A mobile EEG system with dry electrodes

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***Abstract*— A new EEG recording device demonstrating an ultra-high input impedance is presented. Dry electrodes made of conductive rubber were employed for this study with careful shielding of the electrodes and cables. The device has a small form factor, so it is wearable, and has continuous Bluetooth connectivity. Tests were performed to assess features of the proposed device and to compare it with standard clinical devices. Simultaneous EEG recordings were measured from adjacent sites on the scalp using the new EEG device with dry electrodes and a reference EEG device with standard electrodes. The gain and bandwidth settings for the two devices were set similarly. Traditional closing eyes alpha-wave replacement and mu–rhythm were compared in both the time and frequency domains. Results from eight subjects show a high correlation coefficient (0.83 on average) between recordings of contiguous dry and standard electrodes. We conclude that the performance of the new device is comparable with standard EEG recording equipment, but offers a shorter set-up time, the possibility of long-term recording, and a wireless connection – all of which are advantages valuable in the field of brain computer interfaces and neurofeedback.**

***Index Terms*— EEG, bio-signal amplifier, dry electrodes, brain computer interfaces, neurofeedback**

I. Introduction

ELECTROENCEPHALOGRAPHY recordings are increasingly being used in numerous applications, from clinical detection and treatment of brain function anomalies [1] to brain computer interfaces (BCI) [2] and neurofeedback [3]. A substantial difficulty with recording EEGs using standard electrodes is that measuring scalp potentials, which are only on the order of several micro-Volts, necessitates skin preparation and the use of conductive gels and glues. The increased usage of EEG recordings highlights the urgency to reduce the discomfort and preparation time for patients. An additional problem associated with standard electrodes is that, as the conductive gel desiccates or the glue loses its adhesion the increase in the contact impedance between the electrode and scalp, causing a large reduction in the signal-to-noise ratio. Shorts can also occur between neighboring recording sites due to sweat or due to smearing of the conductive gel. Many of these problems can be minimized by using dry electrode systems and some recent studies have shown working prototypes [4]. The analog front-end in such systems must be modified to accommodate the very high contact impedance of the dry electrodes.

In this paper, we present a new bio-amplifier suitable for dry electrodes designed to allow several EEG channels to be referenced to the same electrode potential. This obviates the need for a separate reference lead for each electrode.

Our EEG recording system, Penso, is part of a project to develop hardware and software to create an easy to use and wearable BCI-system. The immediate goal of most BCI applications is to provide patients with severe neuromuscular disorders with capabilities they have lost. Some BCI applications currently provide basic word processing capabilities so subjects can better communicate with those providing them health-care; other applications control neuroprosthesis devices and wheelchairs [5]. The evaluation of Penso focused on particular issues appearing in BCI applications. However, as the dry electrode measurement system is more general than this, we evaluated the system so that comparisons can be made more generally with other EEG equipment.

The evaluation of a new EEG system in real usage situations is difficult as many parameters are involved and EEGs cannot be reproduced in different recordings. The evaluation of a new EEG recording system is typically conducted by visual inspection of the signals in both the time and frequency domain [6] and comparing with a reference EEG system. The test and reference systems are arranged such that electrodes record simultaneously from nearby locations. Alternatively, one can compare performance on particular tasks [4].

In this paper we report on the hardware component of Penso which consists of: (1) an ultra-high input impedance bio-amplifier; (2) new dry electrodes [7] suitable for long-term recording in real environments; and (3) wireless connectivity using a low-power ADC equipped with a Bluetooth module (currently approved for medical devices). In Section II we describe the hardware architecture and specifications of Penso and in Section III we describe two evaluations that we performed: a common eyes-closed-eyes-opened EEG test where features of the EEG were evaluated using visual inspection by an expert assessor (III.A), and a second test in which we measured the correlation between the recordings of Penso and commercial equipment (III.B) in relationship to the mu-rhythm that is commonly used in BCI. Conclusions are given in SectionIV.

