conductive white cloth layer of the reference layer, and as such are called the reference electrodes.

This current showercap reference layer design in the Lewis lab is capable of successfully attenuating unwanted signals during EEG-fMRI scans. Despite the functionality of this current design, the drawbacks are that everything about this design is assembled by hand. It takes several hours to produce one cap, and the saline solution needs to be reapplied to the cloth layer between subjects in order to remain electrically conductive. Improvements can be made to this design especially those that can automate the fabrication process of the reference layer as a whole and remove the need to soak the reference in saline solution every time.

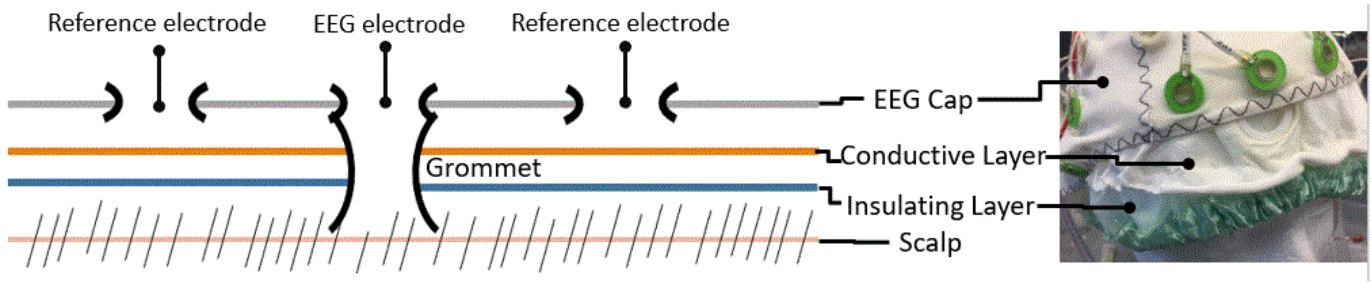


Figure 1. Current reference layer model design used in the Lewis lab.

This provided motivation to design and build a standardized reference layer that is easy to use, simple to manufacture and replicate, and provide equal or better signal attenuation than what is currently available in the Lewis lab. The problem of unwanted EEG signals and the lack of commercially available solutions to this very common issue are the largest technical barriers for success when it comes to simultaneous EEG-fMRI experiments. As such, our long-term goal was to develop a standardized reference layer with the qualities outlined prior. The impact of having such a standardized reference layer is that it will allow for more simultaneous EEG-fMRI data to be collected with less unwanted signals and artifacts. In essence this will improve the overall usability of combined EEG-fMRI since it will allow for a substantial reduction in artifacts. It will also make this technique more reliable by producing reference layer designs that are easy to replicate and manufacture commercially, a result that will benefit all areas of neuroscience that use this technique to study the brain. Increasing access to standardized designs of reference layers will also allow more researchers to start performing more EEG-fMRI studies, advancing the field as a whole.

Our approach to solve this problem has been to create a streamlined and standardized version of this reference layer that can be assembled in a shorter amount of time, does not require reapplication of a conductive solution, requires less materials to produce, and can provide equal or better signal attenuation as compared to the current Lewis model. Making a design that is easier to use and replicate directly solves the problem of no commercially available solutions. The design we developed can serve as a blueprint for researchers to follow in hopes of removing barriers to EEG-fMRI data collection and analysis.

Methods

1. Reference Layer Prototype Designing Methods

1.1 Testing and Selecting fabric for prototype

The first step in the design process for the reference layer prototype was selecting the fabric that the reference layer will be made from. The fabric had two main criteria, namely that it must be stretchy and not porous. Once the fabric was selected it was tested with the PEDOT-P1900 and PEDOT-ESD5000 conductive inks.[1,8] These inks were selected due to their ease in applying them to fabrics to create an electrically conductive layer. The process of applying and testing the conductivity of the ink on the fabric was as follows.

