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Performance evaluation of a new 3D printed dry-contact electrode for EEG signals measurement

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ABSTRACT

Traditional wet silver/silver chloride electrodes are used to record electroencephalography (EEG) signals mainly because of their potential repeatability, excellent signal to noise ratio and biocompatibility. This type of electrode is only suitable for conductive glue, which can irritate the skin and cause injury. In addition, as time goes the conductive gel will be dehydrated so the quality of the EEG signal will decrease. To overcome these problems, 3D printed dry-contact electrodes with multi-pins are designed in this work to measure brain signals without prior preparation or gel application. 3D printed electrodes are made from polylactic acids polymer and coated with suitable materials to enhance the conductivity. Electrode-scalp impedance on human was also measured. To evaluate the dry-contact electrode, EEG measurement are performed in subjects and compared with EEG signals acquired by wet electrode by using linear correlation coefficient. Experimentally results showed that the average electrode-skin impedance change of dry electrode in frontal site (9.42-7.25KΩ) and in occipital site (9.56-8.66KΩ). The correlation coefficient between dry and wet electrodes in frontal site (91.4%) and in occipital site (80%). To conclude, the 3D printed dry-contact electrode can be will promising applied on hairy site and provide a promising solutions for long-term monitoring EEG.

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1. INTRODUCTION

Presently, there are many technologies used to moniter brain activity, include computed tomography (CT) [1], magnatic resonance imaging (MRI) [2], functional magnatic resonance imaging (MRI) [3], positron emission tomography (PET) [4], magnetroencephalogram (MEG) [5] and Electroecephalogram (EEG) [6]. Due to its proper time resolution, EEG signal acquisition is the cheapest and most suitable non-invasive technique that can used to record brain activity in applications such as brain computer interfacd (BCI). In addition, since patients/users are not subject to any strong attaks, EEG technology has relatively safe external electric or magnatic fields.

Electroencephalography (EEG) records the electrical activity of the brain on the scalp surface [7]. However, EEG recording technology is not limited to electrodes on the scalp. For examples, some studies have performed EEG on the ear [8], [9]. Standard wet Ag/AgCl electrodes are the most commonly used electrode for measuring EEG signals.

Indeed, the brain waves obtained by standard wet electrodes have a good quality due to conductive gel application and proper skin preparation [10], [11]. Nevertheless, using of wet electrode requires preparation of the skin before the start of experiment and the use of conductive gel when the skin is in contact with the electrodes. These process can be unpleasant to patients and time consuming. The electrode site preparations includes the clean of scalp by scraping the dead skin layers, which causes some of discomfort for subjects, a waste of time as well as a loss of signal when the gel conductive fluid dries up [12]. To overcome of the limitations of wet electrode. A dry electrodes are considered the possible alternative to wet electrode [13]-[15]. A dry electrode make by using a conductive, inert material which is mechanically couple with skin for transduction of signal, eliminating the skin preparation or the use of gel application [12]. Dry electrodes can be made of semiconductors, metals, polymers and are reported to have soft, flexible or hard types. Recently, many dry EEG electrode methods have been proposed [16]-[19], and several method are now commercially available as shown in Figure 1.

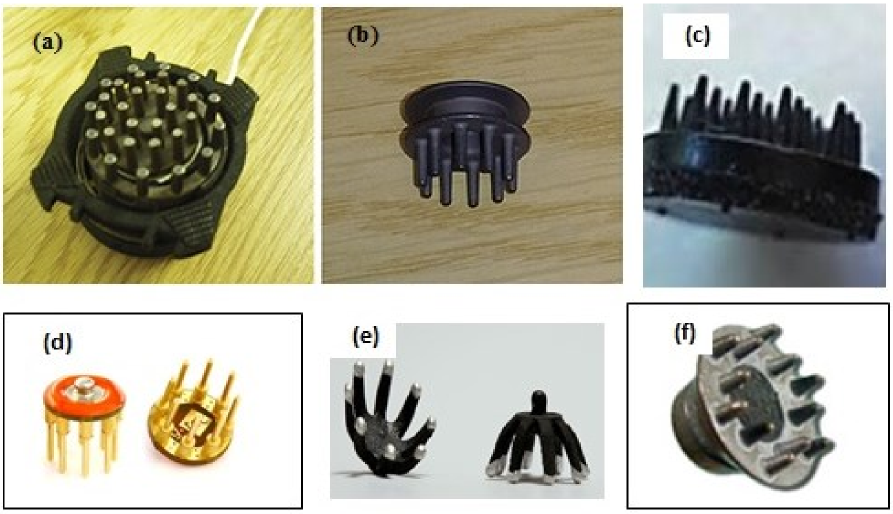


Figure 1. Examples of commercial dry pinned EEG electrode. (a) Wearable sensing [20], (b) Neuroelectrics [21], (c) IMEC. [22], (d) g.tec g.SAHARA [23], (e) Congionics [24], (f) Florida research instruments [25]

