Development of Dry EEG Electrodes and Dry EEG Cap for Neuromonitoring

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***Abstract*— Monitoring and recording of electroencephalogram (EEG) is a non-invasive procedure that is increasingly used in neuromonitoring. Patient management is assessed and tailored based on the acquired brain signals that indicates the neurological state of the patient. Conventional EEG systems are wet systems. EEG recording in itself is not painful, but scalp preparation for the electrode attachment and washing afterwards may be uncomfortable. In this paper, a soft flexible gel-free dry electroencephalogram (EEG) electrodes and dry EEG head cap is developed and proposed. The dry EEG electrodes is a hybrid packaging rigid metal snap connectors, soft and flexible polymer material, and Silver-Silver Chloride (Ag-AgCl) coating. The sensor body/ structure does not use conductive polymer and there is no peeling off of the structure that could lead to concern in signal degradation. The dry EEG head cap is a fully-adjustable one-piece stretchable material integrated with reference and ground electrodes. Impedance reading of wet system is <5 KOhms, mainly due to the use of electrolytic/ conductive paste with such system. The proposed dry electrodes have impedance readings measured at <65 KOhms, which is lower compared to commercially available dry EEG electrodes that have impedance readings between 100 KOhms and 2000 KOhms. Despite the difference in impedance readings between the conventional wet system and the proposed dry electrodes, the captured brain signals / brain wave patterns are comparable. These brain signals are important especially when utilized for brain computer interfaces (BCI) that power and drive limb orthotic for rehabilitation following a stroke. The dry electrodes passed biocompatibility tests, specifically cytotoxicity test per ISO-10993-5 and primary skin irritation tests per ISO-10993-10.**

Keywords—dry EEG electrodes, flexible hybrid electronics, neuromonitoring

I. INTRODUCTION

Neuromonitoring is the process of acquiring neural / brain signals, evaluating potential neurological problems associated with these signals, and providing clinical assessment and intervention [1]. Monitoring and recording of electroencephalogram (EEG) is a non-invasive procedure that is increasingly used in neuromonitoring. In EEG, brain signals are continuously or intermittently recorded. The recorded brain signals usually look like wavy patterns and clinicians could quickly assess the problem based on abnormalities in these patterns [2].

EEG monitoring is done for various reasons, this includes seizures or epilepsy, sleep disorders, brain and head injuries, memory problems, and detection of abnormalities in the brain signals in comatose cases. It is also used for EEG-based rehabilitation of limb control following a stroke.

EEG monitoring is non-invasive and painless and does not require patients on prescribed medication to stop taking their medication prior to the testing [3]. EEG Technologists are also usually equipped to manage situations like epileptic seizures during testing. The discomfort usually comes from the EEG set-up and skin preparation done immediately prior to the actual EEG recording, especially for small children.

In conventional EEG wet systems, aside from the patient required to have a clean hair and free from wax, hairsprays, oil, dirt, or any artificial hair on the day of the testing must be removed. The skin and electrode preparation, which usually lasts for about 20-30 minutes, starts with the EEG technician measuring the patient's head with a cloth tape measure. The head is then marked with a wax pencil the locations onto which the electrodes will be applied. These markings are specific to a person's head and locations are based on internationally-recognized 10-20 system of electrodes position on the head [4].

The EEG technician will then use electrode wires. One end of the wire has a small cylindrical plug for connection to the machine during EEG recording. The opposite end of the wire has metal disc or cup which will be attached to the marked locations on the scalp using the conductive/ electrolytic (adhesive) paste. The electrolyte gel or conductive paste is also used to stabilize the signal and to the impedance between electrode and skin [5]. Before the technician attached the electrodes on the scalp, a small amount of skin preparation gel will be scrubbed on the marked location using a cotton bud or Q-tip. Once scalp scrubbing is done, sufficient amount conducting paste is placed on the metal disc or cup of the electrode then it will be attached to the scalp. Some use cotton ball to cover it, others use gauze. If the patient moves a lot, the gauze is sometime dipped in a chemical that dries very sticky. After all electrodes are attached on all the locations on the scalp, EEG recording starts and usually lasts 30-60 minutes or more, depending on what is required by the clinician. The entire procedure could take around one to 2 hours. After the test is done, the technician will remove each electrode from the scalp. Cleaning or washing of the hair is necessary afterwards.