The inks were applied to a section of the fabric using a small paintbrush such that the area is evenly coated. The ink was then cured at 200°F for 10~15 minutes with a heat gun. Once the ink was cured, the impedance of the ink on the fabric was analyzed by using a multimeter to measure the resistance. The impedances were measured across varying distances in the coated section in order to collect a better profile of its conductivity. For a usable ink coated fabric, the impedance must have been less than 100 kOhm on average (as per impedances measured from the current showercap model in use at the Lewis Lab). It is important to note that the PEDOT ESD-5000 ink was the first ink applied to the fabric. If the impedance was too high (above 100 kOhm threshold), the PEDOT-P1900 ink was added to try to lower it below the threshold. To apply the P1900 ink, it was added to an already cured ESD5000 coat and then cured with the same method. Once the fabric was found to have impedances below the threshold it was used to create the prototype.

1.2 Creating fabric prototype using Cricut

For the designing and creation of the reference layer prototype, the Cricut Maker 3 cutting machine was used. The Cricut Maker comes with a software that allows for different cut designs to be custom made. The design files were uploaded to the machine which then cut out the design on any fabric that was placed into the machine's cutting area.

To create the prototype, a design file was made with the desired shapes and dimensions. The chosen fabric was then placed on a sticky gridded mat that held it in place. The mat was inserted into the Cricut cutting area. Once the design file was completed and sent to the machine, the machine calibrated with the gridded mat, and it began cutting out the design after we pressed the start button. The fabric was added into the Cricut machine without being coated with any conductive ink. The fabric was coated with ink after it was cut out with the desired prototype design shape.

For reference, **Figure 2** below shows the current prototype design in the Cricut design software workspace. The prototype's design shape and specifications can easily be changed if improvements are needed.

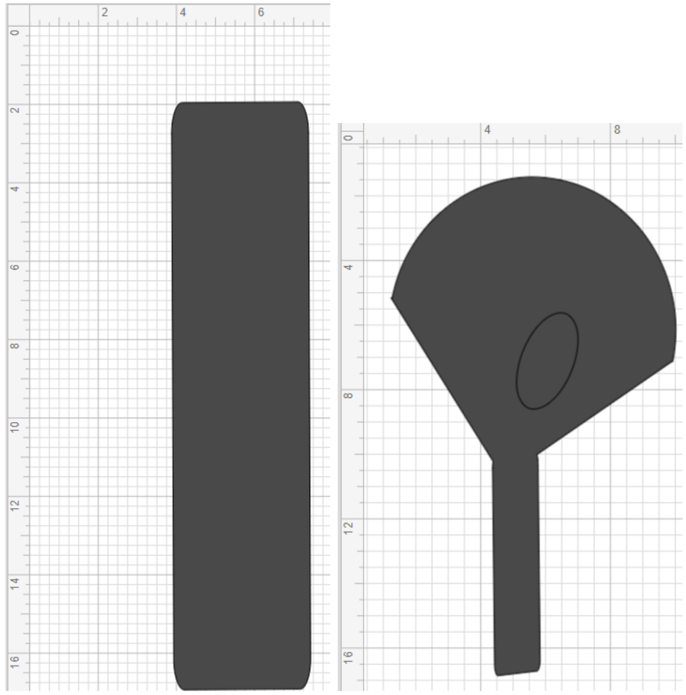


Figure 2: Current designs of EEG reference layer pieces in Cricut design software.

1.3 Assembly of Reference Layer

The reference layer prototype consists of three pieces which are seen in Figure 4: a middle piece (left) that is roughly the length of the distance between the nasion and inion on a human skull, and two copies of the side piece (right) which mirror each other in order to allow for proper ear placement. When these three pieces were printed by the Cricut fabric cutting machine, they were carefully assembled together using super glue. At this point of the fabrication process, the assembled cap did not have any PEDOT:PSS coatings or holes cut out for EEG scalp electrodes. The entire cap was coated in PEDOT:PSS following the method described in Section 1.1 of the Methods. Once the appropriate amount of ink coatings were applied (verified by measuring impedances less than 100kOhm with a voltmeter across multiple lengths of the cap) and the cap was dry, the reference cap was placed on top of a model head and an EEG cap was placed on top of the reference cap. Holes for the EEG scalp electrodes were then marked and cut out through the EEG cap. Once holes were cut, grommets were placed in the holes to allow separation between the scalp electrodes and the conductive area of the reference cap. At this point, the reference cap was ready to be used for testing.