Lately, Wang *et al.* proposed a multi-channel reconfigurable EEG acquisition system with a new type of flexible dry electrode [16]. The electrode is composed of conductive AgNWs/PDMS composite material and a support shell designed and manufactured by 3D printing technology. Experimental results show that the system meets the requirements of multi-channel EEG acquisition and provides a portable and comfortable way for EEG acquisition. Hua *et al.* proposed a flexible multi-layer semi dry electrode for EEG monitoring [17]. This electrode contain a three layer, first: a flexible body layer, second: foam layer and lastly reservoir layer. The electrolyte flows into the foam layer through 5 leak holes with a diameter of 0.25 mm at the bottom of the electrode. The foam layer stores the electrolyte so that it will not be lost quickly, ensuring the stability of the contact between the electrode and the scalp. Experimental results showed the flexible semi dry electrode can be well applied to scalp EEG monitoring of hair parts, and provides a promising solution for daily long-term monitoring for wearable EEG. Juntao *et al.* designed a dry-contact electrode for measuring EEG [18]. The electrode designed to attach the scalp with 6 probes spring. The head of each probe has a spheroid shape with radius of 1.3 mm and coated with Nano particles of platinum to enhance the conductivity. The result showed the proposed electrode has similar performance level to standard wet electrode. Recentely, Li *et al.* developed a printable flexible dry electrode array for EEG acquisition at forehead site only [19]. The flexible dry array electrode was fabricated by using screen printing technique. This electrode composed of polyacetylimide substrate and coated with Ag/AgCl ink. EEG signals of the printable dry electrode show similarity result with EEG signals acquired by wet electrode about 90% but on forehead site only and show this electrode not sufficient at hariy site.

This articles describes our work to manufacture dry EEG electrodes faster than traditional modeling or milling techniques using 3D printing. Therefore, the electrodes can be manufactured very cheaplyly on site, making it easier to obtain dry EEG technology. So a 3D printed dry-contact electrode has been shown in the present work to measure the Electroencephalography signals with no skin preparations or gel application, even on the site with hair. Its efficiency has been compared to the standard wet electrode in a research on ten volunteer.

2. THE PROPOSED METHOD

2.1. Electrode design and fabrication

The 3D printed electrode is designed by using the numerical modelling tools (solid-work simulation). The electrode consist of multi pins (7 pins) with a height of 10 mm and diameter of 2 mm. These pins inserted into a circular base has a diameter of 15 mm and height of 2 mm. The circular base is designed with a button pattern and has a height of 4 mm for connections to recording equipment. The shape of electrode has the ability to pass through hair and make good contact with surface of scalp.

The process of fabrication of the 3D printed electrode includes: first, use standard, nonconductive 3D printer plastic (PLA) to print the mechanical structures of the electrode. The total time for each electrode was approximately about 20 minutes and its varied depending on the setting used. Second, the 3D printed electrode was coated with a conducting material to form the finale dry electrode. The design of the 3D printer electrode is shown in Figure 2.

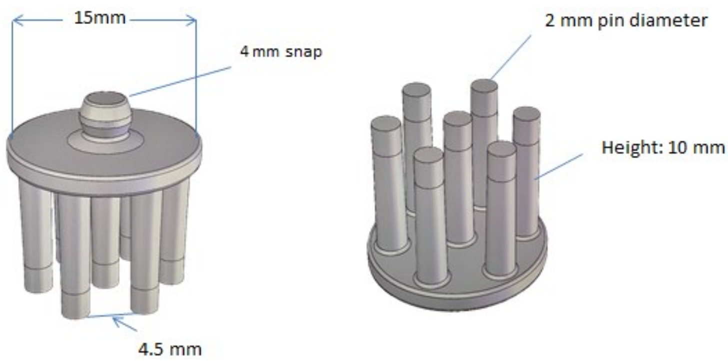


Figure 2. Design of 3D-printed dry electrode

2.2. Coating material

The base of 3D printed dry electrode shown in figure are non-conductive and so are not directly used for measuring EEG signals. So first the electrode activated by depositing layer on the top. Silver conductive paste is used as a conductive material because its readily available and inexpensive in small quantities and it's easy to application.

