Novel Hybrid Bioelectrodes for Ambulatory Zero-Prep EEG Measurements Using Multi-channel Wireless EEG System

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Abstract. This paper describes a wireless multi-channel system for zero-prep electroencephalogram (EEG) measurements in operational settings. The EEG sensors are based upon a novel hybrid (capacitive/resistive) bioelectrode technology that requires no modification to the skin's outer layer. High impedance techniques developed for QUASAR's capacitive electrocardiogram (ECG) sensors minimize the sensor's susceptibility to common-mode (CM) interference, and permit EEG measurements with electrode-subject impedances as large as 107 Ω. Results for a side-by-side comparison between the hybrid sensors and conventional wet electrodes for EEG measurements are presented. A high level of correlation between the two electrode technologies (>99% for subjects seated) was observed. The electronics package for the EEG system is based upon a miniature, ultra-low power microprocessor-controlled data acquisition system and a miniaturized wireless transceiver that can operate in excess of 72 hours from two AAA batteries.

Keywords: EEG, biosensors, high impedance, wireless.

1 Introduction

This paper discusses a novel hybrid (capacitive/resistive) EEG biosensor that can make measurements of through-hair EEG with zero preparation of the scalp. This sensor technology is used as part of an unobtrusive wireless EEG system for ambulatory EEG. In order to be truly unobtrusive, the system (including the sensors) should be donned or doffed quickly by the wearer, be easy to use, worn comfortably for extended periods and require no skin preparation for the sensors to operate with sufficient fidelity.

The EEG is most frequently used in clinical settings for monitoring and diagnosis of epilepsy and subjects with sleep disorders. However, measurements of the EEG have applications in operational settings, in which knowledge of an individual's cognitive state can be used to predict impending cognitive failure and trigger

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appropriate countermeasures [1]. The ability to separate cognitive states, such as cognitive fatigue or overload, has been demonstrated for several applications under the Defense Advanced Research Projects Agency's (DARPA) Augmented Cognition (AugCog) program [2]. Military applications for this technology, such as command and control, communication, and security, have civilian counterparts such as developing countermeasures for pilot or driver fatigue [3]. Future research will lead to a new generation of computer interfaces that can act as brain-computer interfaces for the severely disabled [4].

The implementation of EEG-based systems in operational settings for determining cognitive state is limited, however, by the lack of an EEG sensor technology with high user compliance. Conventional 'wet' electrode technology presently requires preparation of the skin or the application of conductive electrolytes at the skin-sensor interface, which can be time consuming and unpleasant for the subject. Preparation of the electrode site involves abrading the scalp, with consequent discomfort for the subject and an associated risk of infection if the electrodes are not sterilized between subjects [5]. Similarly, a conductive gel leaves a residue on the scalp, and furthermore may leak, resulting in an electrical short between two electrodes in close proximity.

Quantum Applied Science and Research (QUASAR) has recently developed novel capacitive biosensors that meet the AugCog requirements for operational recordings of electrocardiograph (ECG), electrooculograph (EOG), and electromyograph (EMG) signals [6]. The QUASAR sensors couple to the electric fields of the body capacitively, requiring no skin contact and no skin preparation. Further development of QUASAR's capacitive bioelectrode technology was funded through Aberdeen Test Center as part of an effort to develop a biomonitoring sensor suite for Test & Evaluation (T&E) applications. Measuring EEG using the capacitive bioelectrodes became problematic when operating through hair. The sensors' high impedance made them susceptible to triboelectric charge generation due to rubbing between the sensor and hair.

The novel hybrid electrode described in this paper is the result of a research program funded by Aberdeen Test Center to develop a through-hair EEG sensor that is capable of making high fidelity EEG measurements with zero preparation of the scalp. This effort will culminate in a biomonitoring system, measuring EEG, EOG, ECG and EMG signals for T&E monitoring of human-computer interactions.

The miniature data acquisition system and wireless transceiver is discussed with regard to recording fidelity and noise characteristics.

2 Experimental

The measurements described herein were made using the novel hybrid EEG sensor technology developed at QUASAR. We report on simultaneous tests of QUASAR biosensors side-by-side with conventional 'wet' electrodes in laboratory tasks designed to produce variations in EEG rhythms such as theta and alpha bands or spectral patterns. Our focus was on limited tests to permit qualitative and semi-quantitative comparisons with wet electrodes. A total of 5 subjects (divided into two groups) were included in this study, and as such, the present sample sizes do not permit statistical comparisons.

