The invisible electrode – zero prep time, ultra low capacitive sensing

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Abstract

The principle technical difficulty in measuring bioelectric signals from the body, such as electroencephalogram (EEG) and electrocardiogram (ECG), lies in establishing good, stable electrical contact to the skin. Traditionally, measurements of human bioelectric activity use resistive contact electrodes, the most widely used of which are 'paste-on' (or wet) electrodes. However, the use of wet electrodes is a highly invasive process as some preparation of the skin is necessary in order for the electrode either to adhere to the skin for any length of time or to make adequate electrical contact to the skin. This is uncomfortable for the subject and can lead to considerable irritation of the skin over time, an issue of particular concern in measurements of EEG signals, which typically require an array of electrodes positioned about the head.

Despite over 40 years of investigation, including the development of several alternative electrode technologies, no reliable method for making electrical contact to the skin that does not require some modification of its outer layer has been developed. For example, Ag-AgCl dry electrodes, NASICON ceramic electrodes, and saline solution electrodes do not require any skin preparation, but for each electrode the subject experiences skin irritation over extended periods, and there are various issues that cause the performance of the sensors to degrade over time. Alternatively, insulated electrodes that use capacitive coupling to measure the potential changes on the skin have in the past, for noise considerations, used exotic materials to generate a high capacitive coupling (~1 nF) to the skin. The intrinsic noise of insulated electrodes is adequate for bioelectric measurements, but these high capacitance sensors also exhibit long-term compatibility issues with the skin and are sensitive to motion artifact signals due to the electrode's high sensitivity to relative motion between the skin and the electrode itself.

As a result of advances in semiconductor processing techniques and through the use of innovative circuit designs, QUASAR has developed a new class of insulated bioelectrodes (IBEs) that can measure the electric potential at a point in free space. This has made it possible to make measurements of human bioelectric signals without a resistive connection and with modest capacitive coupling to the source of interest. These electrodes are genuinely non-invasive in that they require no skin preparation, have no long-term compatibility issues with the skin, and can measure human bioelectric activity at the microvolt level through clothing while remaining largely immune to motion artifact signals.

This paper will present measurements of bioelectric activity made using QUASAR's IBEs, and corresponding data measured using conventional wet electrodes will also be presented for comparison. The presentation will include through-clothing measurements of bioelectric signals, the rejection of motion artifact signals, non-invasive (i.e. no skin preparation) EEG measurements of alpha-rhythm signals, and the noise levels observed using both types of sensors.

In a series of tests conducted on unprepared skin, it was observed that both the IBEs and conventional wet electrodes had similar noise levels. This noise level was higher than the expected noise level, which had been predicted based upon the intrinsic noise characteristics of the sensors. The fact that both sensors suffered from this higher noise level suggested a common mechanism, which was later identified as skin noise.

It has been reported in the literature that one of the fundamental noise sources for any bioelectric measurement made on unprepared skin is epidermal artifact noise. This noise is due to potentials developed in the skin itself that are indistinguishable from the bioelectric signal of interest. There exist techniques that can reduce this noise level by as much as a factor of 5, but they involve modification of the skin's outer layer either by abrasion or chemical

absorption of conducting fluid. These methods are not comfortable for the subject and may be difficult to perform on subjects with especially sensitive skin, such as neonates, burn victims, or the elderly.

In addition to QUASAR's IBE sensors, this paper will also discuss a new free-space electrode that is designed to be insensitive to epidermal artifact noise, and thus is capable of bioelectric measurements at the microvolt level in the absence of any skin preparation. The new device exhibits significantly less capacitive coupling to the source of interest than the current generation of QUASAR IBEs, without the increase in intrinsic sensor noise that would accompany a reduction in electrode capacitance.

1 Introduction

Over the past 4 years QUASAR has developed a new class of electric potential sensor that can measure the electric potential at a point in free space, in which individual sensors have demonstrated sensitivities at 60 Hz of 5 $\mu V/m/\sqrt{Hz}$ (Krupka, Matthews, Say & Hibbs, 2001), representing an improvement of approximately two orders of magnitude in sensitivity from the previous state of the art. This sensitivity is sufficient for the measurement of bioelectric signals without any resistive electrical connection and with only negligible capacitive coupling to the source of interest.

The QUASAR sensor has been used for the measurement of electrocardiogram (ECG) and electroencephalogram (EEG), physiological measurements that have been identified as useful metrics for the development of a cognitive state gauge by the Augmented Cognition (AugCog) program (initiated by the Defence Advanced Research Projects Agency, or DARPA). See St. John, Morrison & Schmorrow (2004) for a discussion of other psychophysiological measures used to identify changes in human cognitive activity during task performance. This ambitious research program has as its aim the maximization of human cognitive capabilities through long-term monitoring of bioelectric signals in diverse settings. It is a requirement of sensors that they be unobtrusive and that their presence not affect an individual's performance. However, the conventional electrodes used for electrophysiological measurements are not suited for long-term measurements of bioelectric signals because they frequently result in skin irritation and discomfort for the subject. This is described in more detail in Section 2.

