33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Fabric Circuit Board-Based Dry Electrode and its Characteristics for Long-Term Physiological Signal Recording

Jerald Yoo[1,2] and Hoi-Jun Yoo[3]

[1]Masdar Institute of Science and Technology, Abu Dhabi, UAE (jyoo@masdar.ac.ae)
[2]Massachusetts Institute of Technology, Boston, MA, 02139, USA
[3]Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea (hjyoo@ee.kaist.ac.kr)

***Abstract*—This paper presents a dry fabric electrode and its characteristics. For long-term physiological signal monitoring, conventional wet type electrode such as an Ag/AgCl electrode may not be sufficient, because captured signal strength degrades over time as its electrolyte dehydrates. Moreover, the electrolyte may cause skin irritation over a period of time.**

As a complement, a dry electrode can be used. In this work, fabric-based dry electrodes are introduced. Planar-Fabric Circuit Board (P-FCB) technology enables low cost and uniform productions of such electrodes; electrical properties of the electrodes with various materials, sizes, and time are shown. Both the strengths and drawbacks of the fabric-based electrodes are also discussed.

I. Introduction

INCREASING number of patients who have chronic diseases are becoming major issues in many developed countries. Since many chronic diseases are extremely difficult to cure, the best way to deal with it is to not get it in the first place. Even if a patient is already suffering from them, good choice would be to prevent it from getting worse. In both cases, continuous, proactive healthcare is of essential.

In order to realize continuous, proactive healthcare, monitoring physiological signals over an extend period of time is important [1],[2]. Surface electrode is one of the fundamental components in capturing physiological signals, by interfacing between human skin and electronics.

There are largely two types of surface electrodes: wet and dry [2]. Table I compares the two types of electrode. Ag/AgCl electrode is a commonly used wet type electrode. It has lower skin-electrode impedance (around 3kΩ to 50kΩ) than a dry type has (100 kΩ to 1MΩ), which leads to better signal quality. Because of this, Ag/AgCl electrodes with electrolyte gel are popular for ambulatory physiological signal recording (electrocardiogram (ECG), electroencephalogram (EEG), electrooculogram (EOG), and electromyogram (EMG)). Both are weak to motion artifacts, but the dry type tends to be more susceptible to it [3]. When it comes to long term usage, signal strength degrades in Ag/AgCl electrodes as the electrolyte dehydrates over time [2]. Overall, the wet type is more suitable for clinical recording which lasts less than a day, whereas the dry type fits better for long term, continuous monitoring.

TABLE I.
Comparison between Dry and Wet Electrodes

Type	Wet (Ag/AgCl)	Dry (FCB)
Skin-electrode impedance	☺ Low (3k – 50k)	☹ High (100k – 1M)
Mechanism	Ion charge redistribution	Electric field difference
Motion artifact	Ionic current in space charge layer results in interference	Skin extension results in baseline drift
Time variance	☹ Signal degradation as electrolyte dries out	☺ Stable over time
Skin irritation	☹ Problem, esp. for infants	☺ Low irritation
Application	Clinical recordings for precise recordings	Chronic monitoring

This paper provides an introduction to fabric circuit board-based dry electrode and its electrical characteristics.

II. Dry Electrode for Long-Term Bio-Signal Monitoring

There are 3 reasons why the dry electrode is more appropriate than wet types for continuous, long-term physiological signal capturing or monitoring:

1) *Safety*: Wet electrodes have a toxicological issue that the electrolyte gel may cause skin irritation [3]. This becomes more serious as recording time expands over several days. Dry type is free from this issue as there is no electrolyte between skin and the electrode.

2) *No Signal degradation*: Figure 1 shows a skin-electrode circuit model [4]. For wet type, dehydration results in significant increase in R_{Gel}. Consequently, the skin-electrode impedance tends to increase, and signal quality degrades both due to loading effect and more thermal noise. Again, dry type is free from this issue as it does not rely on electrolyte.