2. Reference Layer Prototype Testing Methods

2.1 Preliminary Reference Layer MRI Safety Tests

The initial tests for the prototype involved testing if it was MR compatible.

The first MR compatibility test involved taking several fMRI scans of a phantom, both with the reference layer on and off. In our experiments, the phantom was a watermelon. For the first scans, the reference layer was placed on the phantom and then a regular fMRI scan was performed. Then the reference layer cap was taken off and the same scan was performed on the watermelon again.

The second MR safety test was then performed using the same watermelon phantom model. The following safety test was a heating test which sought to measure the change in temperature of materials by replicating EEG-fMRI conditions. In this test, the reference layer prototype was placed on the phantom model followed by an EEG cap. The watermelon was inserted into the MRI machine in which standard EEG-fMRI signal recordings were performed. Four temperature sensing probes were placed on the watermelon while it was in the MRI machine in order to measure temperature changes. Three probes were placed on different EEG electrodes on the surface of the watermelon and the final temperature probe was placed in the bore of the MRI machine to measure changes in the ambient temperature. Several scans were then performed by the MRI machine for a period of 45 minutes during which the temperature probes were measuring changes in temperature. At the end of the 45 minutes, the range of the data was measured to see how much the temperature of the materials changed in comparison to the ambient temperature measured in the bore of the MRI machine.

2.2 Human Subjects Tests with Reference Layer Prototype

The final test for the prototype was a human subjects experiment. In this experiment the subject had the reference layer prototype put on their head, along with the EEG cap and the added EEG gel in the electrodes like before. The subject then alternated between having their eyes open and closed for one minute intervals for four minutes. For the four minute session, the subject started with their eyes open, then closed their eyes at the start of the second minute, opened their eyes again at the start of the third minute, and closed their eyes again at the start of the fourth and final minute. The EEG signal data was recorded and analyzed at these different epochs of eyes opened and closed.

To compare the EEG scalp electrode and reference electrode channel signals, the Power Spectral Density (PSD) was used as this is the standard for calculating EEG signal power in neuroscience research[3]. After completing all recordings, the PSD was calculated for all occipital EEG electrodes (touching the scalp) and the reference electrodes (in contact with the prototype) and averaged across one stimulus-on epoch and one stimulus-off epoch. The power difference between the reference electrodes and the EEG electrodes was calculated. These EEG results were then compared to other similar results collected with the current shower cap model in the Lewis lab.

Results

New Reference Layer Prototype

Figure 3 shows the new reference layer design that was developed. In this design, the separate insulating and conductive layers of the typical reference layer were combined to form one double sided reference layer. In our design, the fabric chosen for the entire reference layer was 80% spandex and 20% nylon which made it stretchy. As seen in the figure, the top side of this fabric was coated with the PEDOT conductive inks to make it conductive (orange line in Figure 3) while the inner scalp facing side was left uncoated (blue line in Figure 3).[8] Since the spandex fabric was naturally insulating, this worked inherently as the inner insulating layer. The spandex fabric was also not porous and so the ink coated on the top did not seep to the bottom which ensured that the bottom layer remained electrically insulated. This design also used holes for plastic grommets which were also inserted.

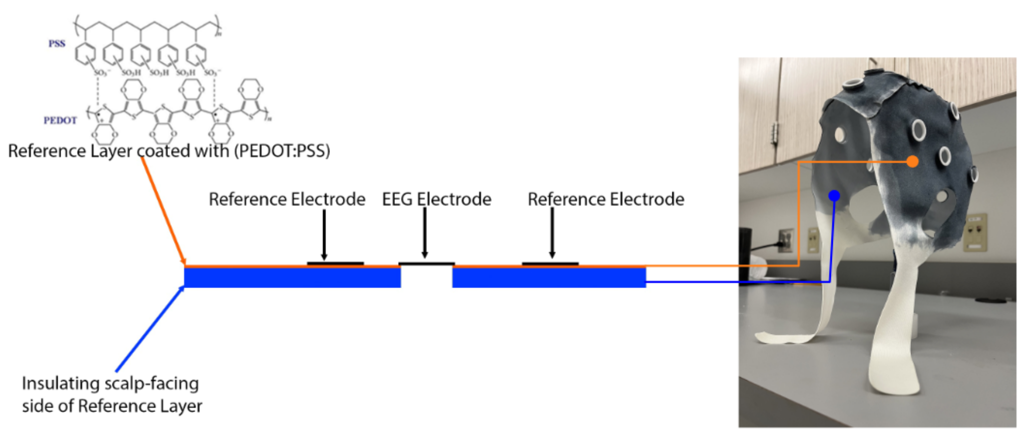


Figure 3: Image of completely assembled new reference layer.