To perform the coating, first the electrode must be cleaned by using alcohol and left to dry for a few minutes. Second, the silver conductive paste is applied by using dip coating way and left to dry for one night. One layer of coating is sufficient to provide good level of conductivity. Final dry electrodes is shown in Figure 3.

(a) (b) (c)

Figure 3. (a) Image of 3D printed dry electrode after fabrication,
(b) Dry electrode after coating with silver paste and (c) Weight of dry electrode

2.3. Measurement procedure
2.3.1. Scanning electron microscopy and energy dispersive x-ray spectroscopy

Scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDX) tests were used to check surface morphology of 3D printed dry electrode and to identify the chemical characteristic of electrode materials before and after coating, respectively. These tests were carried out with a INSPECT S50 microscope, operating at 10 KeV and the electrode observed with different magnification. The 3D printed electrode fixed on a circular substrate and put in the sample cavity. At center of nanotechnology and advanced materials in university of technology there tests were carried out.

2.3.2. Impedance assesment

Electrode skin-electrode impedance (ESI) was analysed by using impedance spectroscopy (LCR meter-8110 G). Two 3D printed dry electrodes were placed on forehead site with distance between the two electrode was 1 cm and the voltage adjusted to the electrodes pair is 1 V with frequency ranges from 0.5-1000 Hz as shown in Figure 4, then electrode-skin impedance changes were measured. For comparison, same experiment was repeated but by using two wet electrodes. Before experiment, the subject's skin was carefully cleaned at the wet electrode site according to standard skin preparation procedure. lower skin-Electrode contact impedance can leads to better signals to noise ratio and accurate EEG signals measurement.