3) *Convenience*: Preparing electrode gel, applying on skin and removing afterwards is annoying process, and time- and cost-consuming. Dry type is relatively convenient.

To overcome the abovementioned issues, several works have shown dry electrodes for long term monitoring [5]–[7]. [5] shows a Au-coated electrode on PCB, and does not cause

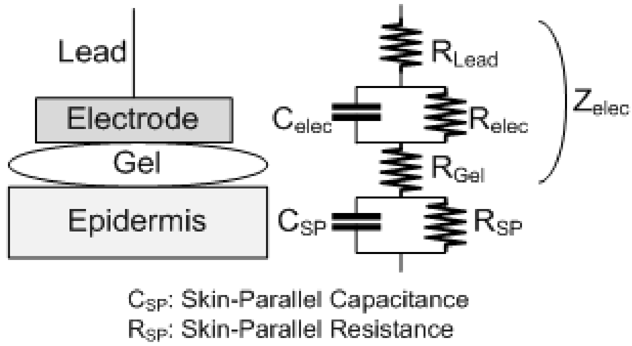

Fig. 1. Skin-Electrode Electrode Circuit Model

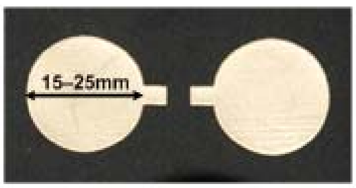

Fig. 2. P-FCB-Based Dry Electrode.

skin irritation. However, as PCB is too stiff to be attached on skin for long term, it is not the best solution. The Biopotential Fiber Sensor (BFS) is free from stiffness by using metal-coated fabric strands [7]. However, the BFS requires complicated electrochemical deposition with the rapid dipping technique, and hence the production cost is high.

III. Planar-Fashionable Circuit Board (P-FCB) Based Dry Electrodes

Planar-Fashionable Circuit Board (P-FCB) is a direct way of building circuit board on fabric [2],[8]. Because fabric is naturally very flexible, electrodes made out of P-FCB adhere to curvy skin very well, and it is a good candidate for long-term recording dry type electrodes. Also, the screen printing process that P-FCB adopts is suitable for mass production with uniform quality. Figure 2 shows a sample P-FCB electrode.

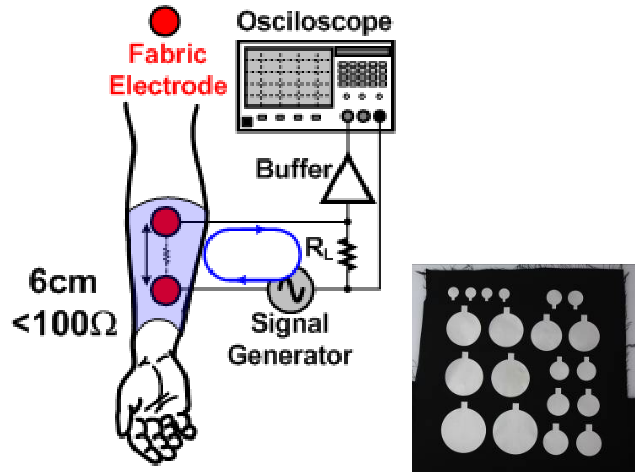

Fig. 3. Electrode Impedance Measurement Environment (Left) and a set of P-FCB Electrodes with Different Area (Right).

There is also a drawback in dry electrodes: skin-electrode contact impedance Z_{elec} is much higher than the wet type has. If Z_{elec} is large, a following amplifier must have higher input impedance to minimize loading effect. Higher Z_{elec} will also lead to more input noise, and this gives additional burden to the amplifier [8]. Therefore, Z_{elec} is an important factor in determining the amplifier specification. In the following Section IV, we are going to investigate Z_{elec} over several variables (time, frequency band, pressure, area and materials).

