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iCap: New method for noise reduction in electroencephalography (EEG) signals

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Abstract

Electroencephalographic (EEG) signal's importance increases as the neurotechnology research and industry accelerate. Therefore, it is crucial to acquire noise-free signals by maximising the signal-to-noise ratio (SNR). Many methods are followed to clean the signals, such as band-pass filters and notch filters. More advanced preprocessing techniques, like independent component analysis (ICA), were also used. These methods can increase SNR, but it is also true that they increase computation time and have the risk of signal distortion. Hence, isolating the noise components in the acquisition stage is more reliable. This work provides a new method for noise reduction by developing an insulation cap (iCap). The designed iCap was inspired by the coaxial cable and had four isolation layers. The iCap was tested on 20 subjects by recording their EEG signals and comparing the cases when the iCap was worn and not worn. The findings revealed that this approach could successfully boost the SNR of the EEG signal in 53.87 % of the case by 57.45±5.93 %.

Keywords: Electroencephalographic, signal-to-noise ratio, noise isolation, electromagnetic field.

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1. Introduction

Electroencephalography (EEG) is an important medical instrumentation for assessing brain functioning (Lotte et al., 2018; Nam et al., 2018). This includes diagnosing different disorders such as epilepsy (Noachtar & Rémi, 2009) and other seizure disorders (Smith, 2005). Additionally, it is used in Brain-Computer Interface systems, which are a communication channel between computers and the brain for translating thoughts into commands (Alchalabi et al., 2021). It is a noninvasive approach for detecting and registering brain electrical activity utilising electrodes placed on the scalp registering changes in electric potential caused by cerebral neuron activity (Abo Alzahab, Baldi, et al., 2021; Lotte et al., 2018).

If the EEG signal is not sufficiently high, electrical noise can emerge and noise can hide the true path of brain waves. Technical and biological artefacts are subcategories of EEG noise, depending on their origin. The effect of artefact sources is proportional to the magnitude of the generated signal and is inversely related to the distance between the sources and the EEG electrodes. Additionally, it is necessary to recognise the variations in conductivity between the electrodes and the brain as artefacts—a low-pass filter typically filters out noise from the EEG data. It can be produced by a variety of sources, including power, medical apparatus, and workstations. Biological artifacts are instead produced by ocular movements, skeleton muscle movements, body motions in relation to electrodes (head tremor), heartbeat, and arterial pulsation, among other sources (Nam et al., 2018; Paszkiel, 2020).

By eliminating the source of interference from which the artefacts originated, it is possible to eliminate the artefacts. The higher is the precision with which the source of interference can be identified, the more effectively noise can be eliminated from the measuring process. Suppose it is almost impossible to isolate the source of interference or to cut off the channel through which the interference is propagating. In that case, the only thing that can be done is to process the recorded encephalogram in order to recover an undistorted EEG signal. Therefore, it is crucial to eliminate or reduce the effect of the external interference sources before using complex preprocessing and digital filtering, which are usually heavy in terms of computation effort (Paszkiel, 2020).

One primary artefact is the presence of electrical impulses that interfere with brain signal data, which is inevitable. These electrical signals might be caused by power lines, faulty electrode contact, and electrode drift. Electromagnetic field (EMF) interference, which an electromagnetic field can generate, can cause aberrant peaks and trends in EEG readings(Ciorap et al., 2014; Usakli, 2010).

In literature, there are many recommendations to reduce the effect of EMF interference. From those, we mention that electronic circuits and cables should be placed in a metal box to reduce EMF interference (Usakli, 2010).

Additionally, the usage of twisted, blended cables can also reduce the noise accumulated in the wires (Usakli, 2010). As well as considering the instrumentation amplifier to have greater than 80 dB common-mode rejection rate. This high CMRR is essential for high Signal-to-Noise Ratio (SNR) signal acquisition.

This work proposes a new method for EMF interference reduction. It is based on the principle of shielding the EEF cap and electrodes themselves. The proposed method is named iCap.

Section 2 of this paper includes the details about the concept and design of the iCap and the experiments to evaluate it. The following section consists of the experimental results and their discussion. Finally, a conclusion from this work and its future perspectives

2. Materials and Methods

This section explores the creation and evaluation of iCap. It starts by introducing the concept of noise reduction, followed by the design details. Afterwards, it explains the iCap evaluation by stating signal recording and data analysis.

2.1. iCap Concept

The concept of iCap creation was inspired form the coaxial cable (Delogne & Laloux, 1980; Silver, 2010). It has an inner conductor (generally solid copper, stranded copper, or plated-copper steel wire), an insulating layer, and a shield (often one to four layers of woven metallic braid and tape). An outer insulating jacket protects the cable. The exterior of the shield is usually grounded, while the centre conductor carries a signal voltage. The advantage of coaxial design is that the signal's electric and magnetic fields are limited to the dielectric, with little leakage outside the shield. The receiving end of the line can also keep electric and magnetic fields from interfering with signal transmission. So the coaxial cable is suitable for both weak signals that can't withstand environmental interference and stronger signals that can't radiate or couple into nearby structures or circuits.