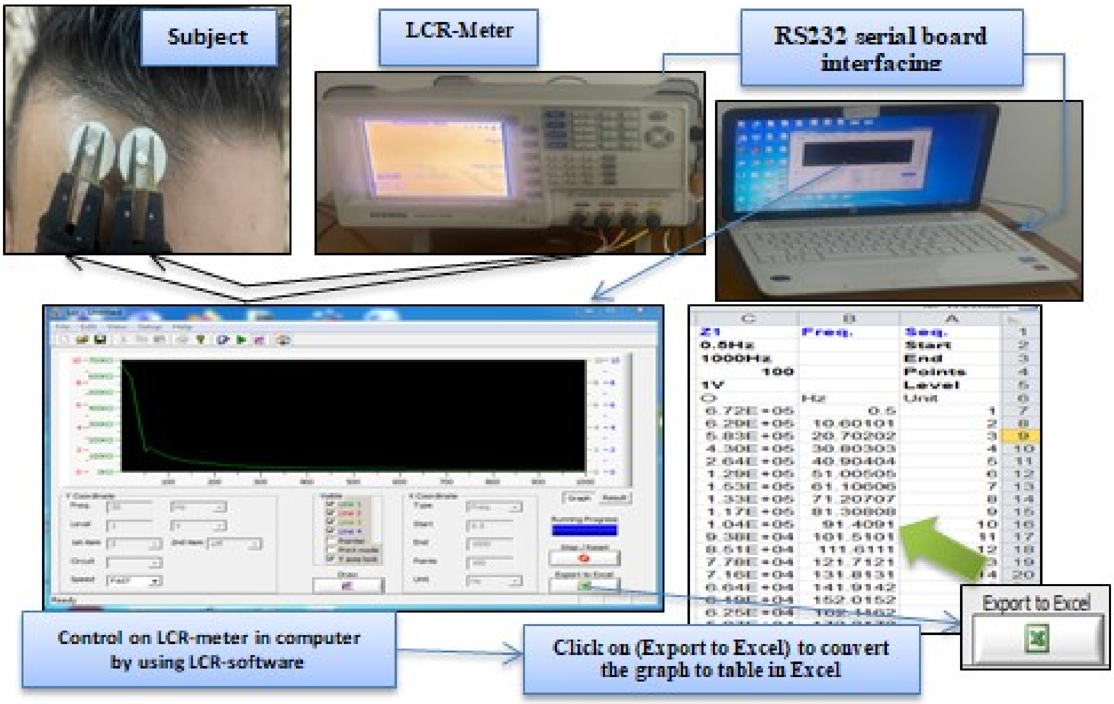


Figure 4. Procedure of measuring skin-electrode impedance by using LCR meter

3.2.3. Electroencephalography test

EEG test carried out on different volunteers male and female, their age between (20-35 years) at Dr. Saad alwatery hospital for neuroscience (Iraq, Baghdad). None of them reported any current mental illnesses or disorders. A comparative experiment was carried out between the dry electrode and the standard wet electrode to evaluate the signal quality of the 3D printed dry electrode. The dry electrodes are placed at positions Fp2 and O2 according to 10-20 system and wet electrodes are placed in the symmetrical position Fp1 and O1 positions as shown in Figure 5. Electrodes are fixed by elastic hand band. Data were recorded by neuroscan system (NIHON KOHDEN model) and to remove power supply noise notch filter was applied.

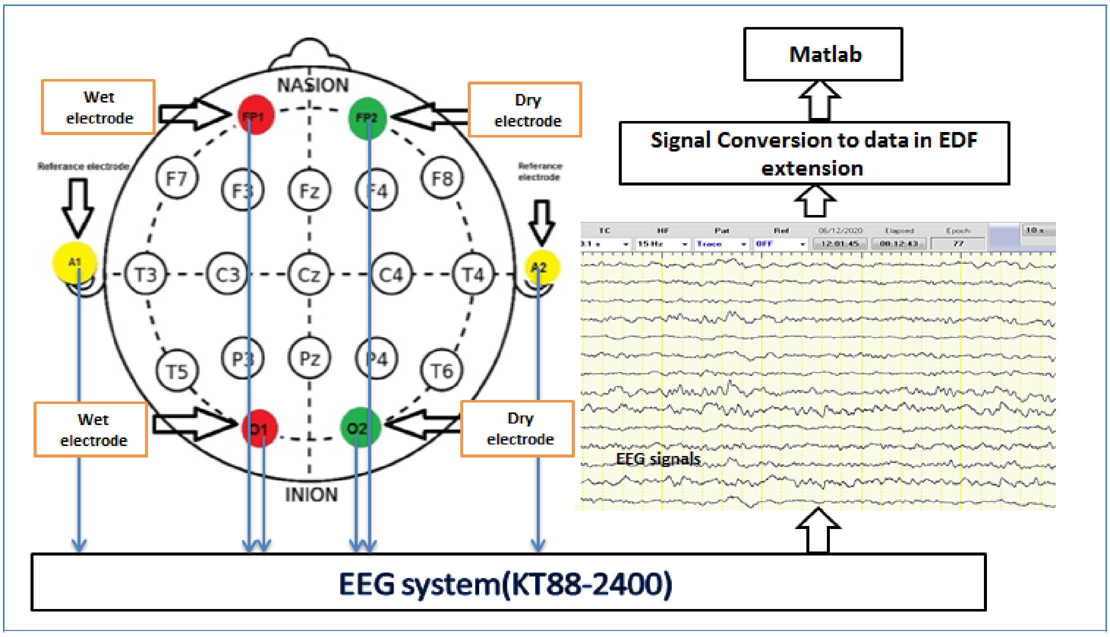
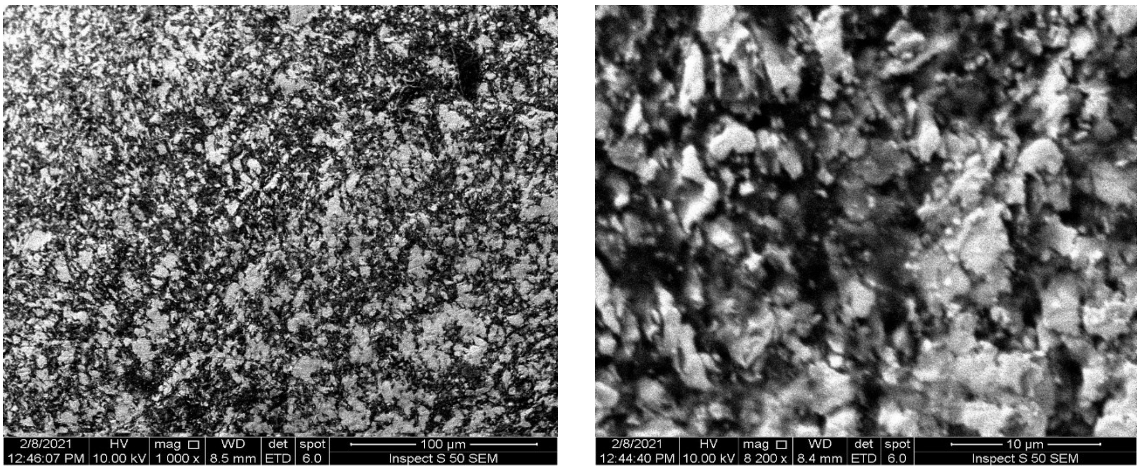