IV. Characteristics of Fabric-Based Dry Electrodes

A. *Measurement Environment*

Figure 3 shows the skin-electrode impedance (Z_{elec}) measurement environment. Two electrodes are placed on right arm, 6cm apart from each other. A signal generator generates sine wave that is applied to an electrode; a load resistor of R_L is placed to form a closed loop with a signal

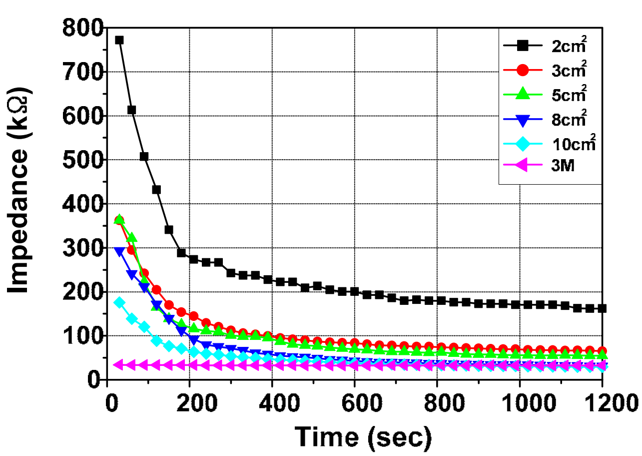

Fig. 4. Fabric Electrode Impedance vs. Time (57Hz Input Signal)

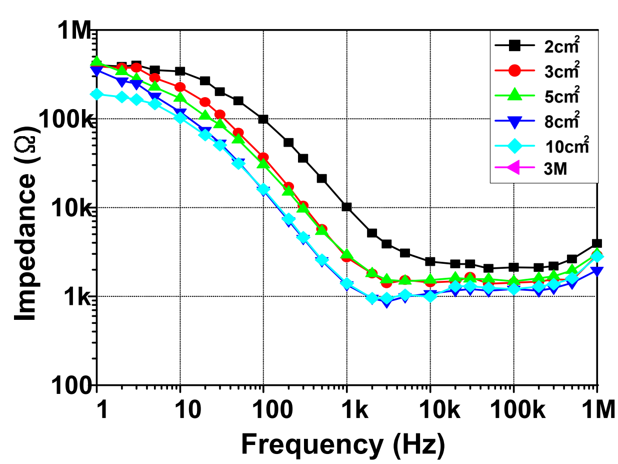

Fig. 5. Fabric Electrode Impedance vs. Frequency

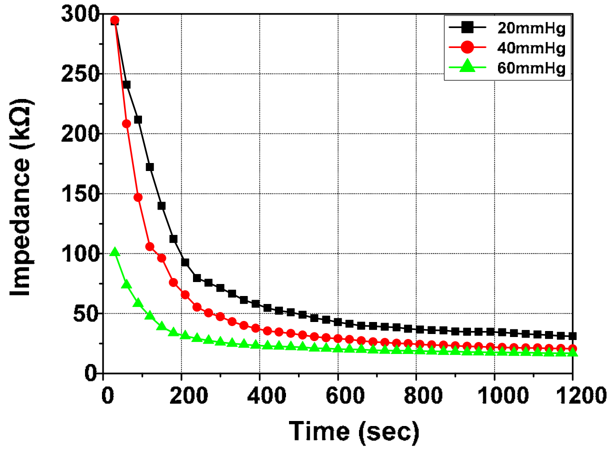

Fig. 6. Fabric Electrode Impedance over Pressure
(Electrode Area=8cm^2, 57Hz Input Signal)

generator, two electrodes, and skin. Electrodes are made with P-FCB, with various area, materials, and annealing time. Pressure is measured by surrounding the skin-attached electrode with an air-powered cuff with pressure gauge.

B. Impedance Variation on Time

Figure 4 shows the Z_{elec} time sweep result. (Input signal source at 50Hz, 40mmHg, R_L=40kΩ). We can observe the dry electrodes need more Z_{elec} settling time than the wet type has; Sweat may contribute to this stabilization time, and Z_{elec} stabilizes after 10 to 15 min. This is a problem for clinical usage, for example, measuring ECG signal which lasts less than several minutes; however, for long term monitoring or recording of physiological signals that will last more than several days, truncating the first 10 to 15 minutes is not a serious problem. Z_{elec} is measured to be 160kΩ for 2cm^2 / 30kΩ for 10 cm^2.

