Feasibility of Patterned Vertical CNT for Dry Electrode Sensing of Physiological Parameters

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***Abstract*—Dry electrodes for impedimetric sensing of physiological parameters (such as ECG, EEG, and GSR) promise the ability for long duration monitoring. This paper describes the feasibility of a novel dry electrode interfacing using Patterned Vertical Carbon Nanotube (pvCNT) for physiological parameter sensing. The electrodes were fabricated on circular discs (ϕ = 10 mm) stainless steel substrate. Multiwalled electrically conductive carbon nanotubes were grown in pattered pillar formation of 100 µm squared with 50, 100, 200 and 500µm spacing. The heights of the pillars were between 1 to 1.5 mm. A comparative test with commercial ECG electrodes shows that pvCNT has lower electrical impedance, stable impedance over very long time, and comparable signal capture in vitro. Long duration study shows minimal degradation of impedance over 2 days period. The results demonstrate the feasibility of using pvCNT dry electrodes for physiological parameter sensing.**

***Index Terms*— Dry impedimetric electrode; CNT-based electrodes; Electrode degradation, EEG sensor, ECG sensor.**

I. Introduction

Many physical signals require impedimetric electrical sensing of potentials or impedances for diagnostics, monitoring and therapy. Examples of such physiological data are EEG (electroencephalography), ECG or EKG (electrocardiography), and GSR (Galvanic Skin Response). The traditional interfacing of wet or gel electrodes only operates for a short span, as the performance of the electrodes deteriorates over time, primarily due to evaporation [1]. Wet or gel electrodes cause gradual decrease of conductivity of electrolytic material in the fluid due to drying, leading to degradation of signal quality over time.

In contrast, dry electrodes have the potential for long duration sensing and ease of use [2], leading to superior performance over long duration. However, there are a number of significant issues that need to be resolved including low impedance surface contact, interfacial half-cell potential, signal quality, tissue compatibility, skin breathing, etc. Some dry electrode technologies have been reported with conductive polymer, PDMS, conductive sponge, non-contact, or metallic pin electrodes [3-9]. Conductive polymer, sponge and PDMS suffer from poor conductivity, metallic electrodes get oxidized over time unless coated with novel (expensive) materials, and non-contact electrodes suffer from high interfacial noise. Significant, ongoing research efforts by various research groups and industry interests are focused on developing dry electrodes that can resolve these challenges [10]. We describe a novel dry electrode that has stable and low impedance over very long period, and can capture comparable signals.

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II. Sensor Description

Carbon nanotubes (CNT) can be electrically conductive in some configurations (e.g. multiwall, armchair) [11]. CNT based biosensors have been shown to provide reliable interface to neuronal signals [12]. CNT based biosensors are shown to be biosafe at low concentration external to the body [12,13]. Previous attempts for CNT dry electrodes [14-19] had limited success, primarily due to: (1) CNTs were not patterned in those electrodes resulting in a dense surface of CNT tips, and (2) the height of the carbon nanotubes was small (tens of µm range).

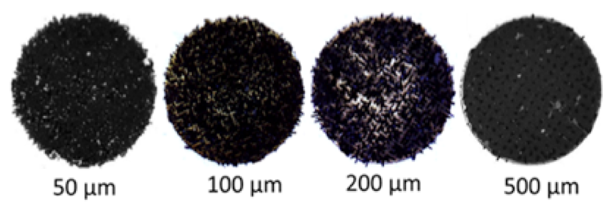

Fig. 1. Photographs of pvCNT sensors with various pillar spacings (labeled at the bottom of each image).

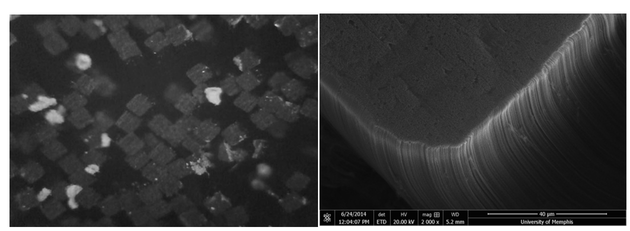

Fig. 2. Left: Optical microscope image of a pvCNT sensor (100 µm spacing) showing the bristle arrangement of top surfaces of the pillars. Right: SEM images of a pvCNT pillar top surface consisting of many CNT strands tightly ensembled vertically in an organized fashion.

We have developed a patterned vertical CNT (pvCNT) for dry impedimetric sensing. Multi-walled carbon nanotubes (MWCNT) were used due to its conductivity property and its strength compared to single walled carbon nanotubes. The pvCNT is an ensemble of an array of MWCNT that forms pillars vertical to the circular stainless steel (SS) substrate (ϕ = 10 mm, 2 mils thick). Each pillar was grown on 100 µm squared, and the height was between 1 to 1.5 mm with four different spacing between the pillars (50, 100, 200, and 500 µm) in an array formation. The pvCNTs were synthesized using Chemical Vapor Deposition system (CVD). Photographs of a sample with different spacing are depicted in Fig. 1.