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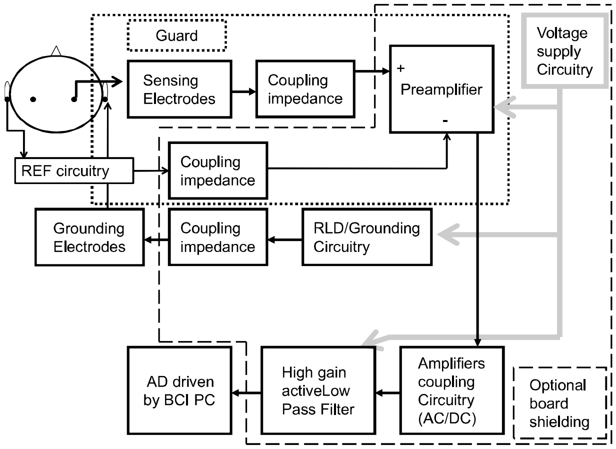

Figure 1: Block schematic of EEG recording equipment

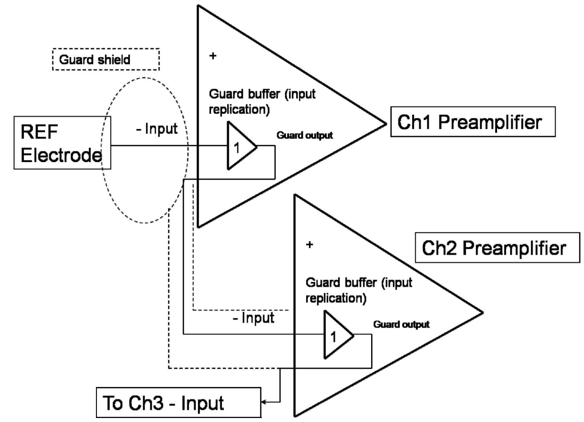

Figure 2: Block schematic of multichannel wiring

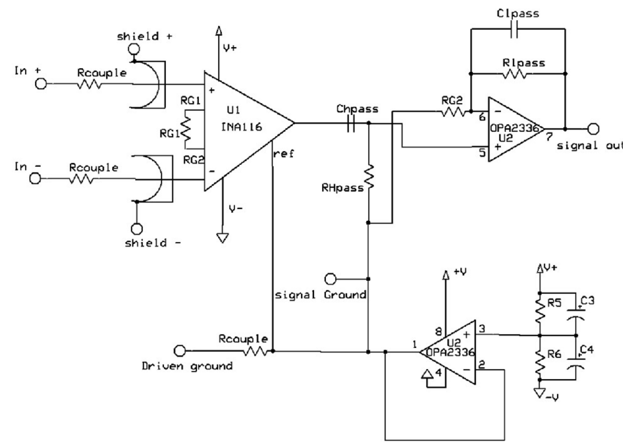

Figure 3: One channel schematic of EEG front end

II. PENSO

Figure 1 shows a block diagram of our EEG recording system. The monopolar signals measured by the electrodes (placed over the motor-cortex area in BCI) are referred to a common electrode placed on the left ear lobe. A grounding electrode is placed on the right ear lobe. The equipment includes special circuitry for micro-shock prevention [8]. All of the circuitry is battery powered and floating with respect to ground, while the leakage current is limited to 200 nA to ensure that the device is safe to use. Careful shielding was adopted to reduce EM interference on the electrode cables and the pre-amplifiers. The signals are digitized at 12 or 16 bits after amplification and filtering and transmitted to a PC via Bluetooth.

As shown in Figure 2 the wiring between the amplifier's input and the skin is protected by an active guard circuit that minimizes noise pick up in the cable [9]. The amplifier has an independent active guard circuit for each input. To provide an active guard feature, the protection circuitry in the amplifier needs to buffer the voltage present at the terminal. This means it can also be used to replicate the reference electrode signal to other amplifiers, thus providing multiple EEG channels with the same reference electrode. This solution was used in Penso to create up to eight channels.

