

Revolutionary optical sensor for physiological monitoring in the battlefield

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ABSTRACT

SRICO has developed a revolutionary approach to physiological status monitoring using state-of-the-art optical chip technology. The company's patent pending Photrode™ is a photonic electrode that uses unique optical voltage sensing technology to measure and monitor electrophysiological parameters. The optical-based monitoring system enables dry-contact measurements of EEG and ECG signals that require no surface preparation or conductive gel and non-contact measurements of ECG signals through the clothing. The Photrode™ applies high performance optical integrated circuit technology, that has been successfully implemented in military & commercial aerospace, missile, and communications applications for sensing and signal transmission. SRICO's award winning Photrode™ represents a new paradigm for the measurement of biopotentials in a reliable, convenient, and non-intrusive manner. Photrode™ technology has significant applications on the battlefield for rapid triage to determine the brain dead from those with viable brain function. An ECG may be obtained over the clothing without any direct skin contact. Such applications would enable the combat medic to receive timely medical information and to make important decisions regarding identification, location, triage priority and treatment of casualties. Other applications for the Photrode™ include anesthesia awareness monitoring, sleep medicine, mobile medical monitoring for space flight, emergency patient care, functional magnetic resonance imaging, various biopotential signal acquisition (EMG, EOG), and routine neuro and cardio diagnostics.

Keywords: Photrode™, physiological sensing, lithium niobate, fiber optic, optical modulator, Mach-Zehnder Interferometer

1. INTRODUCTION

A revolutionary approach to electrophysiological monitoring of military pilots and other defense and security personnel has emerged from an optical voltage sensor technology that uses optical modulator waveguide design. Using light as its medium and innovative optical chip technology at its heart, the award-winning¹ Photrode™ represents a new archetype in biopotential detection. Optical-based Photrodes™ are different from standard, low impedance electrodes due to their high impedance characteristics. This high impedance nature of the Photrode™ allows for non-contact electrocardiogram (ECG) measurements, such as, through the clothing. Unlike conventional electrodes, Photrodes™ are non-invasive and do not require the use of any harsh abrasives or conductive gels in order to make good contact with the skin. Photrodes™ are passive devices that do not have any current pathway to the patient. Another advantage of a light-based sensor is that there is no loss of signal, as in an electrical wire, and there is no need for a pre-amplifier. Photrode™ devices have broad range voltage sensitivity that enables the detection of microvolt level electrophysiological signals, such as the electroencephalogram (EEG).

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1.1 General overview of Photrode™

The basic Photrode™ system consists of a laser source, optical input and output fibers, and an optical receiver and signal processing components as seen in Figure 1. A biopotential signal, produced from a body, such as an ECG, a signal produced by various heart movements, is applied to the Photrode™. Light from a continuous wave (CW) laser source enters the Photrode™, via optical fiber, and becomes intensity modulated by the biopotential signal. An optical receiver for detection and signal processing detects the output of the Photrode™.

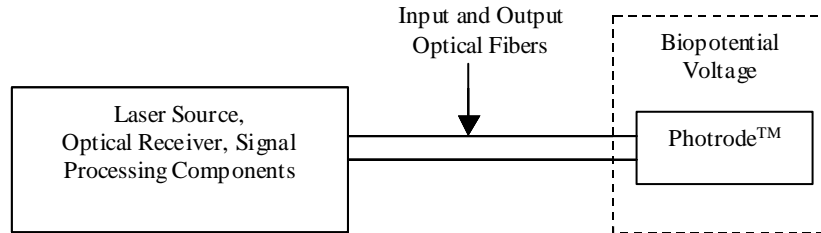


Figure 1. Basic Photrode™ system

2. TECHNICAL BACKGROUND

The key operational component of the Photrode™ device is a miniature, specially designed, optical chip. The Photrode™ is based on integrated optic waveguide technology that has been used over the past two decades in demanding military and aerospace applications and, more recently, in telecommunications networks. The miniature, chip-size device consists of an integrated optical circuit referred to as a Mach-Zehnder Interferometer (MZI).

2.1 Photrode™ design

The Mach-Zehnder Interferometer, shown in Figure 2, consists of an input light path, known as a waveguide, a Y-branch splitter, which divides the light path into two separate waveguides, and a Y-branch combiner, which recombines the two light paths into one waveguide at the output. The MZI is fabricated in a lithium niobate electro-optic crystal substrate. Optical input and output fibers are attached to the substrate using standard techniques from the manufacture of optical waveguide devices.² Thin-film gold electrodes are deposited on the crystal, which concentrate an ambient biopotential signal at the waveguides. The electrodes operate in a push-pull configuration, modulating the light via the electro-optic effect as the two arms of the interferometer are subjected to opposite voltages.