Capacitive electrodes per se for bioelectric measurements are not new. Detection of human body bioelectric signals using purely capacitive sensors (i.e. no ohmic contact to the body) was first reported in 1968 (Richardson, 1968) and patented in 1970 (Richardson & Lopez, 1970). However, prior technology required high capacitive coupling (~1 nF) to the skin. These high capacitances were generated through the use of exotic materials that suffered from biocompatibility issues and resulted in skin irritation. Furthermore, susceptibility to displacement of these electrodes makes them unsuitable for applications in which even a moderate level of aerobic activity is required.

This paper presents performance data for a new class of insulated bioelectrode (IBE) suitable for use in long-term monitoring of bioelectric signals.

2 Conventional Resistive Contact Electrodes

The principal technical difficulty in measuring bioelectric signals from the body lies in establishing good, stable electrical contact to the skin. Before placing a 'paste-on' (or wet) resistive electrode on a patient, the skin is usually cleaned with alcohol to remove sweat and skin oils that would otherwise prevent the adhesive paste from holding the electrode in contact with the patient's skin. However, it has been known since the Apollo space program that long-term wear of electrodes that require resistive (ohmic) contact can result in major skin irritation, to the extent that NASA has to test astronauts for such reactions (NASA, 2005). While a number of improved gels and connection techniques have been introduced in the last 30 years, resistive contact electrodes are still far from ideal.

For example, if a resistive-contacting electrode pulls away from the skin, or if its gel dries out, then it can no longer collect a signal with the required fidelity. Such problems are commonplace in clinical applications of electrophysiology, and are particularly marked for neonates because, unlike most adult patients, they are usually active during an ECG procedure. Many ECG monitors now have impedance-sensing circuits to determine when an electrode has lost contact. While automatic detection of a loss of contact is useful, it does not replace the missing data, nor enable the system to resume operation.

A further problem is the degradation in performance experienced by the electrodes themselves. Leakage current from the electrode into the amplifier used to make the measurement leads to polarization of the electrode. The almost exclusive use of Ag-AgCl electrodes in ECG measurements is probably due to their very low polarization on current flow, an important consideration for early ECG amplifiers (Klinger, Booth & Schoenberg, 1979), as they do not possess a noticeably better noise performance than other electrodes (Huigen, Peper & Grimbergen, 2002). Although the input current of modern amplifiers is considerably smaller, polarization remains a limitation to the use of NASICON electrodes in long-term measurements (Gondran, Siebert, Yacoub & Novakov, 1996).

More importantly, measurements of electrophysiological signals are degraded in high-impact conditions and states of high physical activity. This is due to the presence of relative motion artifact signals. This degradation is usually a combination of increased sensor noise (caused, for example, by increased contact resistance), direct contamination by motion artifacts (e.g. motion of the sensor in the ambient field of the environment), and modulation of the signal due to relative motion to the subject. The following section presents measurements demonstrating an improved rejection of motion artifact signals using the QUASAR IBEs.

3 Capacitive Measurements of Bioelectric Signals

3.1 Principles of Operation

Measurement of bioelectric signals using electrodes without ohmic contact with the skin requires the use of capacitive coupling. The general circuit architecture for capacitive coupling is shown in Fig. 1. A charge Q flows onto the sensing electrode C_s that is given by the product of C_s and the ambient electric potential at C_s.

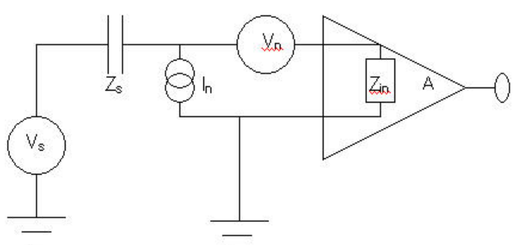


Figure 1: Circuit for a capacitive electrode connected to an amplifier. V_s is the potential at the electrode, Z_s is the sensing electrode, V_n and I_n are the voltage and current noise respectively of the amplifier, and Z_{in} is the amplifier input impedance.

The circuit in Fig. 1 is basically that of an impedance divider. For the ultra high input resistance of presently available amplifiers ($R_{in} = 10^{15}\ \Omega$), the input impedance of the amplifier, Z_{in}, is dominated by the input capacitance at frequencies where $\omega R_{in} C_{in}$, $\omega R_{in} C_s >> 1$, and the system has an essentially flat-band response given by $V_{in} = V_s\, C_s/(C_s + C_{in})$. In most applications it is easy to arrange for $C_s \geq C_{in}$ so that the equation becomes $V_{in} \approx V_s$, thereby yielding a near ideal measurement of the electric potential.