Figure 5. EEG measurement setup using EEG neuroscan amplifiers for symmetrical recording of signals acquired by two different types of electrodes

3. RESULTS AND DISCUSSION

3.1. Coating characteristics

The result show the silver conductive paste coating materials revealed a rough structure. In addition, the high magnification image show the silver paste coating is a closely packed a granular shape and there was no holes appear in the surface of dry electrode shown in Figure 6. The absence of holes mean the dry electrodes have a good electrical contact and increased in conductivity. EDX map show that the presence of Ag element about (54%) as shown in Figure 7, which confirm that the coating material had good covering of the surface of electrode. EDX spectrum analysis also explain all the chemical element that present in the surface of electrode.



(a) (b)

Figure 6. SEM imgage of 3D printed electrode with silver conductive paste, (a) at 100 µm magnification and (b) at 10µm magnification

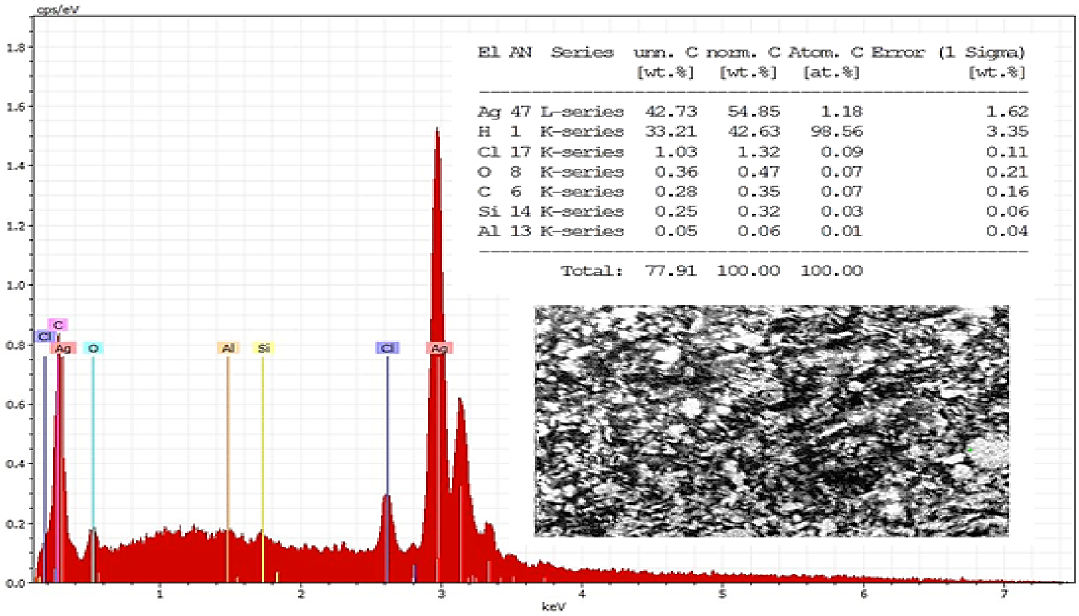


Figure 7. EDX spectrum analysis for coated PLA dry-contact electrode

3.2. Electrode-skin impedance performance

Figure 8 shows the average values of impedance's change between the electrode and the skin for ten subjects. Figure 8(a) in frontal site, the impedance of PLA-silver dry-contact electrode was approximately similar to the standard wet electrode, the impedance of PLA-silver dry electrode pair without gel application and skin preparation between (9.42-7.25KΩ) and the impedance change's between wet electrode pair with gel application about (8.79-5.77KΩ), the two electrodes measured the impedance's change of Fp2 region below 20 KΩ. Figure 8(b) in occipital site, the result shows the impedance changes of dry electrode is close to that of the wet electrode, the impedance of PLA-silver dry-contact electrode changed between (9.56-8.66KΩ) and for wet electrode between (9.54-8.05 KΩ) and all value located in acceptable range. Generally, when the electrode-skin impedance located in the range of acceptable value (below 20 KΩ), the EEG acquisitions can be conducted [26], [27].