2.1 QUASAR Hybrid EEG Electrodes

The hybrid biosensor (Fig. 1a) uses a combination of high impedance resistive and capacitive contact to the scalp, thereby enabling through-hair measurements of EEG without any skin preparation. The hybrid biosensor contacts the skin with a set of 'fingers,' each of which is small enough to reach through hair without trapping hair beneath the finger (thereby preventing electrical contact to the scalp). The sensors were held in place using the cap in Fig. 1b.

(a) (b) (c)

Fig. 1. (a) QUASAR hybrid biosensor. (b) Harness for holding QUASAR biosensors on scalp. (c) Common-mode follower (CMF) placed on earlobe of subject.

In contrast to conventional EEG electrode technology, which relies on a low impedance contact to the scalp (typically less than 5 kΩ in clinical applications), the contact impedance between the scalp and each electrode finger can be as high as 10^7 Ω in the bandwidth of interest. Therefore the amplifier electronics are shielded and placed as close as possible to the electrode in order to limit interference caused by the pickup of external signals, and innovative processing electronics are used to reduce pickup of and susceptibility to common-mode signals on the body [6].

The sensor is used in combination with QUASAR's proprietary common-mode follower (CMF) technology (situated on the subject's earlobe in Fig. 1c). The CMF is a separate biosensor that is used to reduce the sensitivity of the hybrid biosensor to common mode signals on the body. It operates by measuring the potential of the body relative to the ground of the amplifier system. The ultra-high input impedance of the CMF (~10^{12} Ω) ensures that the output of the CMF tracks the body-ground potential with a high degree of accuracy.

The output of the CMF is then used as a reference for EEG measurements by the hybrid sensors. In this way, the common-mode signal appearing on the body is dynamically removed from the EEG measurement. This typically achieves a common-mode rejection ratio (CMRR) of 50 to 70 dB.

2.2 Data Acquisition

During these experiments, six channels of EEG were recorded simultaneously: three QUASAR hybrid biosensors and three conventional wet electrodes. The hybrid electrodes were positioned at the nominal Cz, Fz and F_3 positions [7], and the wet electrodes were positioned 2 cm to the right and posterior to the hybrid electrodes

(Subjects 1 and 2), or 2 cm anterior to the hybrid electrodes (Subjects 3-5). Preparation of the scalp for the wet electrodes included abrasion with Nu-Prep, followed by cleaning with alcohol and then application of Grass EC2 electrode paste. No preparation of the scalp was performed at the QUASAR electrode sites.

Independent grounds were used for the wet and hybrid electrodes. The electrical ground for the hybrid electrodes was a high impedance ground via a fabric strip in contact with the subject's forehead. The site was not prepared. The high impedance ground was connected to the ground of the data acquisition system. The ground reference for the wet EEG electrodes was a standard pre-gelled disposable Ag-AgCl electrode placed upon a prepared site on the left mastoid (Subjects 1 and 2), or the mid-posterior aspect of the subject's right pinna, as in Fig. 1c (Subjects 1-3). Differential amplifiers were used to generate the output for each wet electrode, thereby maintaining isolation between the two grounds.

The CMF for the hybrid electrodes was placed below the ear (Subjects 1 and 2), or on the right earlobe (Subjects 3-5).

The data acquisition system was a National Instruments NI-4472 PCI (24-bit, 8 channel delta-sigma) card installed in a desktop computer running a LabView-based data acquisition application. Anti-aliasing of the data was not necessary before digitization because of the details of the sigma-delta data acquisition. Signals were sampled at 12 kHz, then digitally filtered with a 300 Hz (-3dB) low-pass anti-alias filter before the samples were decimated to a sample rate of 1200 Hz. Each signal was corrected for the intrinsic gain of the sensors and ancillary electronics (gain=20 for all EEG channels). Signals were displayed in real time for monitoring purposes and saved on the hard disk drive.

For the purposes of analysis, the time series data were digitally filtered using a 8th order Butterworth bandpass filter between 1 and 40 Hz (with an additional notch filter at 60 Hz). Power Spectral Density functions (PSDs) were computed using Welch's method from the digitally filtered EEG with window length = 2 s, overlap = 1 s and FFT length = 2400 (sample frequency 1200 Hz).