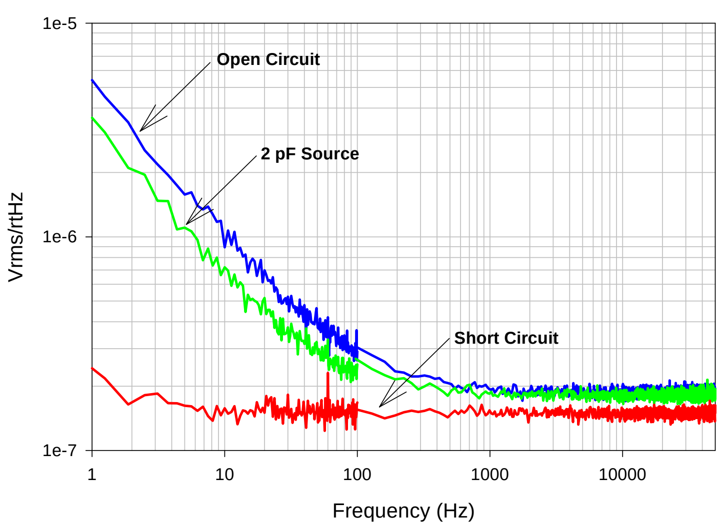


Figure 2: Noise spectrum referred to its input for a QUASAR bioelectrode.
Open Circuit: $C_s = 0$.
2 pF Source: $C_s = 2$ pF.
Short Circuit: Sensor short circuit

The amplifier input current noise acts on the very high impedance of the capacitive electrode, producing an effective input voltage noise that dominates at low frequency. The intrinsic sensitivity (referred to the sensor input) of the current generation of QUASAR bioelectrode technology is shown in Fig. 2. The noise for a shorted input (lowest curve) reflects the input voltage noise of the amplifier. A 1/f dependence for the voltage spectral density is visible in the behaviour of the two upper curves below 100 Hz. For this reason, capacitive bioelectrodes have traditionally used exotic materials to generate a high capacitive coupling (~1 nF) to the skin.

In comparison, QUASAR IBEs use a low dielectric material whose function is to resistively isolate the electrode from the subject. This material exhibits none of the biocompatibility issues of those exotic materials used in traditional high capacitance IBEs, and allows the sensor to measure bioelectric signals when separated from the skin by several layers of fabric. This level of performance has been made possible as a result of recent improvements in transistor technology. State-of-the-art (SoA) devices now have input current noise, $I_n = 0.1$ fA/√Hz, which provides an effective input voltage noise of order 2 μV/√Hz at 10 Hz (low enough for off-body EEG). For larger capacitance to the source, or at higher frequency, the effect of the current noise is reduced to even lower levels and the sensor approaches its voltage noise, which is of order 20 nV/√Hz (see Fig. 2).

Two generations of IBEs developed at QUASAR are shown in the photographs of Fig. 3. The first generation is the larger, square sensor (1”x1”) in Fig. 3, left (IBEv1). These were used for measurements of human bioelectric signals without touching the body through a cotton T-shirt (reported by Matthews, Krupka, Say & Hibbs (2001)). Under a DARPA Phase I SBIR program, this technology was further developed into the much smaller circular sensor in Fig. 3, right (IBEv2).

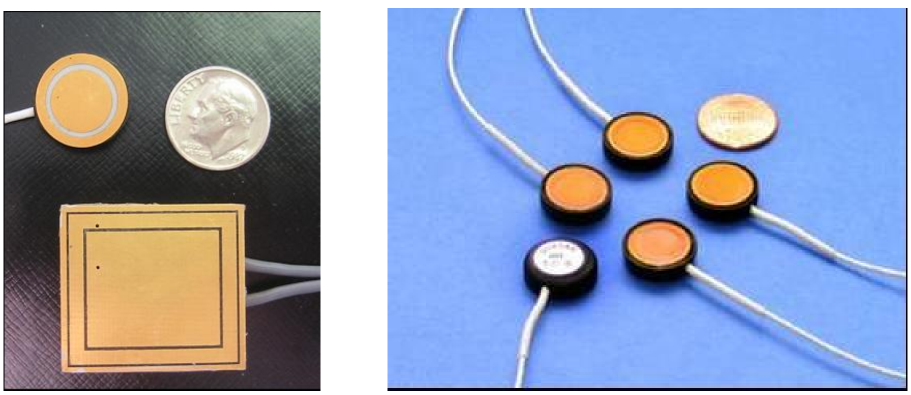


Figure 3: Photographs of QUASAR IBEs.
Left: QUASAR IBEv1 sensor (square sensor) and IBEv2 sensor with a dime for scale.
Right: QUASAR IBEv2 sensors with a US penny included for scale.

3.2 Measurements of Bioelectric Signals Using IBEs

3.2.1 Through-Clothing ECG Measurements

A clinical trial of measuring ECG through clothing, involving 40 healthy people of both sexes and a range of sizes, was conducted at the Walter Reed Army Institute of Research (WRAIR) in the summer of 2002 (Lee, Pearce, Hibbs, Matthews & Morrisette, 2004). All measurements were made through cotton T-shirts that were not modified or prepared in any way. Three IBEv1 sensors were positioned over the T-shirts using a low-cost elastic strap. A typical output for all three sensors obtained when sitting is shown in Fig. 4, in which the top trace is a paste electrode connected to a conventional ECG system. The bottom three lines (tagged by circles, squares and triangles) are the QUASAR electrodes referenced to two other sensors and operating through the T-shirt. The data have been filtered using a 30 Hz low-pass filter, but are otherwise unprocessed.