For longer EEG monitoring, like in ambulatory cases which takes 24 hours or more of recording [6], there is a high possibility of degradation of the brain signal/ impedance quality as the electrolyte gel dries out.

There are wet systems that uses a cloth head cap with electrode hole locations corresponding to 10-20 position and is used in conjunction with electrode with cavity. BioSemi introduced this head cap along with sintered Silver-Silver Chloride (Ag-AgCl) electrodes with cavity. They do not require skin preparation. The electrolyte gel is dispensed on each electrode cavity in the cap [7]. However, hair washing is still needed after EEG monitoring because electrolyte gel is used.

Dry EEG electrodes do not require skin preparation nor conducting paste when used. The electrodes are often made of a number of rigid metal pins [8]. Some consist of spring-loaded golden alloy metal pins to maintain a close contact between sensor to scalp [9]. However, the combination of cloth EEG head cap and rigid metal pins could pose discomfort to patients if the system is used for a period of time. It also leaves metal pin marks on the scalp and forehead.

There are also dry EEG electrodes made of 3D-printed flexible materials coated with conductive polymer [10]. The corresponding headset is made of both plastic and metal components. However, because the conductive polymer is only coated on the surface of the electrode structure, peeling-off of conductive polymer is expected and encountered on repeated use. This also leads to degradation in impedance readings.

The proposed dry EEG system – dry EEG electrodes and dry EEG cap- shortens the preparation time by eliminating the scalp procedure. The dry EEG electrodes are made of soft flexible material that conforms to the contours of the scalp. In order to integrate dry EEG electrodes, a customized stretchable dry EEG head cap is also proposed. Current available dry EEG headsets in the market are made of rigid thermoplastic materials. For this study, the dry EEG head cap is made from fully-adjustable one-piece stretchable material. Snap connector wires for reference and ground electrodes are also integrated in the cap. The head cap follows the standard 10-20 position recognized to describe the location of the electrodes on the scalp. The head cap also has a built-in harness for easy repositioning of the electrodes. The size of the dry EEG cap can be further adjusted based on the actual head measurement of the user following 10-20 position

II. DESIGN CONCEPT

A. Dry EEG Electrodes

The proposed dry EEG electrode is a hybrid packaging of rigid metal snap connector, flexible polymer material, and Silver-Silver Chloride (Ag-AgCl). As shown in Fig.1, the sensor structure is designed with six (6) legs. This could be redesigned to have more and to have a different form/ structure depending on the location on the head. A rigid metal snap connector is used on top of the sensor structure. This connector matches with the snap connectors that is located in the proposed dry EEG head cap. A soft and flexible polymer material, like polydimethylsiloxane (PDMS), is used for the sensor body/ structure. PDMS do not peel-off as compared to sensors/ electrodes with conductive polymer coating on the body. The tip of the electrodes structure or recording electrodes will be coated with Silver-Silver Chloride (Ag/AgCl). Only the tip will have the coating and not the whole structure. Ag-AgCl is used because of its stability in sensing biopotentials.

The whole dry EEG sensor structure will be attached to the to the snap connector of the dry EEG cap and the recording electrode portion will be touching the scalp during brain signal recording.