C. Impedance Variation on Frequency Band and Area

Z_{elec} change over frequency band (with different electrode area) is shown in Figure 5. Most of physiological signals lie below 1kHz, and within this range, dry type has approximately 5 to 10 times higher Z_{elec} than the wet type for a given electrode area. We can also notice that R_{elec} of Figure 1 decreases inversely proportional to the electrode area, hence, Z_{elec} also decreases; practically, the dry electrode should have an area of larger than 2cm^2 to have good signal quality. The measurement confirms that the fabric dry electrodes are more suitable for long term, health monitoring applications rather than for precise clinical recordings.

D. Impedance vs. Pressure

Z_{elec} variation over different pressure on skin is shown in Figure 6. A pair of 8 cm^2 dry fabric electrodes is attached on lower right arm, with load R of 45kΩ. It shows the more the pressure over the electrode pair, the less Z_{elec} we get. 20mmHg pressure gauge is approximately the same as firmly attached electrode patch. With an increased pressure, we can also reduce motion artifact.

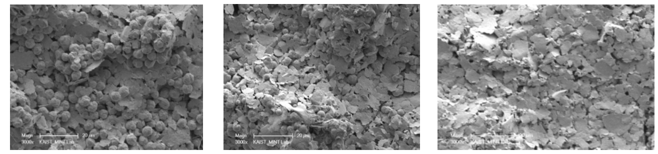

Fig. 7. Electrode Materials: Silver Paste with (a) Copper (10g), (b) Fe (7g) and (c) Tungsten (7g).

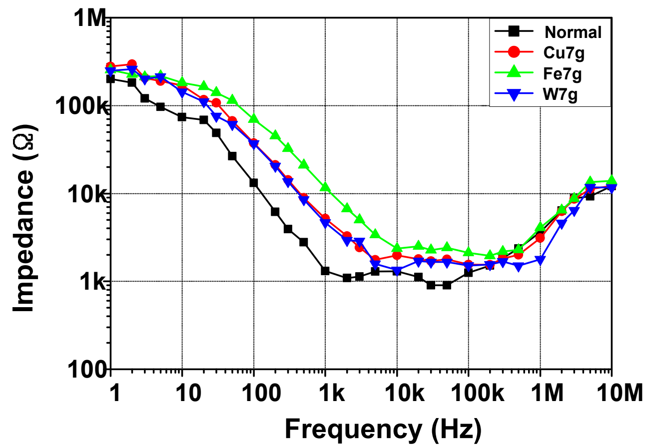

Fig. 8. Fabric Electrode Impedance with Metal Powders Added

E. Impedance vs. Material

So far all the measurement was done with Silver paste only. We can also add copper (Cu), iron (Fe) and tungsten (W) powder to the silver paste to reduce motion artifact, as the power helps increasing the adherence with the skin (Figure 7). Figure 8 shows the Z_{elec} measurement result. We can observe normal (Ag paste only) has the lowest Z_{elec} under 300kHz band; W, Cu and Fe follows. As expected, motion artifact was reduced at the cost of slightly increased Z_{elec}.

F. Annealing

When implementing the P-FCB electrode, we can control annealing condition Figure 9 shows the SEM photo of the electrode cross section, with different annealing time (all at 180°C). As we have the more annealing time, we get the more uniform coating of pastes layer. Even with more annealing time, Z_{elec} did not change more than 10%. However, sample-to-sample variation was reduced as annealing time was increased.