2.3 Tasks

Task 1 - Eyes Open/Closed (Desynchronization of EEG alpha rhythm). Recording of EEG with a subject at rest with eyes open or closed is part of a standard clinical EEG test. A prominent feature of the eyes-closed EEG is a pronounced alpha rhythm, which disappears (or desynchronizes) when the eyes are opened [8]. To measure this effect, we recorded EEG with the subject's eyes open while the subject was still for a period of 30 seconds. This was repeated with the subject's eyes closed. This was repeated at the conclusion of the tests for Subjects 1 and 2.

Task 2 - Memory/Cognition Measurements (Modulation of EEG alpha and theta rhythms). Memory load and mental arithmetic are frequently used to control mental workload and produce distinct effects on EEG spectra, including modulation of theta (4-7 Hz) and alpha (8-12 Hz) bands [8], [9], [10]. Such effects are key features used by real-time algorithms to monitor human cognition during decision-making and control tasks [11], [12].

This task was conducted with the subjects seated and then walking in place. While seated, Subjects 1 and 2 were asked to count down from 1000 in steps of 2 for a period of 120 seconds (easy task), and then count down from 1000 in steps of 7 for a period of 120 seconds (hard task). The easy and hard tasks were then repeated while the subject walked in place.

While seated, Subjects 3-5 responded to a sequence of alphabetic characters displayed on a screen with either a 'y' or 'n', depending upon whether the current character was the same as the previous character, for a period of 300 seconds (N0, easy task), and then responded to a sequence of alphabetic characters displayed on a screen with a 'y' or 'n', depending upon whether the current character was the same as that prior to the previous character, for a period of 300 seconds (N2, hard task). The easy and hard tasks were then repeated while the subject walked in place.

3 Results

3.1 Sample Recordings and Inter-sensor Correlations

A segment of a time-series recording comparing the signals obtained for Subject 3 from the Cz electrodes during the eyes closed session is shown in Fig. 2. Also included on the plot is the Pearson correlation over 0.25 second segments. Although only a single 4-s segment is shown, the recording quality was consistent for all subjects without obvious changes in signal quality or noise levels. Very significant correlations, in excess of 90%, are evident throughout the record.

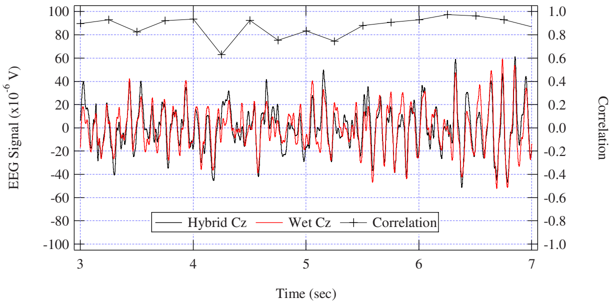

Fig. 2. Comparison of wet and hybrid Cz signals for Subject 3 during eyes closed session. The correlation data are calculated using 0.25 second segments.

However, regions of low EEG signal level reduce the Pearson correlation coefficients for the QUASAR-wet electrode pairs at Cz, Fz, and F_3 in 1-second segments of the sensor time series, averaged over the entire 30 second record, to 0.7423, 0.7691, and 0.7106, respectively. The average correlation coefficients were not observed to vary significantly as the segment length was varied between 0.25 seconds and 1 second.

A segment of a time-series recording comparing the signals obtained for Subject 2 from the Fz electrodes during the hard counting task (walking in place) is shown in

Fig. 3. The benefit of the CMF is illustrated in these data because although triboelectric charge generation while walking increases the CM signals appearing on the body, very significant correlations, in excess of 80%, are evident throughout the record.

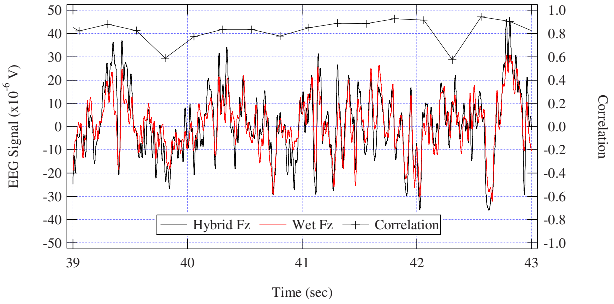

Fig. 3. Comparison of wet and hybrid Fz signals for Subject 2 performing the hard counting task while walking in place. The correlation data are calculated using 0.25 second segments.