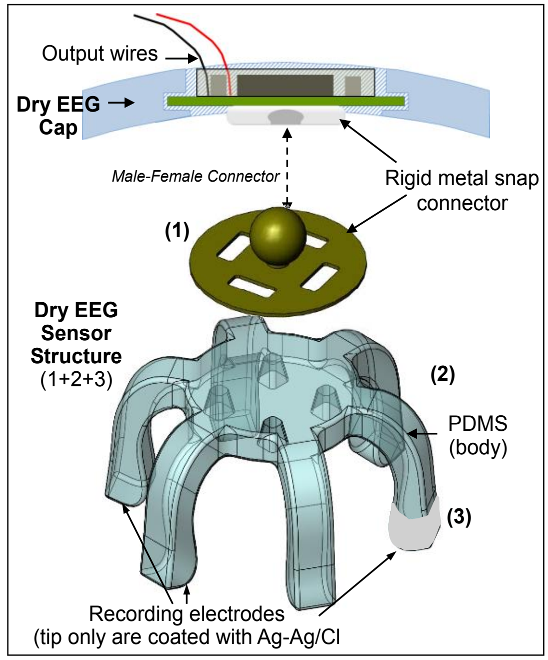


Figure 1: Schematic of the packaging of the proposed dry EEG electrodes. Main components are rigid metal snap connectors, PDMS, and Ag/AgCl.

B. Packaging of Dry EEG Head Cap

The concept for the packaging of the EEG head cap is shown in Fig. 2. The head cap is proposed to be a one-piece stretchable and adjustable structure while following the international 10-20 system for electrode location. The 10-20 system is the internationally recognized method for placement of electrodes on the scalp during EEG monitoring. The 10-20 refers to 10% and 20% of the actual distance measured from front to back and left to right of the head [xx].

The proposed dimension is suitable for children's head sizes of 46-52 cm and up to 60 cm for adults. The EEG wires or cables with 1.5 mm DIN connector plug on one end and with rigid metal snap connectors on the other end will be integrated with the cap. These include the wires for the ground and reference electrodes. The quantity of these cables will be adjustable based on the number of utilized channels / electrodes. Any signal amplifier will be placed on the snap connector portion.

For this study, only 10 channels are proposed. Active circuit, i.e. signal amplifier on the snap connectors at the dry EEG cap portion, will not be included yet because it is necessary to verify first the functionality of both dry electrodes and head cap. It is also necessary to determine if the user could easily use the head cap and electrodes without any scalp preparations.

III. Fabrication & Assembly

A. *Dry EEG Electrodes Fabrication*

Figure 3 shows the fabricated dry EEG electrodes. There are three different designs fabricated. Design A and B, which are legged structures, are meant for the hairy part of the scalp since the structure legs can go through the hair. Design C, which is the flat disc type, is meant for forehead or less-hairy part of the scalp. The difference in the dimension of the three designs are listed in Table 1. There is no difference in the assembly, packaging method, and functionality of the three structures. All are fabricated using the same process flow and using the same parameters. After the rigid snap connectors are integrated with the flexible polymer, the sensors are cleaned and inspected. Silver-Silver Chloride (Ag-AgCl) is coated at the tip of the electrodes by dipping process. Ag-AgCl is cured for 5 minutes at 130ºC.

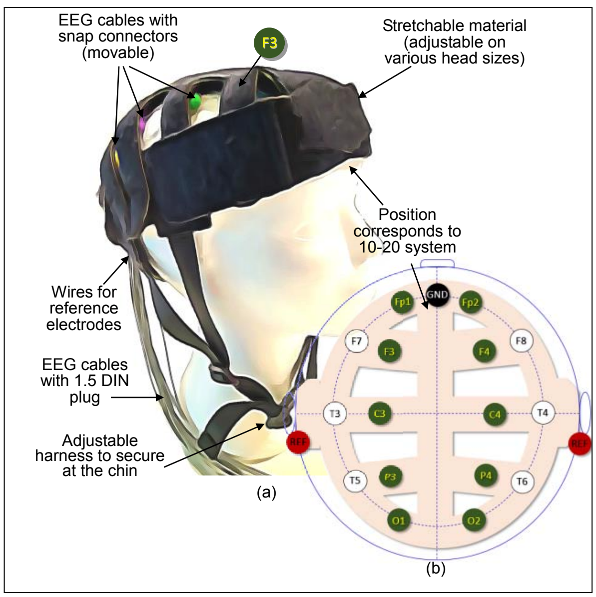


Figure 2: Schematic of the packaging of the proposed head cap. (a) The number of EEG cables with snap connectors corresponds to the number of channels. The snap connectors are movable for easy repositioning of electrodes. Adjustable harness at the chin will be used to secure the cap during testing. (b) The head cap structure corresponds to 10-20 system. Green-coloured dots correspond to 10 channels. Two reference and ground electrodes are located as shown in the illustration.