V. Dry Electrode Model

From the measurement results, the following skin-electrode impedance model of a P-FCB based dry electrode (after stabilization time) is fitted with respect to area S and frequency f:

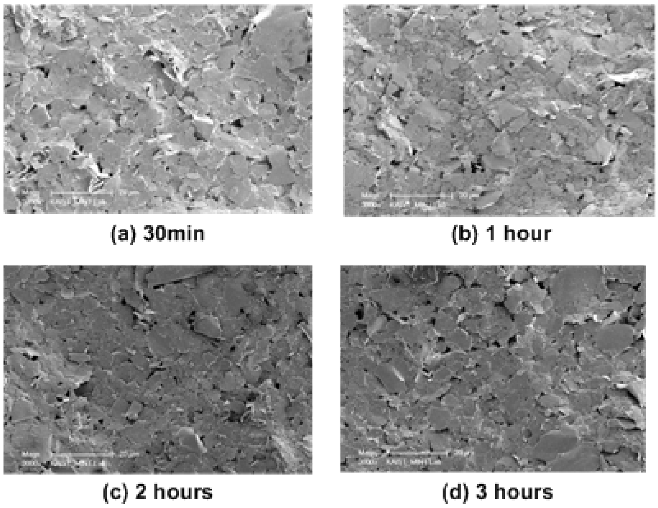

Fig. 9. SEM Photograph of Electrode Annealing over Time: (a) 15min, (b) 1 hour, (c) 2 hours, and (d) 3 hours (All at 180 °C).

$$\left|Z_{electrode}(S,f)\right| = \delta \frac{\left(1+\dfrac{f}{c_1 \cdot e^{-2.25S}}\right)\left(1+\dfrac{f}{c_2}\right)}{\left(1+\dfrac{50f}{S}\right)} \quad (1)$$

$$where\ \delta = 4.5\times10^5, c_1 = 10^4, S = area(cm^2).$$

(1) can be used to determine specifications of a biopotential acquisition amplifier which will accompany the P-FCB electrodes.

VI. Discussion

A. Summary

Table II summarizes the characteristics of P-FCB dry electrodes. Prospective electrode area is between 2 to 10cm^2, and the electrode material is silver paste with optional Cu, Fe or W powders for less motion artifact. The electrode requires 10+ minutes of stabilization time, and hence it is best fit for long term (that lasts more than a several days) physiological signal monitoring applications, in which missing the first 10 minutes does not impose problems.

B. Remaining Issues

Even with addition of steel powders, motion artifact is still a problem with dry electrodes. Adopting a small form-factor, adhesive patch that will firmly attach to a skin [8] is a good way to minimize the artifact. Investigation on other electrode materials is necessary as well.

VII. Conclusion

A dry electrode has strength over a wet electrode when it comes to continuous physiological monitoring: the dry type is free from electrolyte dehydration and skin irritation problem. Planar-Fabric Circuit Board (P-FCB) technology enables easy and low cost ways to build the dry electrodes.

TABLE II.
P-FCB Electrode Properties

Technology	Planar-Fashionable Circuit Board
Electrode Area	2 to 10 cm^2
Material	Ag on Fabric / Cu, Fe, W powders (Optional)
Stabilization Time	10 minutes
Skin-Electrode Impedance Range	100k – 1M (At DC) 30k – 200k (At 100Hz)
Application	Long Term Physiological Signal Monitoring and Recording

Skin-electrode impedance (Z_{elec}) of P-FCB-based fabric electrodes is examined under different conditions: 1) Z_{elec} over time, 2) Z_{elec} over the electrode area, 3) Z_{elec} over various materials, and 4) Z_{elec} over pressure. Experiment and measurement confirms dry electrode requires a stabilization time of 10 minutes or more, with larger area having smaller value. Silver-only paste shows the least Z_{elec}. Annealing condition did not show noticeable difference in Z_{elec}, but sample-to-sample variation was decreased with more annealing time. The fabric-based dry electrodes enable long term physiological signal monitoring at low cost.

Acknowledgment

The authors thank Mr. Long Yan for his helpful discussions, and Mr. Hyungwoo Lee and Miss Sunjoo Hong for their assistance in measurements.

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