The correlation between ECG measured by “gold-standard” skin-contacting paste electrodes and the new capacitive sensors through a T-shirt (i.e. without skin contact) was greater than 99% when averaged over all 40 subjects in the trial. Fig. 5 shows correlation between the three QUASAR electrodes and the skin-contacting electrode.

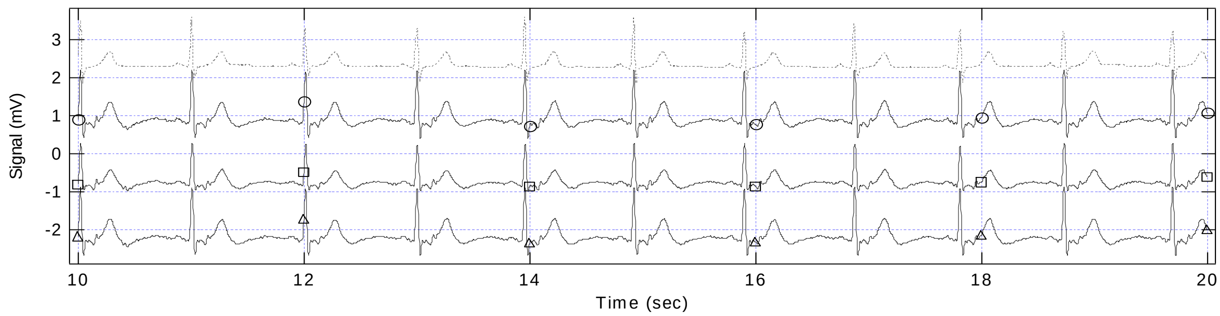


Figure 4: Clinical trial data comparing a conventional skin-contacting electrode (top) with QUASAR electrodes operating through a T-shirt (circle, square, triangle). Subject was sitting.

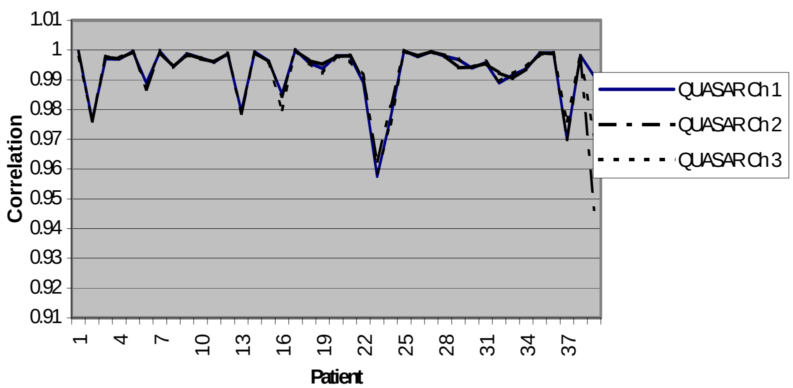


Figure 5: Correlation between each of the three QUASAR electrodes operating through clothing and a skin-contacting paste electrode for all 40 subjects in the clinical test at WRAIR

3.2.2 Effect of High Physical Stress on System Noise

A comparison of the noise performance was made between IBEv2 sensors and a conventional skin-contacting wet sensor. In order to minimize artifacts from other bioelectric signals (EMG, ECG), the IBEv2 measurements were made with two sensors in the center of the forehead. The skin was not prepared in any way and the sensors were held against the subject using a simple elastic strap. To provide a baseline comparison, data were also collected in a subsequent experiment from a pair of conventional wet electrodes attached with their usual adhesive backing. For the wet electrodes, the skin was prepared with an alcohol wipe, but not abraded. In each case the signals from each electrode were differenced using an analog circuit with a very high common mode rejection ratio (CMRR) and subsequently processed using high and low pass digital filters.

Fig. 6 shows time-series and frequency data taken from a 2-minute experiment for a subject sitting in a standard office chair. There is very little difference between the QUASAR sensor and conventional wet electrodes. Around 10 Hz, the wet electrode appears to perform slightly better than the QUASAR sensor, but the wet electrodes exhibit intermittent transient noise spikes. The level of noise for the two sensors is similar in magnitude, suggesting a common mechanism.

The critical issue for many practical applications is the sensor noise level during periods of physical stress on the subject, such as when the subject is moving. Accordingly, data were taken with the subject nodding his head, walking, and running in place. As expected, significant motion artifact was measured from the wet electrode in all modes of motion. This is exemplified by the plot in Fig. 7, left, in which the noise level of the wet electrode has increased to over 150 μV, more than 8 times higher than with the subject at rest. In contrast, the two QUASAR sensors exhibit very little motion artifact for all levels of physical activity, with a noise level almost identical to the level collected while the subject was sitting still. This can be seen in Fig. 7, right. This is an exceptional result, as it has been long believed that significant degradation in signal quality is always experienced when measuring EEG data in motion.