B. *Dry EEG Headcap Fabrication*

The dry EEG cap fabricated is shown in Fig. 4. It is fabricated using a breathable Neoprene fabric of at least 3mm thick cut into a one-piece structure. Neoprene fabric is commonly used for wetsuits. As shown in Fig. 4(a), a low-lint Velcro backing and fastener is utilized for the cap as well as for the snap connector portion of the electrode wires. The lining inside the cap is made of waterproof material to make more it sweat-proof and for easy cleaning on repeated use. When the electrode wires are removed, the cap is machine-washable. This is necessary when wipe-cleaning is not enough or if the head cap is already soiled and dirty. Figure 4(b) shows that the head cap has built-in harness for easy repositioning of the electrodes. The built-in harness also allows the option for additional electrode wires for more channels while still following the international 10-20 system. The reference wires located behind the ears and the ground electrode wire at the forehead are already integrated with the head cap, therefore, ear clips or conducting paste are not required. There is no need for external electrodes for this purpose. The chin strap is adjustable to secure the cap in the head while the Velcro behind the ears cater for different ear sizes. The whole cap is foldable and packable. This may be helpful in ambulatory cases. The head cap is currently is used for wired system, i.e. the electrode wires are directly plugged in the recording / monitoring system.

TABLE I. Dry EEG Electrode Design difference

Description	Sensor Electrode Design		
	Design A (Thin-Legged)	***Design B (Thick-Legged)***	***Design C (Disc)***
Span (as is)	24.0 mm	16.0 mm	16.0 mm
Total Thickness (including snap connector)	11.7 mm	13.6 mm	4.5 mm
Span (pressed down)	30.0 mm	22.0 mm	16.0 mm
No. of Legs	6	6	N/A
Leg Width	2.4 mm	3.0 mm	N/A
Leg Length	~10 mm	7.0 mm	N/A
Leg Thickness	1.93 mm	3.5 mm	N/A
Ag-AgCl on Tip	Yes	Yes	Yes

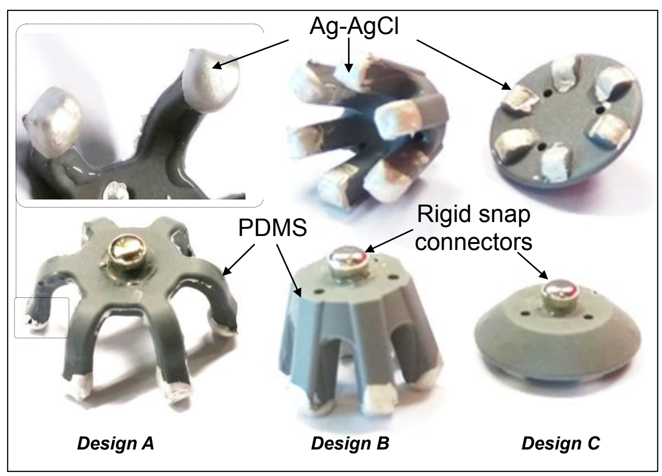


Figure 3: Photo of the fabricated dry EEG electrodes. There are three (3) designs which differ in shape. Design A and B are for portion of the scalp with hair. Design C is meant for forehead. All are with Ag-AgCl at recording site by dipping process.

Figure 4: Photo of the fabricated dry EEG head cap integrated with EEG electrode wires as well as ground and reference electrode wires. It could be disassembled into one-piece component only. The cap is suitable for children's head sizes of 46-52 cm and up to 60 cm for adults. The built-in harness allows for repositioning of electrodes and for adding or replacing of electrode wires while maintaining to 10-20 system for placement of electrodes on the cap.