Figure 3 shows the implementation of a single channel. The Burr-Brown INA-116 instrumentation amplifier is used for its extremely high input impedance. Power is supplied by a high capacity NiMh battery regulated to 3.3 V (single supply). A virtual signal ground is derived from the battery using a voltage divider (R5/R6). The virtual ground is buffered to provide a driven ground connection for the right ear lobe via a calibrated coupling impedance R_{couple}.

The pre-amplifier gain can be set to 6 kV/V for use with dry electrodes or to 50 kV/V for golden and Ag/AgCl electrodes. The INA116 is designed to work with a 9 V dual power supply, but thanks to the very low bandwidth requirement and the small amplitude of the EEG signal, we were able to use it with a single voltage supply down to 2 V.

The cut-off frequency for the high pass filter is tunable from near DC up to 5 Hz by changing the value of C_{Hpass} while R_{Hpass} is kept fixed at 390 kΩ. The second stage of amplification and filtering provides enough gain and high frequency suppression to directly feed the ADC. The cut-off frequency of the low pass filter is regulated (100 Hz maximum) by tuning C_{Lpass} while keeping R_{Lpass} fixed at 1 MΩ. Using commercially available precision components, we implemented a bandwidth of 0.38–44 Hz (±5%). The second stage amplification and the driven ground are implemented using the low-power, precision operational amplifier OPA2336 from Burr-Brown. This IC is also designed for low-power, battery equipped medical devices.

The ultra high input impedance of our bio-amplifier allows us to use a new kind of dry passive electrodes. Our electrodes are made with commercially available 1.5 mm thick silicone conductive rubber shaped in discs of 8 mm diameter. This material has been used as electrodes for decades, but mainly to make stimulation electrodes because of its intrinsic high Ohmic resistance [10]. Figure 4 shows an illustrative diagram of the dry electrode. The active side of the electrode is capacitive coupled through a layer of insulating silicon rubber with a metal shield wired to the active guard shield. The impedance of the realized electrodes at 100 Hz is greater than

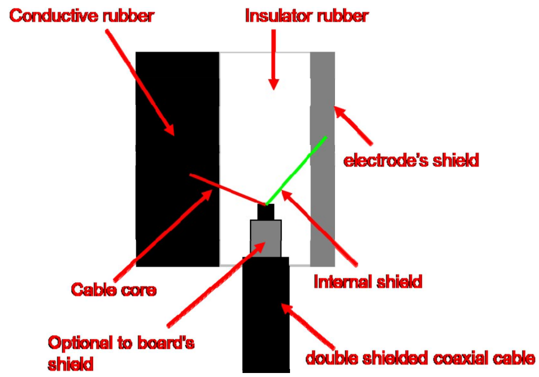

Figure 4: Passive dry electrode block schematic.

20 MΩ with a parasitic capacitance no greater than 2 pF. Laboratory tests demonstrate that a tolerance of 20% for the electrode's impedance is acceptable and does not influence the quality of the measurement, even in a multi-channel montage. The quality of the measurement it is not influenced either by contact impedance imbalance between electrodes. In fact, it is possible to mix the electrodes – some dry and some wet – in our system.

Careful PCB design and shielding that extends to the top of the electrode allow us to measure clean EEG signals. The measured input referred noise was less than 2 μVpp in the bandwidth up to 10 Hz.

III. Evaluation

We compared Penso with a clinically approved system for recording EEGs used at the RPA Hospital in Sydney. Both EEG systems were first characterized using a signal simulator. Penso has a measured bandwidth of 0.4-40 Hz while the control system had a bandwidth of 0.5-35 Hz. The gain in our system is 6100 V/V for dry electrodes, and 50000 V/V for standard wet electrodes. The gain is not known for the control system. The low and high pass filter responses were of first order in both cases. The control system had additional notched filters at 50 Hz and 60 Hz.