Those characteristics of the coaxial cable inspired the development of a head cap that isolate electromagnetic interference with EEG electrodes.

2.2. iCap Design

Inspired from the Co-axil cable, iCap was designed by considering the EEG electrodes as the inner conductor of the coaxial cable, which has the valuable information to be transmitted. Above the EEG electrodes, a four-layer cap was placed as flows, from Internal to External, as shown in Fig 1.

1- Inner Insulating Layer (IIL). It is made of non-conductive material. Its purpose is to isolate the electrodes from the external environment and ensure they are well placed.
2- Grounding Layer (GL). It is made of conductive material. Its purpose is to ground the noise signals transfer from the net layer. It is

connected to the ground of the EEG acquisition system.

3- Net Layer (NL). Made of conductive material in the shape of the woven metallic braid. Its purpose is to catch the noise single's from the external environment and transfer it to the next layer. It works similar to the Faraday cage principle (Wu et al., 2001).

4- Outer Insulating Layer (OIL). It is made of non-conductive material. Its purpose is to ensure that all layers are well placed.

2.3. EEG recording.

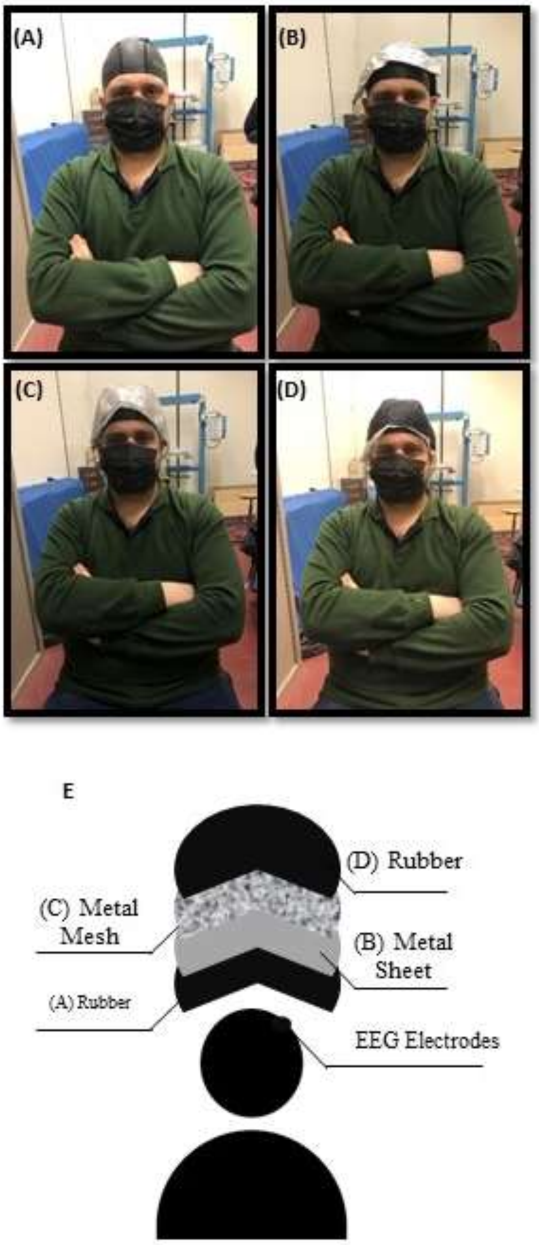


Figure 1 Design of the iCap. (A) Inner Insulation Layer. (B) Grounding Layer. (C) Net Layer. (D) Outer Insulation Layer. (E) Graphical representation of the iCap

In order to evaluate the efficiency of the proposed method, the EEG data were recorded from 20 subjects with and without the iCap. The subjects were sited on a comfortable chair facing a black wall. OpenBCI ganglion board was used for signal acquisition. Four experiments were conducted as follows:

- Eyes Open Without iCap.
- Eyes Closed Without iCap.
- Eyes Open With iCap.
- Eyes Closed With iCap.

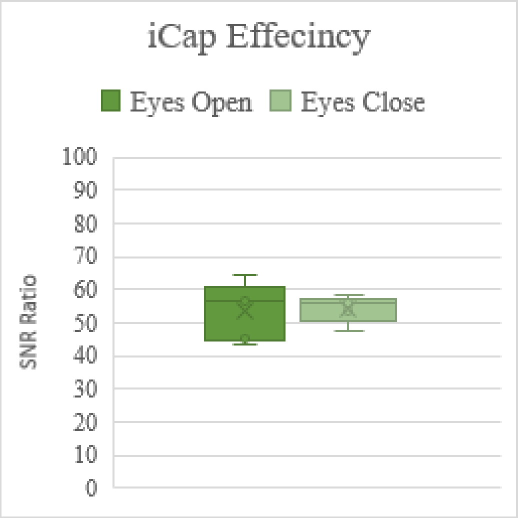
Each experiment was repeated for three sessions where each session lasted for two minutes. EEG data were recorded from 4 electrodes: T7, F8, Cz, and P4 (10-10 International EEG electrodes system). The electrode choice was made in order to cover the different areas of the scalp. More details about the dataset are available on (Abo Alzahab, di Iorio, et al., 2021)