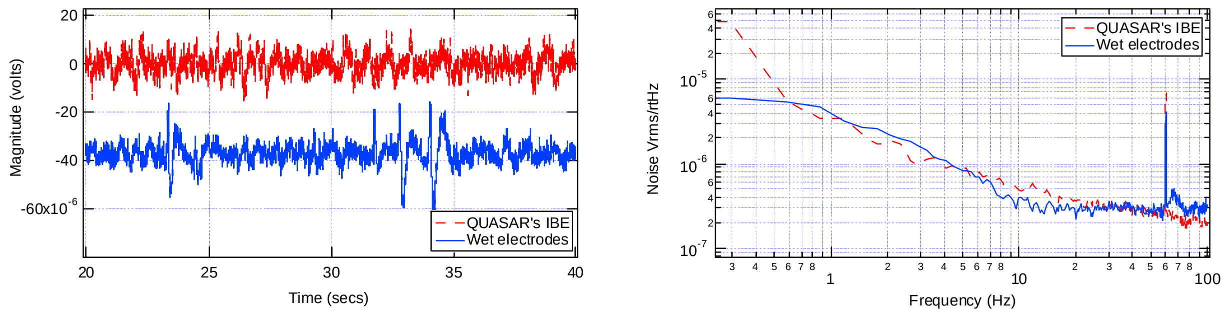


Figure 6: *Left:* Time domain comparison for subject at rest (1-50Hz Bandwidth).
Right: Voltage spectral density for subject at rest

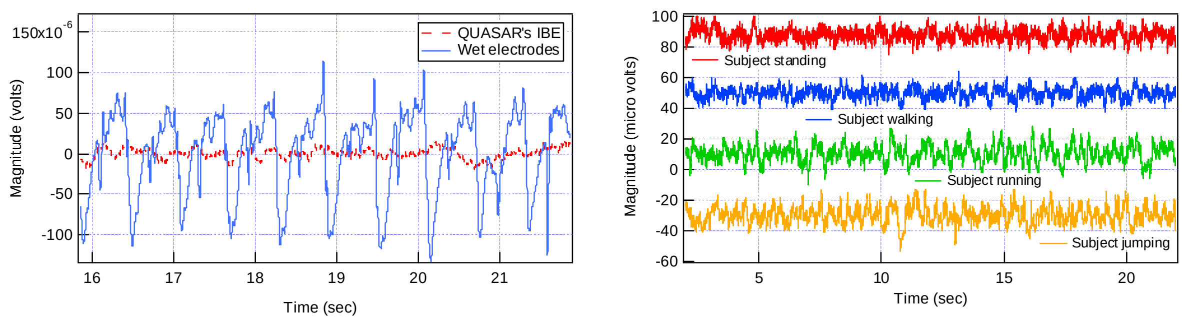


Figure 7: *Left:* Time series comparison between wet electrode and IBEv2 sensor for the subject running in place.
Right: Time series for all levels of physical activity measured by IBEv2 electrodes.
All data filtered using 1-50 Hz bandwidth.

3.2.3 Effect of High Physical Stress on ECG Signals

The effect of physical activity on a bioelectric measurement was determined in a measurement of ECG by IBEv2 electrodes placed on the chest. The electrodes were held in place by an elastic strap. ECG data were recorded while the subject was still and again while the subject was running in place. These measurements were repeated with the ECG recorded through a layer of cotton. The results are presented in Fig. 8, which shows plots for a subject still (lower) and running (upper). Both graphs show excellent ECG signal fidelity with the subject stationary and only slight degradation in signal quality for the subject running in place.

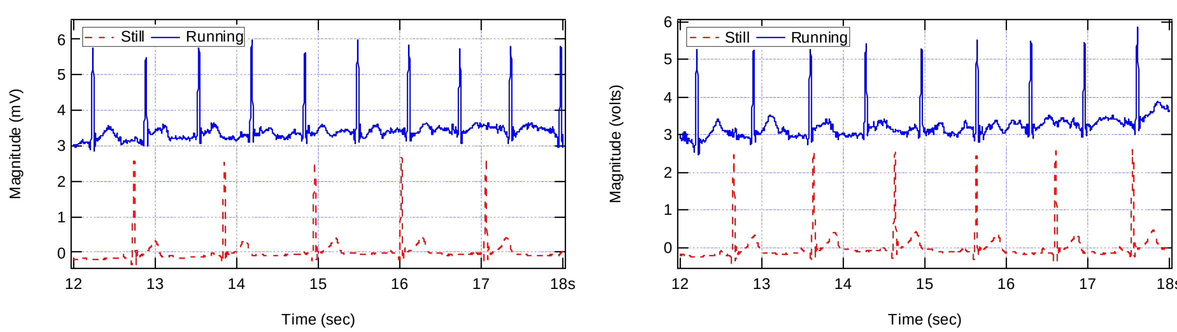
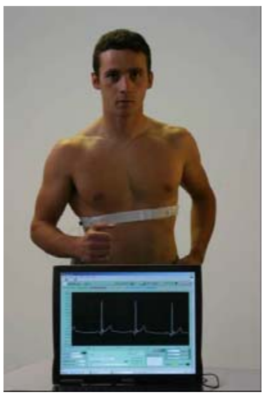