Next, we evaluated the system by placing electrodes from Penso and electrodes from the control system simultaneously on the scalp of a subject. Two additional evaluations were supervised by EEG practitioners and these represent the type of activities in which the system would normally be used.

A. Alpha wave replacement

The closing of both eyelids in a relaxed subject causes a typical change in the EEG signals termed "alpha wave replacement". This well known phenomenon can be used as a preliminary evaluation in EEG recordings by expert EEG practitioners [8]. In awake relaxed subjects alpha wave replacement shows as a visible increase in alpha wave magnitude (8-13Hz) that starts after the closing of the eyelids and stop with the opening of the eyes [11]. We tested alpha wave replacement using standard EEG recording positions such as: C3, C4, Cz. Figure 5 presents a direct comparison

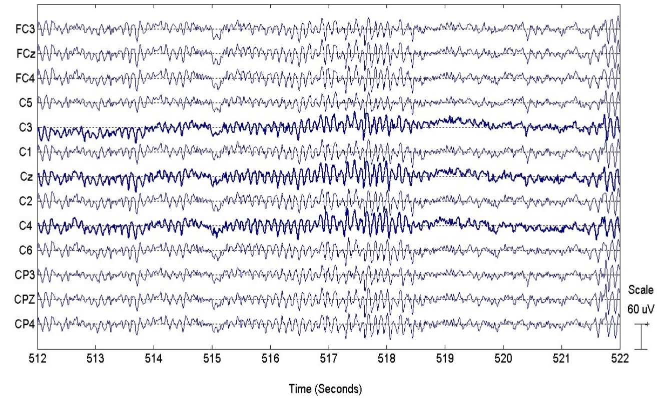

Figure 5: Alpha wave replacement, dry electrodes are in bold.

between dry and standard system during recording of alpha wave replacement and alpha wave reactivity. These signals were evaluated by neurologist. On the same subject we placed 3 dry electrodes in the standard positions C3, Cz and C4 connected to our system, surrounded by 10 standard golden brass electrodes connected to the RPAH machine.

The phenomenon is more apparent in the frequency domain as shown Figure 6. Observe the difference in the spectrum around 9 Hz between the eyes open (bold) and eyes closed cases as recorded by a dry electrode (solid line) and a standard wet electrode (dashed line) recorded in standard position C4 and Cp4, respectively. The figure shows clearly that both electrodes yield similar results.

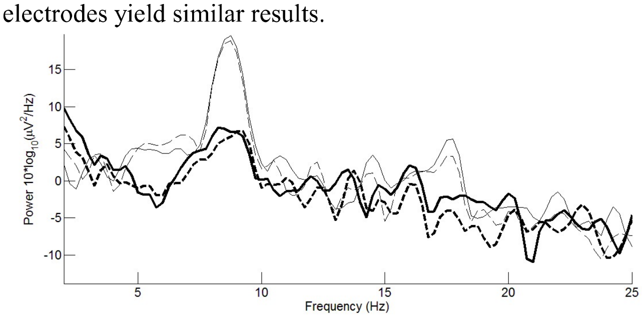

Figure 6: Power spectral density showing alpha wave replacement.

B. Mu-rhythm

Eight untrained subjects were asked to perform a BCI cursor control task (left-right movement). The protocol consisted of: 1) a familiarization trial lasting 3 minutes during which the subjects were asked to manually press a button with their right or left hand when a target appeared on the respective side; 2) a pre-BCI trial of 3-6 minutes, where the subjects were asked to imagine pressing the button instead; and, 3) a number of BCI L-R control tasks, where a cursor was moved based on the EEG signals recorded. This final task typically lasted about 12 minutes to avoid tiring our subjects unduly. EEG signals were recorded in parallel by both machines using the following montage: dry electrodes were placed at C3, C4, and Cz and were surrounded by wet electrodes at Cp3, Cp4, Cpz, C1, C2, C5, C6, Fc3, Fc4 and Fcz with wet electrodes.