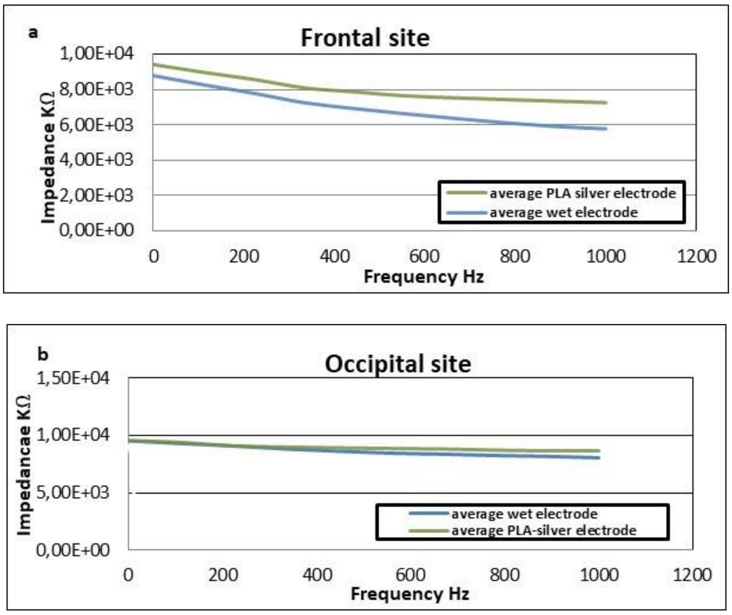


Figure 8. Electrode-skin impedance interface for two electrodes:
(a) in frontal site (without hair) and (b) in occipital site (hairy)

3.3. EEG signals acqusition

In order to approve the suitability of dry electrodes, EEG test must be performed on subjects. Comparative experiment between the dry and wet electrodes show the dry electrodes have the ability to measure EEG activity without any skin preparation and gel or saline application and had excellent consistency with the wet electrode. the average time correlation of the EEG signals collected by PLA-silver electrode and the wet electrode on forehead site is 91.4% as shown in Figure 9 (subjects were asked to close and open their eyes and could hyperventilation during the test), and it can reach 80% at the occipital as shown in Figure 10. This result show that the performance of the PLA-silver dry electrode in EEG collection in this state is almost equivalent to that of the wet electrode.

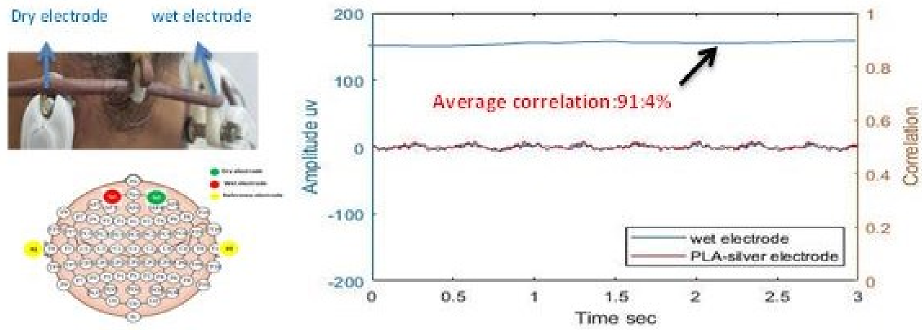


Figure 9. Signal comparison, as recorded by the wet electrodes and the PLA-silver dry electrodes at Fp1 and Fp2 site