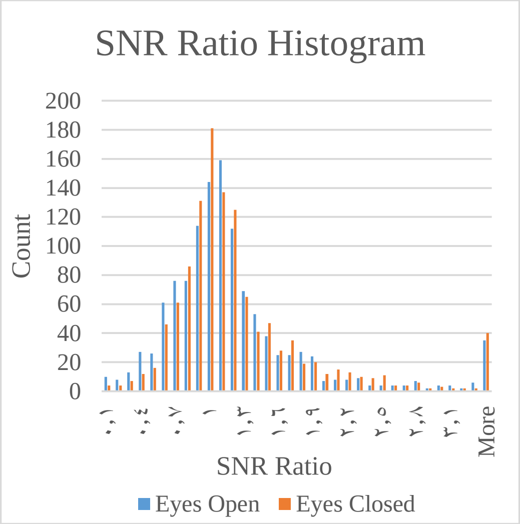
2.4. Digital Signal processing

Table 1 Cases when the iCap could efficiently reduce the interference

Band	Eyes Open	Eyes Closed
Delta	104 (43.33 %)	114 (47.5 %)
theta	136 (56.67 %)	140 (58.33 %)
alpha	154 (64.17 %)	129 (53.75 %)
beta	138 (57.50 %)	135 (56.25 %)
gamma	109 (45.42 %)	134 (55.83 %)

To analyses the Data, a filter bank was used to obtain the five frequency EEG bands: Theta, Delta, Alpha, Beta, and Gamma. Then, the SNR was calculated for each signal according to equation (1).





$$SNR = 20\log_{10}\frac{RMS\ Signal\ Voltage}{RMS\ Noise\ Voltage} \quad (1)$$

Figure 2 iCap efficiency for eyes open and eyes closed cases

Figure 3 Histogram of SNR Ratios between with and without the iCap

2.4. Data analysing

To measure the efficiency of the iCap, the ratio between SNR with cap, and SNR without iCap (For the same eye condition; open and close) was calculated for each session. The number of comparison samples is 240 samples ($2\,Subjects \times 4\,Electrodes \times 3\,Sessions$) for each frequency band.

This ratio will determine whether the iCap has successfully increased the SNR in EEG.

3. Results and Discussion

Data analysis revealed that the iCap influences the noise reduction in EEG signals. The ratio between SNR with and SNR without shows that in most case (53.87±6.45 %), the SNR with the iCap was higher than the without cases. Fig 2 shows a histogram of SNR Ratios between with and without the iCap for eyes open and eyes closed cases. The details of each band are shown in Table 1. The SNR ratios, represented in Table 1, are illustrated in Fig 3 as a box and whisker plot for better presentation. The details of SNR ratios for each eye state and frequency band are shown in Fig 4.

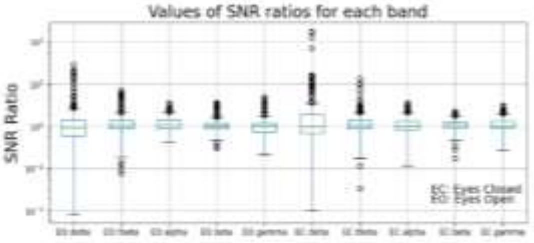


Figure 4 details SNR ratios for each eye state and each frequency band

The focus of this study is to reduce the noise accumulated on EEG signals due to EMF interference. The results showed that this method could efficiently enhance the SNR of the EEG signal (53.87%) by 57.45±5.93%. The not perfect ratio could be explained that this method can reduce the interference resulting from electrical field interference while the magnetic interference was not affected.

4. Conclusion

EEG signals generated by the cerebral cortex are always contaminated by some disturbances. Despite the fact, a novel method for shielding artefacts due especially from mild magnetic fields with its advantages and limitations has been presented in this paper. Research on handling artefacts present in typical EEG recordings is still an active area of research. The prototype headset we proposed, despite not being optimized for particular applications is able to provide promising performance regarding offline analysis, despite the high computational complexity and the nature of EEG signals. This work studied the effect of a new method (iCap) on the SNR. The results showed that this cap works for 53.87% of the recordings. It can increase the SNR by 57.45%. This method has the potential towards acquiring more pure signals and reduce the need for complex digital preprocessing. Further studies are needed to characterize the interference removal properties commonly encountered during acquisition in order to be able to observe the desired brain signal. Finally, the future direction will be to provide specific solutions for online applications.

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