MR Safety Tests

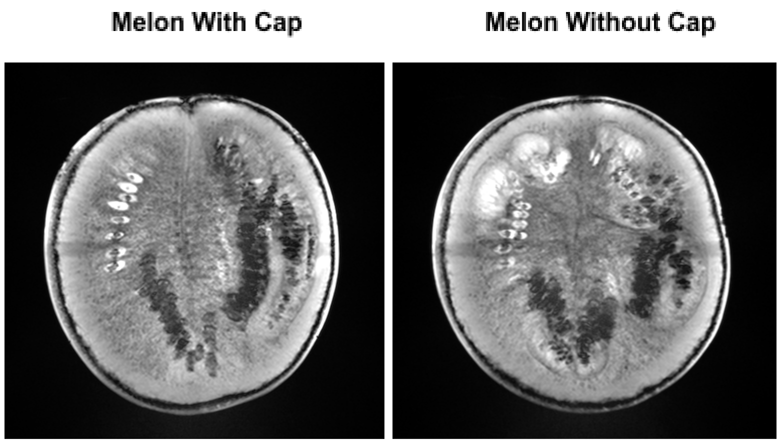
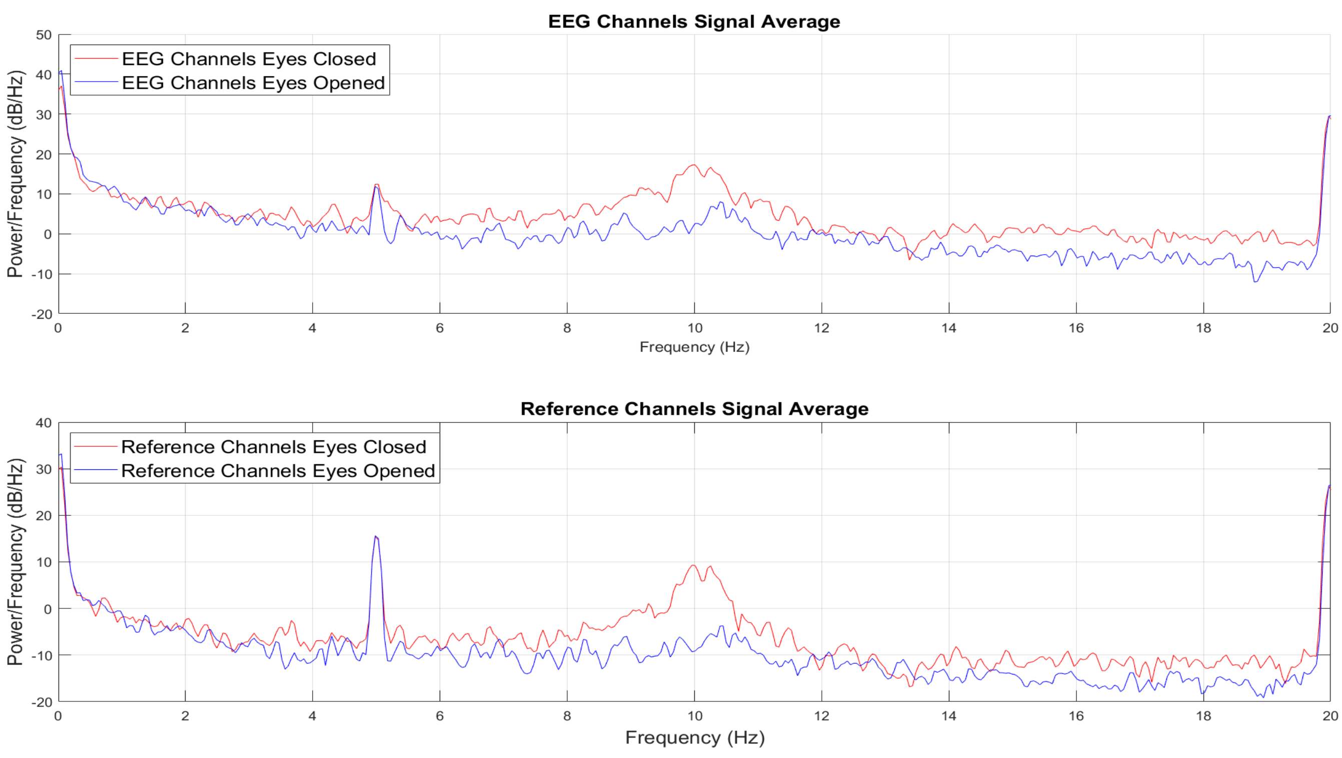