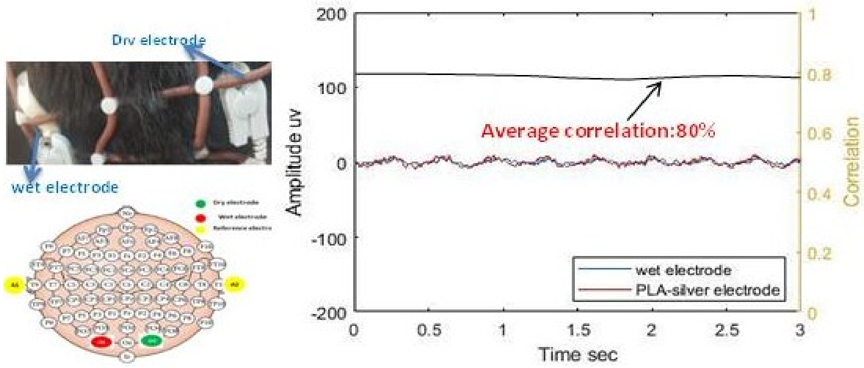


Figure 10. Signal comparison, as recorded by the wet electrodes and the PLA-silver dry electrodes at O1 and O2 sites

To discuss the results, the most relevant results from above reported experiments consists in the fact is that the proposed 3D printed PLA dry electrode allowed the recording of EEG. The signal trace and spectrum are very similar to the signal recorded by stansard wet electrode at the same time (Figure 10). The electrode-skin impedance characteristics of the dry electrodes are greatly affected by its actual contact surface. The contact surface is calculated based on the geometery of the pins (Figure 2). For multi-channels EEG application, the most important thing is th weight of electrodes (up to 256 electrodes can be used), here the 3D printed PLA dry electrode have only one gram in weight (Figure 3(c)). This make PLA dry electrodes are very suitable for long term measurements.

4. CONCLUSION

In the present work a 3D printed dry-contact electrode was designed and manufactured, and the EEG signal measurement was verified through experiments without any skin preparation or gel application. The advantage of a new dry electrode can be summaryzed in these points; (1) it can accomplish the required skin-electrode impedance to operate without conductive gel and skin preparation; (2) it designed with multi-pins to allow to pass through hair and make good electrode- scalp contact and measure EEG signal in site without hair and hairy site (3) it can provide good electrode-skin fitting without saline or gel conductive; (4) this process enables a low cost and rapid fabrication of the required electrode geometry. The experimental result show that the EEG signal quality achieved by a 3D printed dry electrode was coherent to that of conventional wet electrode. On the other hand, the 3D printed electrode weight only one gram which make it comfortable and painless for patient and make it suitable for EEG measurement with long-term.