Scanning Electron Microscope (SEM) images were taken at the Integrated Microscopy Center (IMC) of the University of Memphis. Fig. 2 shows the pillar arrangement with 100 µm spacing (left) and the top corner of a pillar (right).

III. Experimental Setup

A. Impedance

The impedance of pvCNT and the traditional wet electrode (GS26) was analyzed by Agilent 4294A Precision Impedance Analyzer (Agilent Technologies Inc., Santa Clara, CA, USA) using two different methods and fixtures (16451B and 16089B) in room temperature (~23 ºC). All fixtures were calibrated to ensure highly accurate measurements. Before every measurement the compensation and calibration were applied to the fixtures as per manufacturer instruction for error minimization. MATLAB (MathWorks, Natick, MA, USA) and Microsoft Excel (Microsoft Corp, Redmond, WA, USA) were used to collect and analyze the data.

1) Sensor Impedance using Dielectric Fixture: Agilent 4294A Impedance Analyzer with a Dielectric Fixture 16451B was used to measure the impedance of the pvCNT and GS26 electrodes. The pvCNT and GS-26 (Bio-Medical Instruments, USA) electrodes were placed between the parallel plates of the fixture. The plates contact the SS substrate and the top end of the pvCNT pillars. In all cases, the AC measurement of the impedance analyzer was set to the frequency range from 40 to 100 kHz. Same procedure was applied to the GS-26 electrode.

2) Interfacial Impedance with Agar: All interfacial impedance measurements have been done using skin phantom model built using Agar gel. Agar solution was prepared by adding 4.35gm of sodium chloride (NaCl) and 15gm of Agar powder (A10752, Alfa Aesar) to 500mL of water. The solution was boiled at 75ºC for couple of hours then poured into an Al foil wrapped petri dish and naturally cooled. A flexible PCB (flex-PCB) was designed and prototyped (Cirexx Intl., CA, USA) specifically for this test. The pvCNT was affixed on the flex-PCB using a double-sided z-axis conductive tape (Electrically Conductive Adhesive Transfer Tape 9703, 3M Company, MN, USA). The electrode was placed (face down) on the top of the agar gel and connected to the impedance analyzer via Agilent Fixture 16089B. The other terminal of the fixture was connected to the Al foil (Fig.4).

B. Long Duration Operation

Some biopotential measurements need long duration study. For wet electrodes electrolytic gel is applied to the skin to reduce skin-electrode impedance. After a few hours, the gel might dry and can cause skin irritation and increase the impedance. In this study we have conducted long duration study to the pvCNT and GS26 electrodes. Fixture 16451B was used in this study and the software was programmed to get the data every one hour for two days.

C. Signal Capture in Bench Test

The pvCNT electrodes must capture similar quality of signals compared to commercial sensors. Half-cell potential is the interface potential between anions and cations, and appears as an offset in ECG, EMG and EEG electrodes. Experiments to measure comparable signals in the presence of half-cell potential were conducted using Al foil and skin emulation (Agar gel). A signal was applied to Al foil and measured using the gel electrode (GS-26) and pvCNT electrode on agar gel.

IV. Experimental Results

In this paper we reported our results in terms of the amplitude (|Z|) of the impedance.

A. Impedance

1) Sensor Impedance measurement with dielectric fixture: Measurement of the impedance of pvCNT electrodes was collected using Fixture 16451B with barely touching CNT tips (one click of the torque knob). Fig.3 shows the plot of the amplitude of the impedance of three different samples (50, 100, and 200 µm spacing between the pillars) of the pvCNT electrode.

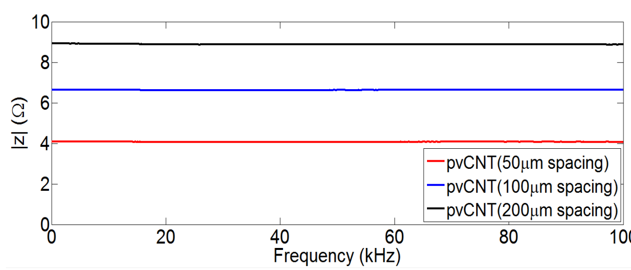

Fig. 3. The amplitude of the impedance of pvCNT electrode with three different pillar spacings (50,100, 200 µm).

Lower spacing between pillars leads to higher number of pillars per electrode, therefore, lower impedance. As expected the pvCNT with least spacing (50 µm) has least impedance value due to more number of pillars contacting the electrode in parallel.

2) Interfacial Impedance with agar: Two different electrodes were used in these experiments, wet (GS-26) and dry (pvCNT 200µm spacing) electrodes. Fig.4 shows the interfacial impedance decreases in both electrodes when the frequency increases. The impedance of the pvCNT in range 40 to 100Hz (i.e. the frequency of physiological parameters) is less than the impedance of wet electrode.