The average Pearson correlation coefficients for the QUASAR-wet electrode pairs at Cz, Fz, and F_3 in 1-second segments over the entire 120 second time-series were 0.8226, 0.8409, and 0.8350, respectively.

3.2 Eyes-Open/Eyes-Closed EEG Task

The power spectral density (PSD) functions of the EEG signals for QUASAR and wet sensors were highly similar across eyes-open and eyes-closed tasks. Desynchronization of the alpha rhythm was observed in both electrode technologies for all five subjects when their eyes were open. For Subject 3 (Fig. 4), the beta rhythm (15-25 Hz) also desynchronized when the eyes were open.

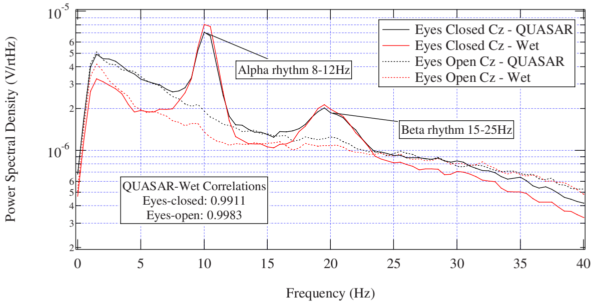

Fig. 4. Power spectral density functions of 30-s EEG recordings for Subject 3 at Cz during the eyes-open session and the following eyes-closed session

In the eyes-open/eyes-closed session for Subject 3, the inter-sensor Pearson product-moment correlation coefficients of the PSDs for QUASAR-wet sensor pairs at Cz, Fz, and F_3, calculated for all frequency bins below 40 Hz, were 0.9911, 0.9898, and 0.9825, respectively. In the eyes-open session, the corresponding correlation coefficients for QUASAR-wet sensor pairs at Cz, Fz, and F_3 were 0.9983, 0.9975, and 0.9976, respectively. Correlation coefficients in excess of 0.957 were observed across all 5 subjects for QUASAR-wet sensor pairs at Cz, Fz, and F_3 for EEG data sets recorded during this task.

3.3 Memory/Cognition Task

The PSD functions of the EEG signals for QUASAR and wet sensors were highly similar for all subjects across the two levels of the memory/cognition tasks. The inter-sensor Pearson correlation coefficients of the PSDs for QUASAR-wet sensor pairs at Cz, Fz, and F_3, calculated for all frequency bins below 40 Hz were in excess of 0.935 for all subjects in each cognition task, with the exclusion of Subject 3 while walking. The residual CM signal on Subject 3 resulted in a 2 Hz peak in the PSD, corresponding to the impact frequency while walking. However, the correlation coefficients for QUASAR-wet pairings for the bipolar derivations Cz-Fz, Cz-F_3 and Fz-F_3 for Subject 3 (walking) possess correlation coefficients greater than 0.96.

Other authors have reported synchronization of theta band power and desynchronization of alpha band power as the difficulty of cognition task increases [8], [9]. We observed modulation of alpha band and theta band power in data for individual subjects, though not consistently across all 5 subjects. For example, the data for Subjects 1, 3 and 4 show evidence of a decrease in alpha band power during the hard counting and N2 task while seated, but no effect is evident in the theta band for either electrode technology. Alternatively, Subject 2 possesses a decrease in theta band power, but no change in alpha band power, while seated during the hard counting task. No modulation of the theta and alpha and band powers is evident in the data for Subject 5. Similarly, neither is any modulation of the theta and alpha band powers evident for any subject for either sensor technology.

4 Deployable Neurocognitive Monitoring System

A truly deployable mobile neurocognitive monitoring system must possess several key features. The electrodes for the system must be noninvasive and require no modification of the outer layer of the skin to obtain EEG recordings with sufficient fidelity to classify cognitive states. Furthermore, in order to be deployed in operational settings, the electrodes must operate for periods longer than 8 hours with no maintenance and no discomfort for the user. The harness holding the sensors must also be comfortable and, not least when considering user compliance, have a stylish appearance. The electronics to digitize and record the signals need to be small and lightweight, have a sleek appearance, and operate for a minimum of 24 hours using small batteries that are easy to obtain.