REFERENCES

[1] D. J. Brenner and E. J. Hall, "Computed tomography-An increasing source of radiation exposure," *New England J. Med.*, vol. 357, no. 22, pp. 2277-2284, 2007, doi: 10.1056/NEJMra072149.
[2] M. L. G. Martín and P. L. Larrubia, Eds, "Preclinical MRI," *New York, NY, USA: Springer*, 2018, doi: 10.1007/978-1-4939-7531-0.
[3] R. B. Buxton, "Introduction to Functional Magnetic Resonance Imaging," *Cambridge, U.K.: Cambridge Univ. Press*, 2009, doi: 10.1017/cbo9780511605505.
[4] V. Kapoor, B. M. McCook, and F. S. Torok, "An introduction to PETCT imaging," *RadioGraphics*, vol. 24, no. 2, pp. 523-543, Mar. 2004, doi: 10.1148/rg.242025724.
[5] P. Hansen, M. Kringelbach, and R. Salmelin, "MEG: An Introduction to Methods," *London, U.K.: Oxford Univ. Press*, 2010, doi: 10.1093/acprof:oso/9780195307238.001.0001.
[6] P. L. Nunez and R. Srinivasan, "Electric Fields of the Brain: The Neurophysics of EEG," *London, U.K.: Oxford Univ. Press*, USA, 2006.
[7] A. J. Casson, D. C. Yates, S. J. M. Smith, J. S. Duncan, and E. Rodriguez-Villegas, "Wearable Electroencephalography," in *IEEE Engineering in Medicine and Biology Magazine*, vol. 29, no. 3, pp. 44-56, May-June 2010, doi: 10.1109/MEMB.2010.936545.
[8] P. Kidmose, D. Looney, M. Ungstrup, M. L. Rank, and D. P. Mandic, "A Study of Evoked Potentials From Ear-EEG," in *IEEE Transactions on Biomedical Engineering*, vol. 60, no. 10, pp. 2824-2830, Oct. 2013, doi: 10.1109/TBME.2013.2264956.
[9] V. Goverdovsky, D. Looney, P. Kidmose, and D. P. Mandic, "In-Ear EEG From Viscoelastic Generic Earpieces: Robust and Unobtrusive 24/7 Monitoring," in *IEEE Sensors Journal*, vol. 16, no. 1, pp. 271-277, Jan. 2016, doi: 10.1109/JSEN.2015.2471183.
[10] T. C. Ferree, P. Luu, G. S. Russel, and D. M. Tucker, "Scalp electrode impedance, infection risk, and EEG data quality," *Clinical neurophysiology*, vol. 112, no. 3, pp. 536-544, 2001, doi: 10.1016/S1388-2457(00)00533-2.
[11] A. S. Oliveira, R. Schlink, W. D. Hairston, and D. P. Ferris, "Induction and separation of motion artifacts in EEG data using a mobile phantom head device," *Journal of Neural Engineering*, vol. 13, no. 3, p. 036014, 2016, doi: 10.1088/1741-2560/13/3/036014.
[12] M. Teplan, "Fundamentals of EEG measurement," *Meas. Sci. Technol*. vol. 2, no. 2, pp. 1-11, 2002.
[13] A. Searle and L. Kirkup, "A direct comparison of wet, dry and insulating bioelectric recording electrodes," *Physiological Measurement,* vol. 21, no. 2, pp. 71-83, 2000, doi: 10.1088/0967-3334/21/2/307.
[14] C. Fonseca *et al.,* "A Novel Dry Active Electrode for EEG Recording," in *IEEE Transactions on Biomedical Engineering,* vol. 54, no. 1, pp. 162-165, Jan. 2007, doi: 10.1109/TBME.2006.884649.
[15] A. Gruetzmann, S. Hansen, and J. Müller, "Novel dry electrodes for ECG monitoring," *Physiological Measurement*, vol. 28, no. 11, pp. 1375-1390, 2007, doi: 10.1088/0967-3334/28/11/005.
[16] Z. Wang *et al.,* "A Multichannel EEG Acquisition System With Novel Ag NWs/PDMS Flexible Dry Electrodes," *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2018, pp. 1299-1302, doi: 10.1109/EMBC.2018.8512563.
[17] H. Hua, W. Tang, X. Xu, D. D. Feng, and L. Shu, "Flexible Multi-Layer Semi-Dry Electrode for Scalp EEG Measurements at Hairy Sites," *Micromachines (Basel)*, vol. 10, no. 8, p. 518, 2019, doi: 10.3390/mi10080518.
[18] L. Juntao *et al.,* "A noval dry-contact electrode for measuring electroencephalography signals," *Sensors and Actuators A: Physical*, vol. 294, pp. 73-80, 2019, doi.org/10.1016/j.sna.2019.05.017.
[19] G. Li *et al.,* "Towards emerging EEG applications: A novel printable flexible Ag/AgCl dry electrode array for robust recording of EEG signals at forehead sites," *J. Neural Eng*, vol. 17, no. 2, 2020, doi: 10.1088/1741-2552/ab71ea.
[20] Wearable Sensing. Available online: http://www.wearablesensing.com/ (accessed on 28 January 2021).
[21] Neuroelectrics Enobio. Available online: http://neuroelectrics.com/ (accessed on 28 January 2021).
[22] V. Mihajlović, B. Grundlehner, R. Vullers, and J. Penders, "Wearable, Wireless EEG Solutions in Daily Life Applications: What are we Missing?," in *IEEE Journal of Biomedical and Health Informatics*, vol. 19, no. 1, pp. 6-21, Jan. 2015, doi: 10.1109/JBHI.2014.2328317.
[23] g.tec. Available online: http://www.gtec.at/ (accessed on 28 January 2021).
[24] Cognionics. Available online: http://www.cognionics.com/ (accessed on 28 January 2021).
[25] Florida Research Instruments. Available: http://www.floridaresearchinstruments.com/ (accessed on 28 January 2021).
[26] M. Lopez-Gordo, D. Sanchez-Morillo, and F. Valle, "Dry EEG Electrodes," *Sensors*, vol. 14, no. 7, pp. 12847-12870, Jul. 2014, doi: 10.3390/s140712847.
[27] E. Habibzadeh Tonekabony Shad, M. Molinas, and T. Ytterdal, "Impedance and Noise of Passive and Active Dry EEG Electrodes: A Review," in *IEEE Sensors Journal*, vol. 20, no. 24, pp. 14565-14577, Dec. 2020, doi: 10.1109/JSEN.2020.3012394.