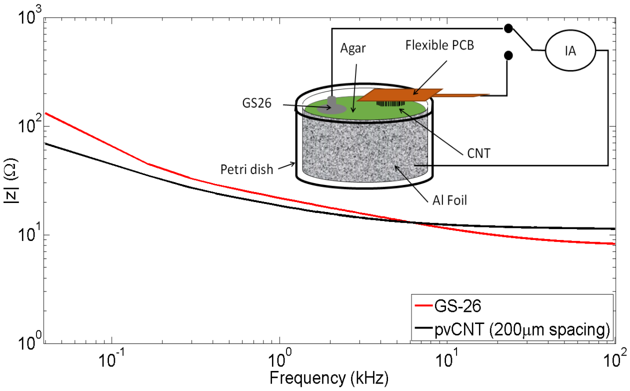

Fig. 4. The interfacial impedance (with agar solution) using two different electrodes wet (GS26) and pvCNT electrode. (IA: Impedance Analyzer.)

B. *Long duration operation.*

Fig. 5 shows the impedance measurement for three different electrodes (pvCNT 100µm and 200µm spacing and GS-26) for 45 hours. The data was taken every one hour at frequency 40 Hz. In pvCNT electrodes the impedance values decrease slightly, whereas for GS-26, the impedance increases significantly after the first 10 hours and then remains constant.

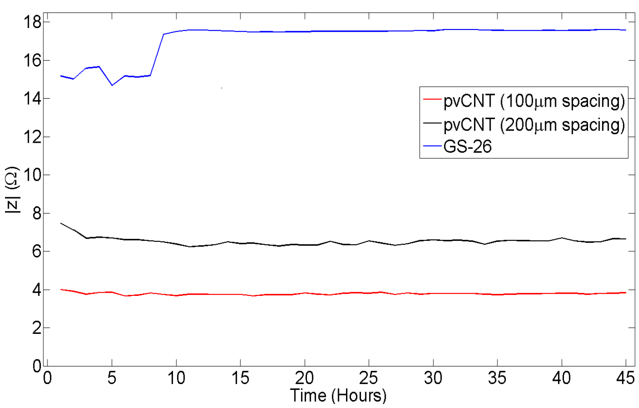

Fig. 5. The amplitude of the impedance of three electrodes for 45 hours.

C. *Signal Capture in Bench Test*

The potential drops on the electrodes using Al foil are 809.4 mV and 15 mV for GS-26 electrode and pvCNT electrode, respectively, as shown in Fig. 6a. Fig. 6b shows the results of signal capture in bench test for half-cell potential with an agar phantom model and a simulated ECG signal generated from a function generator and applied to the bottom Al foil surface of the agar gel. Data captured from the electrodes (GS-26 and pvCNT) at the top of the agar using an oscilloscope shows comparable half-cell potential, where half-cell potential of pvCNT is slightly lower than that of GS-26.

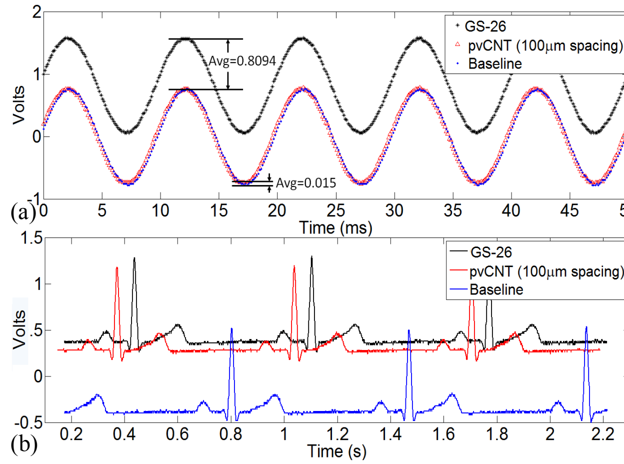

Fig. 6. (a) Test results of pvCNT and GS26 with Al foil. (b) Half cell potential for pvCNT and GS26 with Agar phantom model.

V. Conclusions

A novel dry electrode, pvCNT, was fabricated using patterned and vertically aligned CNT pillars on SS circular disks (ϕ = 10 mm). The characteristics of pvCNT ware compared with commercially available ECG electrodes (GS-26) for short and long duration studies. Results show that pvCNT has stable impedance over time. We also observed lower electrical impedances, and a comparable signal capture from the pvCNT dry electrode in contrast to GS-26. The results suggest that pvCNT dry electrode can be used for long duration physiological signal monitoring with minimal impedance degradation. This pilot study shows the potential of pvCNT as a dry electrode for physiological monitoring of patient centric healthcare in natural environments.

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