IV. Experimental Results

A. Biocompatibility Testing

Cytotoxicity test per ISO-10993-5 and primary skin irritation test per ISO-10993-10 of the dry EEG electrodes are performed. Test results showed that the dry electrodes passed biocompatibility with no cytotoxic effect. During the 72-hour observation period, no skin irritation was observed. Primary Irritation Index is 0, which means a negligible irritation response category.

B. Comfortability of the dry EEG head cap

To test for the comfort to the user, technicians are asked wear the head cap with electrodes and are asked basic questions answerable by yes and no only. Table 2 summarizes the results. The proposed dry EEG system comfortable to use when sitting and up to a certain time when lying down.

C. Institutional Review Board (IRB Approval)

Since functionality testing requires human subjects, an Institutional Review Board (IRB) approval is obtained. The IRB ensures the safety of the study and the recruitment of human subjects is equitable. The study protocol Wearable Wireless EEG Recording System with Gel-free Active Electrodes for Long-Term Epilepsy Monitoring was approved through Singhealth Centralised IRB (CIRB) under reference number 2017/2118.

D. Functionality Testing

For functionality testing, Design B is used. Testing of the dry EEG system is performed by comparing its performance with a conventional wet system. Nihon Kohden EEG System is used. Initially, impedance readings were taken and then brain wave/ signal patterns were taken using two conditions: (a) during eyes closed and (b) during eyes open. Then three (3) test protocols were run in the following sequence:

1). *All dry system.* Test using dry EEG head cap and all dry EEG electrodes first. This includes dry reference (A1 and A2) and ground electrodes (Z).

2). Change five dry to wet electrodes. Switch the five (5) dry electrodes (A1, A2, C3, C4, and Z) to wet electrodes while keeping the rest of the dry electrodes.

3). *All wet electrodes*. Finally, test using all conventional wet electrode system.

This order was done in order to carefully evaluate a full dry system without any tampering of the target area, where scalp preparation/ cleaning and conductive paste is necessary in the wet electrode set up.

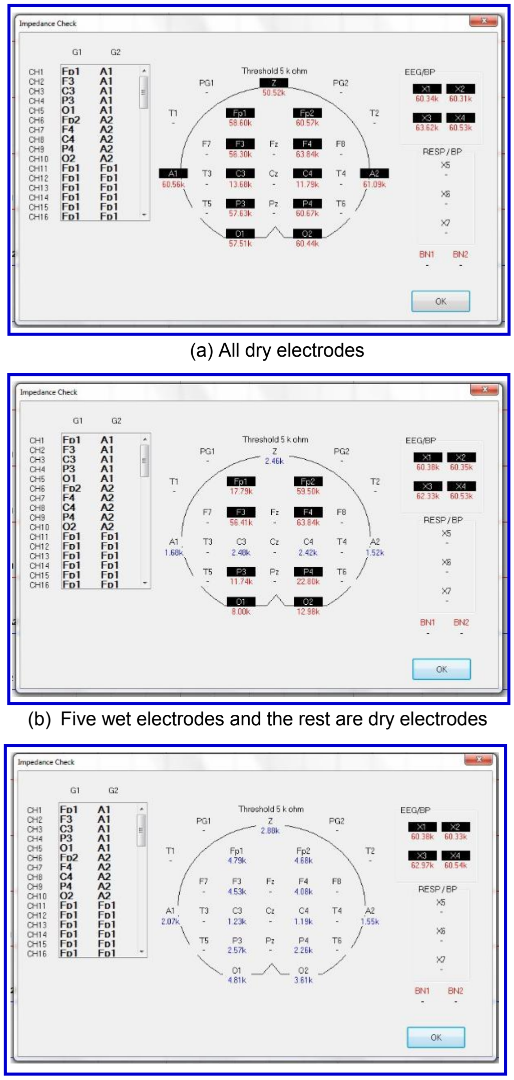
As shown in Fig. 5(a), the impedance of all the dry system, is measured at <65 KOhms. This is the same even when reference and ground electrodes were replaced as shown in Fig. 5(b). The wet system is only in the range of <5 KOhms only as shown in Fig. 5(c). This is expected when skin preparation is performed and conductive paste is used on each electrode.