Figure 8: *Left:* Time series comparison still/running in place for IBEv2 sensors placed on the skin.
Right: Time series comparison still/running in place for IBEv2 measurement through cotton.
All data filtered using a 0.05-50 Hz bandpass IIR digital Bessel filter.

3.2.4 Clinical Test of IBEv2 Sensors

The ECG measurements presented in Fig. 8, right demonstrated the fidelity of QUASAR's IBEv1 electrodes in through-clothing measurements of ECG. Fig. 9, right presents data for a clinical demonstration of the IBEv2 sensors placed in cotton pockets of small elastic belts. For the purposes of comparison, wet electrodes were also installed as close as possible to the QUASAR electrodes. ECG data for both sets of electrodes were collected at 1200 Hz. Fig. 9 left shows an ECG chest strap used to position the sensors for measurements on a subject in motion.

The data collected in the clinical tests showed excellent signal fidelity in both lead configurations. A cardiologist who analysed the reported data (Scott, 2004) said that the QUASAR electrodes were "at least equivalent, and often superior, to the standard wet electrodes. The morphologies of the individual components (P, QRS and T waves) were easily recognized and very similar with the two sets of electrodes." In discussing the noise, it was concluded that "despite the noise, the tracings were of sufficient quality for diagnostic use, and similar to some I have seen in clinical settings. In the majority of the recordings the noise level using the QUASAR electrodes was subjectively less than that using the wet electrodes."



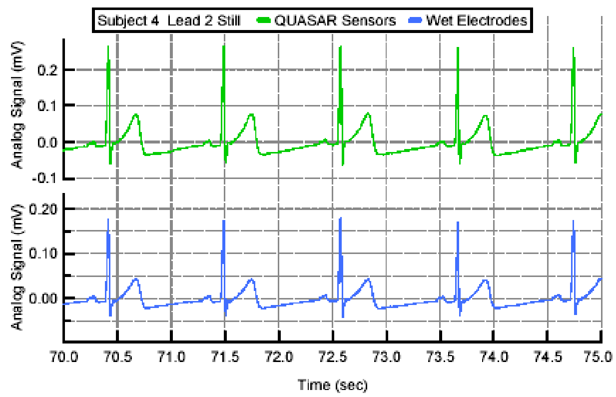


Figure 9: *Left:* ECG chest strap used to position IBEv2 sensors on the chest.
Right: Clinical data recorded with the sensors in the lead-2 configuration.
Upper trace – QUASAR sensors *Lower trace* – wet electrodes

Further tests were conducted to evaluate the electrodes under moderate-to-high levels of physical activity. For the purposes of comparison, a Polar S180i heart rate monitor system was installed immediately below the QUASAR electrodes on the midline of the chest. Data were collected from three test subjects as they moved through an obstacle course that involved the following physical activities: running in place, stepping up and down from a small block, crawling along the ground on hands and knees, pulling on an elastic rope, lifting a 20-lb weight above the head, climbing up and down a step ladder, and climbing over a 3-ft-high obstacle. Averaged over all of the data collected for the 3 test subjects, the QUASAR electrodes achieved a 99.8% correct classification of the heart rate. This corresponded to 23 points incorrectly classified or missing in 10,417 points. By contrast, the Polar system achieved a 94.5% correct classification of the heart rate.

3.2.5 Comparison of IBEv2 and Wet Electrode for Measurement of EEG

A comparison of EEG signal fidelity for IBEv2 sensors and a conventional skin-contacting wet sensor was conducted using a single IBEv2 sensor and a conventional wet electrode placed side-by-side, with the IBEv2 sensor held in place against the forehead using an elastic strap. The skin under the wet electrode was prepared with an alcohol wipe (with no abrasion), while no skin preparation was used for the IBEv2 sensor. The onset of alpha activity is shown in Fig. 10. In this plot there is near perfect agreement between the sensors (whose traces are shown slightly offset to illustrate the temporal correlation between the two sensors).