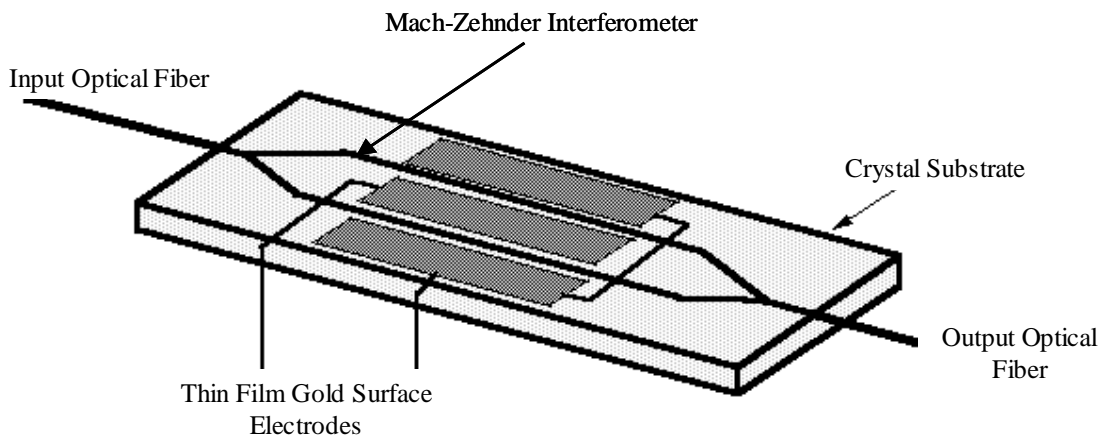


Figure 2. Photrode™ schematic

Figure 3 shows the prototype Photrode™ package currently used for biopotential measurements although the actual commercial device would be much smaller. For instance, placing the Photrode™ across the chest with the biopotential contacts touching the skin of the subject produces differential ECG measurements. The grounding tag, connected to the Photrode™ package, is used as an extra ground reference.

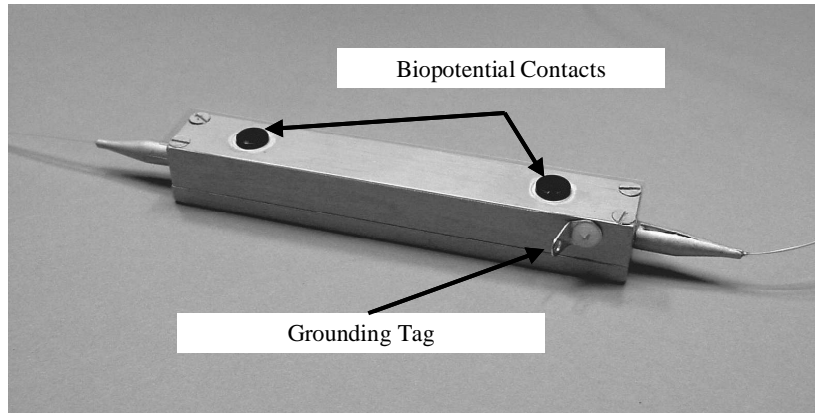


Figure 3. Prototype Photrode™ package

2.2 Photrode™ characteristics

This uniquely designed Photrode™ is ultra sensitive, functions as a high impedance device, and provides a high bandwidth especially capable of detecting low to high frequency ranged signals.

The response characteristic of the Mach-Zehnder interferometer Photrode™ is a cosine-squared function shown in Figure 4. To achieve the desired sensitivity needed to detect biopotential signals, Photrodes™ are selected to operate for small signal modulation, i.e. in the linear region of the cosine-squared curve, also known as phase quadrature. Therefore no external dc bias voltage is needed for the device to operate with maximum sensitivity.