The proposed dry EEG electrodes have impedance of <65 KOhms, which is lower than commercially available dry EEG electrodes that have impedance readings in the range of 100 ~ 2000 KOhms [11].

After the impedance checking, recording of the brain signal/ brain wave patterns was done. During the recording, eye open and close actions were done to observe if the dry EEG electrodes are able pick up brain signals. Figures 6 and 7 shows the captured brain signals by the electrodes during the recording.

TABLE 2. SUMMARY OF ASSESSMENT ON COMFORT OF THE DRY EEG HEAD CAP WITH DRY ELECTRODES

Item	**Reviewer**		
	Tech1	***Tech2***	***Tech3***
Easy to Assemble	Yes	Yes	Yes
Easy to wear	Yes	Yes	Yes
Easy to reposition electrode connectors	Yes	Yes	Yes
Comfortable (sitting position)	Yes	Yes	Yes
Comfortable (lying down)	Yes, depending on the electrode type	Yes, up to 30min of use	Yes, up to 30min of use



(a) All dry electrodes

(b) Five wet electrodes and the rest are dry electrodes

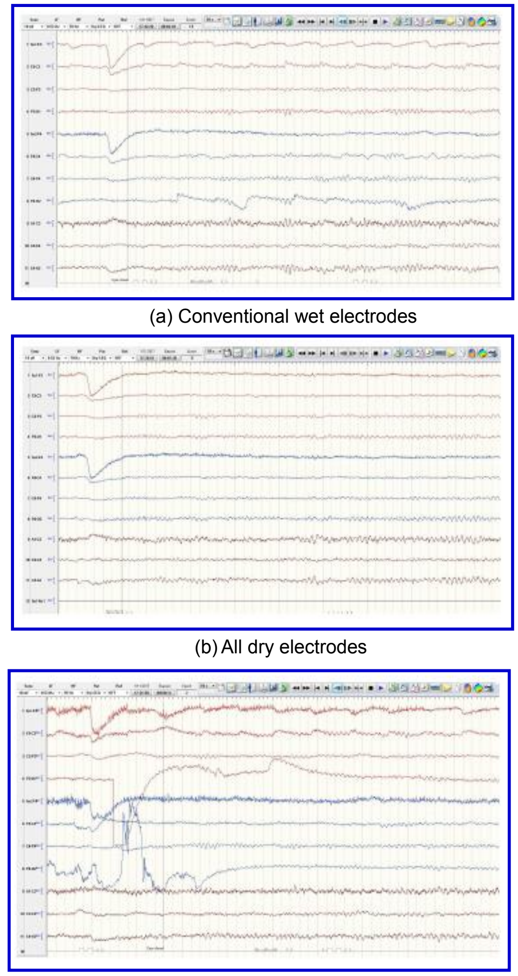
(c) All conventional wet electrodes

Figure 5: Impedance readings of (a) full dry system using dry EEG head cap and dry EEG electrodes wet electrodes is <65 KOhms. (b) The readings are the same when reference and ground electrodes are changed. (c) Impedance of wet system is <5 KOhms. This is due to scalp cleaning and conductive paste.

Figure 6(a) and 6(b) shows that during eyes closed, both wet and dry systems could capture brain signals, with brain wave appearing to be similar. The same is true for recording with eyes open, as shown in Figure 7(a) and 7(b). During EEG recording with eyes closed and eyes open, the dry EEG head cap and dry EEG electrodes are able to pick up the brain signals/ wave patterns that were similar to the ones picked up by the conventional wet electrodes. Capturing the brain signals is important in neuromonitoring since it can be translated to correlation between ischaemic and metabolic changes. It could also be used to assess non-convulsive seizures.

As for the comfort to the user, technicians are asked wear the head cap with electrodes and are asked basic questions answerable by yes and no only. Table 2 summarizes the results. The proposed dry EEG system comfortable to use when sitting and up to a certain time when lying down.