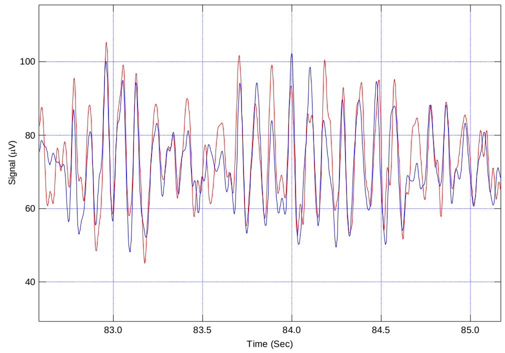


Figure 10: Alpha wave activity observed using QUASAR IBEv2 sensor and conventional resistive contact electrodes. Electrodes were in contact with the top of the head. The two curves are offset to illustrate the temporal correlation between the two sensors. *Blue (darker) trace:* skin-contacting wet electrode. *Red (lighter) trace:* QUASAR IBEv2 sensor.

4 Integrated Bioelectrode Systems

To date QUASAR has developed 6 integrated bioelectric systems based upon the IBEv2 sensors. Fig. 11 presents photographs of five other systems. In the top right photograph of the Figure, IBEv2 sensors have been discretely integrated into a chair for non-contact measurements of ECG. The top center photograph shows a subject lying on a stretcher that similarly has integrated IBEv2 sensors. In both ECG systems, ECG measurements are taken through at least two layers of material (the subject's clothing and the material covering the sensors). In each photograph, there is a real-time display of the ECG measurements (filtered for R-R timing) on the computer screen. The red markers on the plots correspond to the R-wave peak determined using a simple peak algorithm.

The top right photograph is a photograph of a pull-on, adjustable shirt with integrated sensors that is suitable for quick, prep-free measurements of ECG, giving good R-R determination even under high levels of physical motion.

The bottom left photograph shows four sensors mounted in an ordinary baseball cap. The display EEG signal is shown on the laptop screen in the foreground of the photograph. No skin preparation was performed on the subject for this measurement. The bottom right photograph in the Figure shows IBEv2 sensors integrated into a pair of glasses for the measurement of EOG. Data taken with the EOG glasses is shown in Fig. 12.

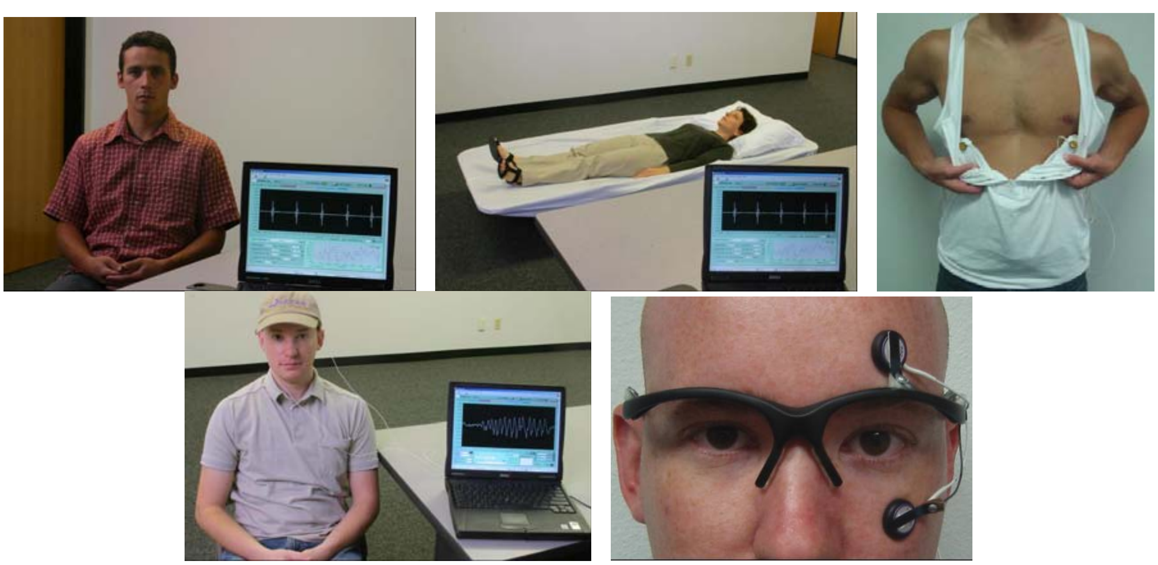


Figure 11: Photographs of integrated ECG systems.
Top Left: ECG chair system. *Top Center:* ECG stretcher. *Top Right:* ECG shirt.
Bottom Left: EEG cap system. *Bottom Right:* EOG glasses.

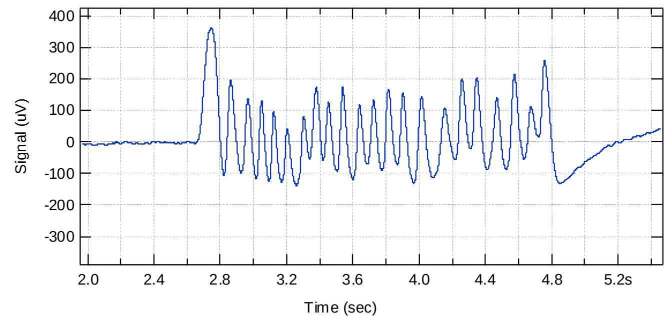


Figure 12: Data taken with EOG glasses

5 Elimination of Skin Noise

It was remarked in Section 3.2.2 that the noise levels shown in Fig. 6 for the QUASAR IBEv2 sensors and conventional wet electrodes were similar in magnitude. This suggests a common mechanism, which can be identified as residual epidermal artifact signal. The epidermal artifact signal is the potential developed in the skin itself (Edelberg, 1973). This skin signal is the primary source of movement-related (motion) artifact even when the subject is still, although contribution to the observed noise can be reduced by careful preparation of the skin. This usually involves abrasion of the skin (Tam & Webster, 1977) and the application of a conducting gel to improve the electrical contact between the electrode and the skin.