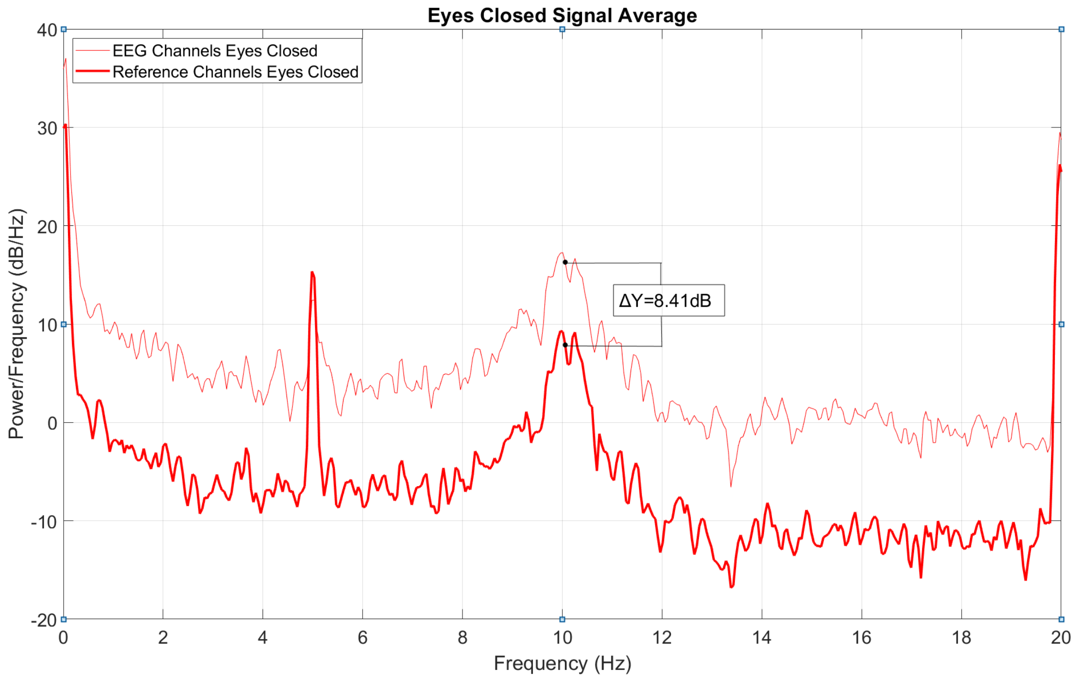
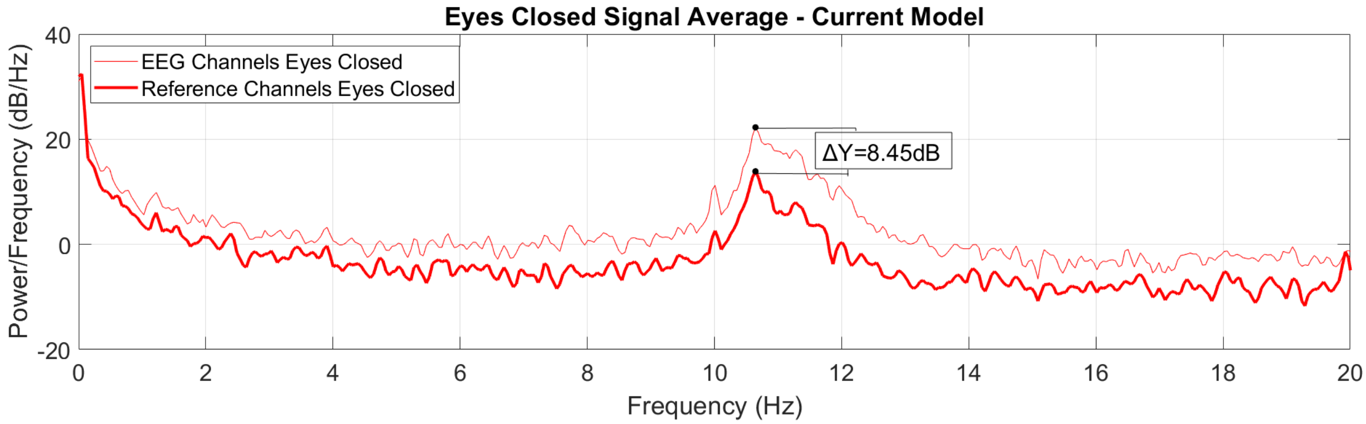