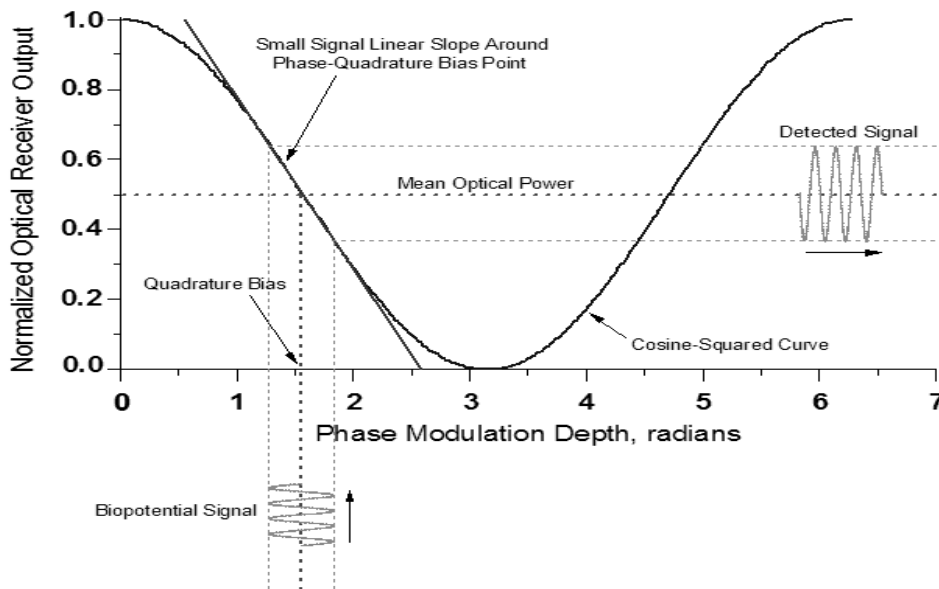


Figure 4. Mach Zehnder cosine squared response

The simplified equivalent circuit for the Photrode™ is that of a very small capacitance (i.e., a few picofarads) in parallel with a very high resistance (i.e., 10^{14} Ohms). This is illustrated in Figure 5. It is this ultra-high electrical impedance that gives the Photrode™ one of its remarkable properties for measuring biopotentials, unlike the standard low impedance electrodes commonly used in medical device technology. A resistive component is connected in parallel with the Photrode™ to lessen the likelihood that Electro-Static Discharge (ESD) could damage the Photrode™.

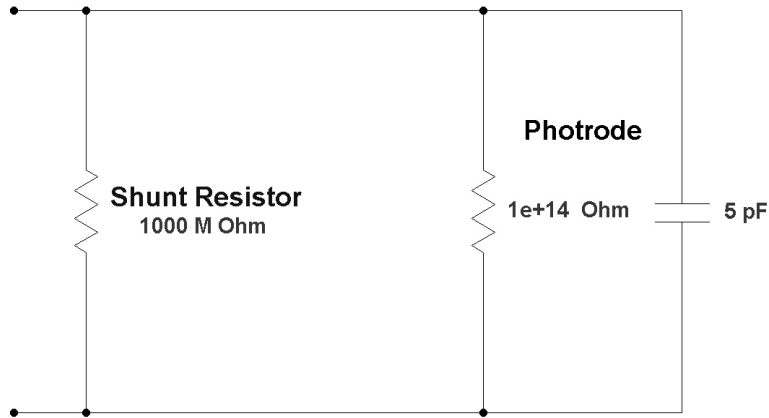


Figure 5. Equivalent Photrode™ circuit

Mach-Zehnder interferometer electro-optic modulators used in telecommunication networks are well known for their high frequency characteristics, but their low frequency response is typically limited to about 100 kHz. In order to detect biopotentials using MZI modulator devices, low frequency operation is imperative. In the case of the ECG signal, the frequency range is 0.1-150 Hz.³ At 1 kHz, typical commercially available integrated optic modulators produce considerable differentiation and tilt, as seen in Figure 6. The performance of the conventional modulator will affect the measurement of the ECG signal, causing severe distortion of the ECG waveform. This data was taken using a conventional high frequency SRICO modulator, oscilloscope, and signal generator.

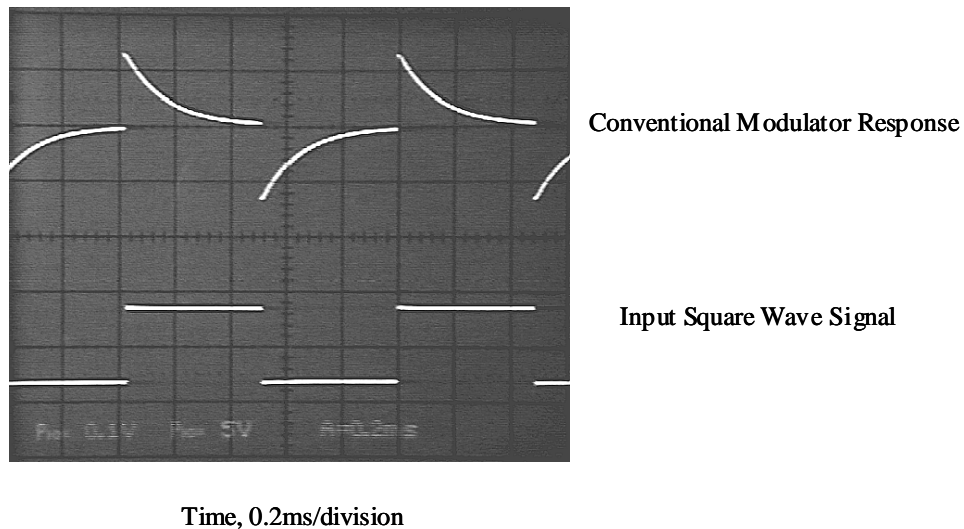


Figure 6. Conventional electro-optic modulator response at 1 kHz

Figure 7 shows the characteristic of the Photrode™ device driven with an input square wave signal at a frequency of 1 kHz. The Photrode™ reproduces the input square wave signal data with no distortion or tilt, unlike the conventional high frequency modulator response of Figure 6.