Cytotoxicity test per ISO-10993-5 and primary skin irritation test per ISO-10993-10 of the dry EEG electrodes are performed. Test results showed that the dry electrodes passed biocompatibility and skin irritation testing.



(a) Conventional wet electrodes

(b) All dry electrodes

(c) Dry electrodes with wet reference and ground

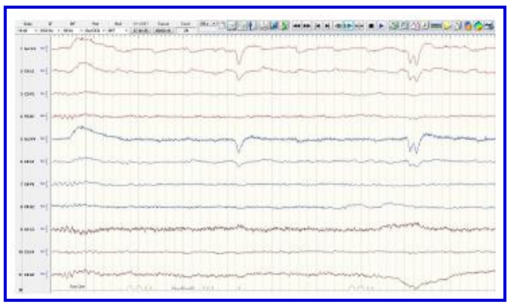
Figure 6: Brain wave signals acquired when the EYES ARE CLOSED. Regardless of the impedance readings, the brain wave patterns for both (a) wet and (b) dry system using the head cap are similar.

V. Conclusion

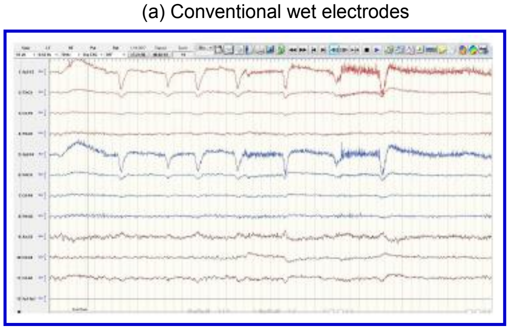
In this work, we presented a dry EEG system composed of dry EEG electrodes and dry EEG head cap. The dry EEG electrode is a hybrid packaging rigid metal snap connector, polymer-based sensor structure, and Silver-Silver Chloride (Ag-AgCl). The use of Ag-AgCl at electrode tip ensured stable sensing /acquisition of biopotentials. The impedance readings obtained are in the range of <65 KOhms which is lower than commercially available dry electrodes that are in the 100 KOhms ~ 2000 KOhms range. Although impedance vastly differs with conventional wet system, which is only in

<5 KOhms range, the dry electrodes managed to acquire similar brain signals/ brain wave patterns as the wet system.

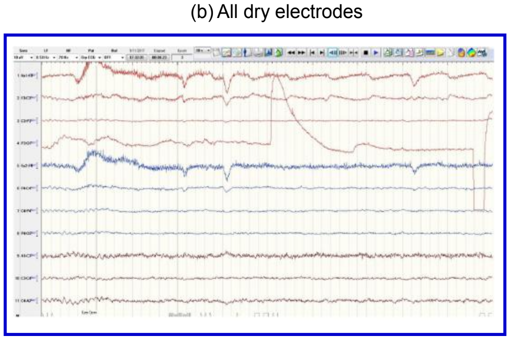
The use of flexible polymer for sensor structure ensured that no peeling-off of conductive layer during continuous or repeated usage. The dry electrodes also passed biocompatibility and primary skin irritation tests. As this is a dry system, no scalp scrubbing is required and electrolyte/ conducting paste is not used. The dry EEG cap is fully-adjustable, stretchable, and is packaged/ assembled with a built-in harness for the easy re-adjustment of the electrode wires while following the 10-20 system. Breathable Neoprene fabric with Velcro-compatible backing and a waterproof lining is used for easy cleaning on repeated use. Therefore, the developed dry EEG electrode and head cap can be used for brain signal acquisition that could be used for neuromonitoring. Further optimization/ modification of the electrode and cap may be needed based on specific user requirements.



(a) Conventional wet electrodes



(b) All dry electrodes



(c) Dry electrodes with wet reference and ground

Figure 7: Brain wave signals acquired when the EYES ARE OPEN. Regardless of the impedance readings, similar brain wave patterns for both (a) wet and (b) dry system using the head cap are recorded.

VI. ACKNOWLEDGMENT

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