Figure 4: fMRI images of watermelon phantom.




Eyes Closed Signal Average
EEG Channels Eyes Closed
Reference Channels Eyes Closed
ΔY=8.41dB
Power/Frequency (dB/Hz)
Frequency (Hz)
40
30
20
10
0
-10
-20
0
2
4
6
8
10
12
14
16
18
20



Eyes Closed Signal Average - Current Model
EEG Channels Eyes Closed
Reference Channels Eyes Closed
ΔY=8.45dB
Power/Frequency (dB/Hz)
Frequency (Hz)
40
20
0
-20
0
2
4
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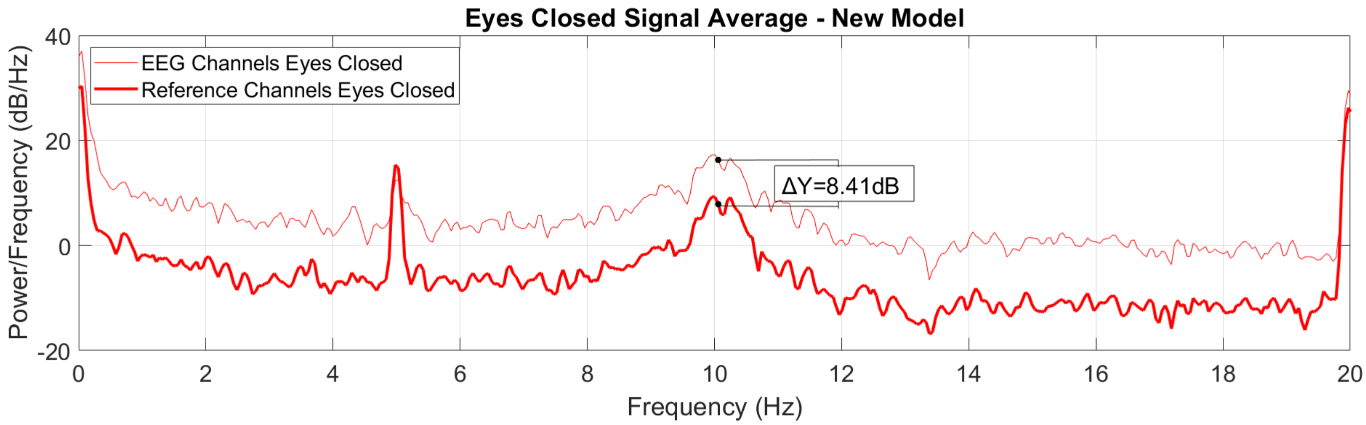

Eyes Closed Signal Average - New Model
EEG Channels Eyes Closed
Reference Channels Eyes Closed
ΔY=8.41dB
Power/Frequency (dB/Hz)
Frequency (Hz)
40
20
0
-20
0
2
4
6
8
10
12
14
16
18
20

Discussion (~1 pages)

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