Fig. 13 presents data from EEG measurements taken using resistive contact electrodes. The ‘no prep’ curve (lower) is an example of noise in an EEG measurement using a conventional resistive EEG electrode in the absence of any skin preparation. The noise in the ‘no prep’ curve is more than an order of magnitude greater than the expected noise that can be explained by the contact impedance. For example, a typical skin-electrode contact resistance of 100 kΩ would possess Nyquist noise with an amplitude equal to 0.4μV/√Hz (corresponding to approximately 1.2μV peak-to-peak (p-p) in a 100 Hz signal bandwidth). The ‘prep’ curve (upper) shows results obtained using a thorough preparation of the scalp involving abrasion combined with the application of a conducting gel. A good surface preparation typically results in a reduction of the surface resistance to ~5 kΩ. This behaviour is in agreement with the results of Huigen *et al.* (2002), which show a clear relationship between electrode noise and the electrode-skin impedance, even though the resulting noise level is still considerably larger than that expected for the electrode-skin contact resistance.

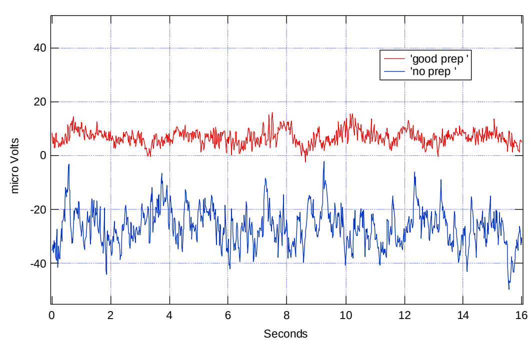


Figure 13: Output of resistive contact EEG electrode. No surface preparation of the scalp was involved for ‘no prep’ (lower) curve. The surface preparation for the ‘good prep’ (upper) curve involved abrading the skin and the application of a conducting gel.

QUASAR has developed a new sensor design that is intrinsically insensitive to epidermal artifact noise. The new sensor, which is currently under construction, represents a radical new direction in capacitive electrode technology. Most significantly for this application, it is able to discriminate between skin noise and the bioelectric signal of interest, allowing the sensor to measure EEG signals with a noise level determined by the sensor electronics. More generally, it will allow the operation of capacitive electrodes with significantly lower noise levels.

6 Concluding Remarks

The deployment of bioelectric sensors in settings beyond a clinical environment requires the use of sensors that are non-invasive, unobtrusive, and easy to use. In this paper we presented high fidelity bioelectric signal data collected using QUASAR's IBEv2 technology in the absence of any skin preparation, in which the sensors achieved noise levels similar to those obtained using conventional resistive contact technology. In a clinical trial of measuring ECG through clothing there was excellent agreement between QUASAR's IBEv1 sensors and "gold standard" resistive contact electrodes, with a correlation of greater than 99% when averaged over 40 subjects. Independent analysis of ECG data by a board certified cardiologist from a clinical test using QUASAR's IBEv2 found that the morphologies of individual components in the ECG trace were readily recognizable with a signal fidelity that was often superior to that observed using standard wet electrodes. Furthermore, the QUASAR IBEs exhibited significantly less sensitivity to motion artifact signals than resistive contact electrodes, and bioelectric signals were successfully measured with sensors incorporated into items of clothing including shirts, elastic belts, and glasses.

The QUASAR IBEv2 sensors are state-of-the-art bioelectric sensors that are suitable for most applications involving measurements of ECG or EEG. However, extremely low-noise measurements of bioelectric signals, such as the measurement of event-related potentials (ERPs) require the removal of the epidermal artifact noise, which at present is only possible by aggressively preparing the skin. This limits such measurements to clinical environments and renders long-term monitoring impossible.

The next generation of QUASAR sensors will remove the need for any skin preparation in low-noise bioelectric measurements. The new QUASAR sensors will not only be capable of ultra-low noise, non-contact, through-clothing measurements of bioelectric signals, but they will also be insensitive to epidermal artifact noise. The new design will immediately find uses in any application requiring long-term, high fidelity monitoring of bioelectric signals, such as DARPA's Augmented Cognition program. The combination of long-term monitoring capability, absence of biocompatibility issues, and ease of use will finally allow the real-world deployment of a system to monitor cognitive performance.

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