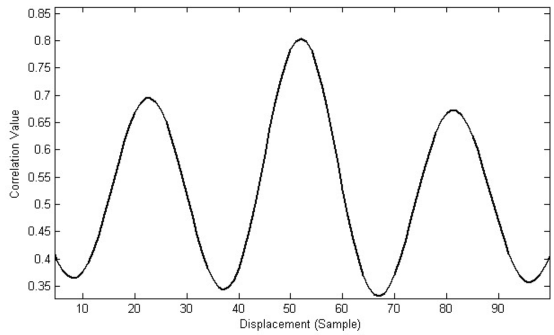

Figure 7: Correlation of dry electrode with average of 4 surrounding electrodes, for increasing time lags

Since we are interested in evaluating how the experimental burden is reduced using Penso, the time required to prepare the subjects was recorded. For the RPA Hospital wet electrodes, full skin preparation, and contact impedance checking are required. The wet system required 2-3 minutes set-up time per electrode. The dry system only required 10 seconds per electrode, which was the time needed to dry the collodium applied directly to the surface of the electrode. In order to minimize the differences in the acquired signal due to hardware differences, the data were equalized in bandwidth to 0.5-35 Hz using a band pass filter (50 order FIR) and a 50Hz IIR notch filter was applied to the recorded signals.

Time and frequency domain evaluation was performed on the data. In the time domain, in order to minimize the effect of clock misalignment and different ADC jitter in the two recording systems, an analysis based on the maximum of the correlation between signals recorded with the two systems was used. Using a 1 second long (256 samples) moving window, we calculate the correlation between electrode signals. An example is shown in Figure 7. We found that the maximum correlation of a 3 minute recording, i.e., when the two series are time aligned, was 0.90 when comparing electrodes from the same machine. The average of the maximum correlation between a dry electrode and the mean signal from its surrounding wet electrodes was 0.76.

The difference is caused by the presence of artifacts that introduce high amplitude noise. Since each machine has slightly different recovery times and filter responses, these artifacts reduce overall correlation between the two systems. In further analysis the signals were visually inspected by a neurologist who was unaware which signals had been recorded by which system and based on his expertise periods within the trials that contained artifacts were removed. Figure 7 shows the correlation when recalculated using these cleaned signals from a dry electrode at C4 and the mean of the signals from four wet electrodes surrounding this position. The best correlation obtained between the two was 0.94 in one subject and the average for all subjects was 0.83. Additionally, in Figure 8 it can be seen that the power spectrum of the signals from the dry electrodes is very similar to that of the signals from the surrounding wet electrodes.

IV. CONCLUSION

An ideal EEG recording system is easy to use, requires little time to install and remove, and minimizes the burden on the subject. Furthermore, it is portable so it can be used in daily activities and uses wireless communication so that in applications such as BCI the data can be processed remotely by a powerful computer. Our evaluation shows that Penso has the capability of offering such a solution. The alpha wave replacement experiment shows that similar results are obtained with our system as with a standard system, while the recordings from a BCI experiment show excellent correlation between the two systems in both time and frequency domain.

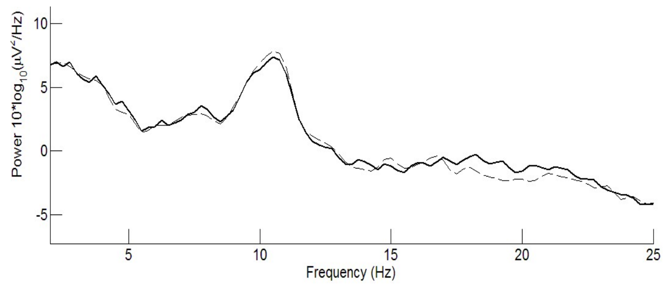

Figure 8: Frequency domain comparison between C4 (dry, bold) and Fc4 (wet, dashed)

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