4.1 Data Acquisition/Wireless Electronics for EEG System

The electronics package for the EEG system is based upon a miniature, ultra-low power microprocessor-controlled data acquisition system (DAQ) and a miniaturized wireless transceiver (Fig. 5). Presently, power consumption of the system is dominated in approximately equal parts by the DAQ and the transceiver. In order to conserve power, the microprocessor operates in a low-power “sleep” mode when not acquiring data and the wireless transceiver transmits information in a data “burst” mode. Wireless data rates up to 2.5 ksamples per second have been achieved using the present system operating in a low power mode. Current estimates show that the run time for the system is in excess of 72 hours from two AAA batteries.

Fig. 5. (left) Prototype data acquisition board with credit card for scale. (right) Prototype miniature wireless transmitter.

In order to facilitate the calculation of high CMRR difference signals in software, the input filters on each analog channel have been matched to better than -72 dB below 50 Hz. Additionally, the timing error between ADC channels is less than 1 μs (i.e., a phase error less than -80 dB below 100 Hz).

Data acquisition is performed using 16-bit sigma-delta ADCs. The input noise of the DAQ channels has been measured to be 400nV/√Hz for a sampling frequency of 4 kHz. Aliasing of out-of-bandwidth signals is less than -80 dB below 50 Hz.

4.2 Sensor Harness

One of the principal benefits of the QUASAR hybrid sensor is the ease with which the sensors may be applied. The user can simply pull the sensors on using a simple combing motion to work them through the hair. Ideally, the harness will serve several functions, primarily as a set of headphones or glasses and secondly, but equally important, to hold the sensors to the head in a comfortable manner (Fig. 6). Note that in the glasses configuration, extra sensors can be included for measurements of the EOG.

The sensor harness will also need to hold the electronics package which will provide power to the sensors, digitize the signals and either write the data to flash memory or wirelessly transmit it to a base station. The base station can be a central computer, or a PDA carried by the user, allowing full deployment of the system in the field.

Fig. 6. Two concepts for a sensor harness suitable for operation in a C2 environment

5 Discussion

Although the present experiments were limited to five subjects, the quality and consistency of the recordings and the effects we measured show that the QUASAR hybrid biosensors function as well as conventional 'wet' sensors. Our results provide clear and convincing evidence of EEG signals which correlate extremely well with simultaneously recorded wet electrodes. Correlations of alpha activity in the time domain were typically in excess of 0.8-0.9, but correlation coefficients averaged over an entire data set were found to be considerably lower. This is due to the effect of regions of low EEG signal level and the presence of skin noise reducing the signal-to-noise ratio (SNR) of the EEG signal. Regions of low SNR have a correspondingly small correlation coefficient.

In the spectral domain, the PSD functions of QUASAR and wet EEG recordings within the EEG band of 0-40 Hz were remarkably high, typically above 0.99. The frequency domain correlations appear to be immune to SNR considerations because of the stability of the skin noise, which possesses a predominantly $1/f$ characteristic. Only one subject recorded correlations below 0.9 for EEG measured while walking in place due to interference from common-mode signals.

Besides showing that the signals of interest are correlated across sensor types, both sensor technologies demonstrate sensitivity to the effects typically used for human-computer interaction – namely modulation of EEG rhythms, such as alpha and theta. These effects were seen in both sensor technologies when present in a particular subject, but the results were not observed consistently across all 5 subjects in the memory/cognition task. It is likely that the small sample size and limited acquisition time are responsible.

Performance tests for the EEG system have demonstrated that the system possesses specifications suitable for multi-channel EEG acquisition. The common-mode follower technology enables measurements of EEG using contact impedances several orders of magnitude greater than that considered acceptable for conventional electrodes. The pickup of common-mode interfering signals will be further reduced by the wireless nature of the system because the coupling of the system's ground to earth ground is considerably reduced.

The technology described in this paper directly addresses user compliance issues. The biosensors can be donned or doffed quickly by the wearer, require no skin preparation, produce no skin irritation, and be comfortably worn for extended periods. The wireless EEG system's small size and long operating time make it ideal for measurements of ambulatory EEG in a C2 setting.

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