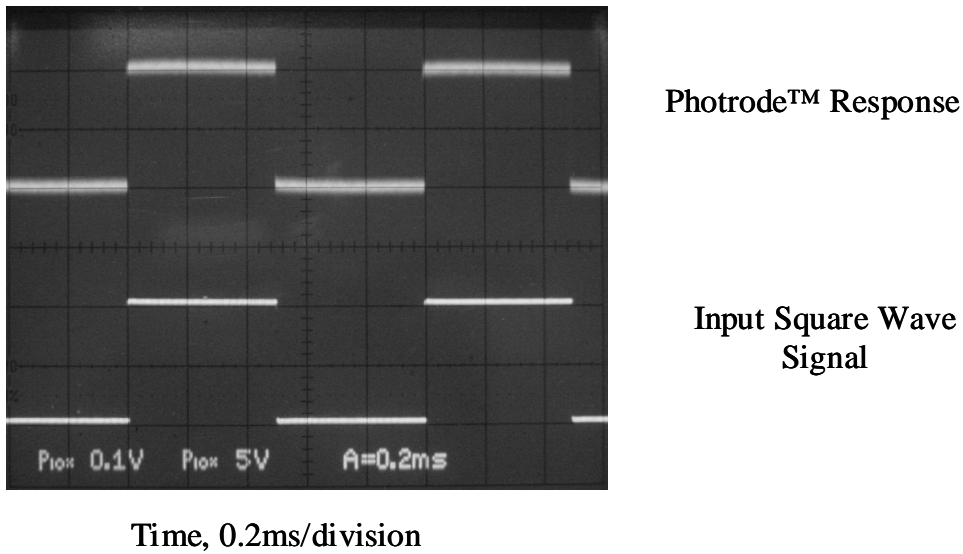


Figure 7. Photrode™ characteristic response at 1 kHz

In order to detect biopotentials such as ECG and EEG, the Photrode™ is required to faithfully respond to signals in the frequency range of sub one-Hertz to 100 Hz. Figure 8 shows the characteristic of the Photrode™ driven with an input square wave signal at a frequency of 1 Hz. This flat response indicates that the Photrode™ is capable of detecting electrical signals even below 1 Hz.

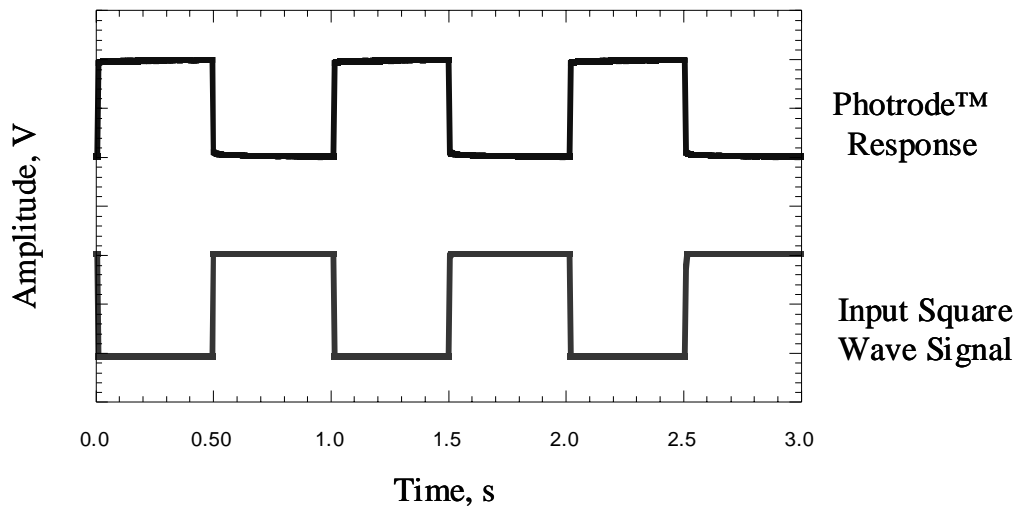


Figure 8. Low frequency Photrode™ characteristic

Figure 9 represents the biopotential signal levels and the contributions from the various noise sources associated with the Photrode™ system. The calculated optical carrier to noise ratio (CNR) of 154 dB/Hz is based on a received optical power of 1 mW at the operating wavelength of 1550 nm. The quantum noise refers to the noise associated with the statistical arrival of photons. Thermal noise, also referred to as conventional Johnson noise, is the noise produced by all electrical circuits above temperatures of absolute zero. An EEG signal, i.e. an electroencephalogram produced by the activity in the brain, is represented at a signal level of 1 μV over a frequency range of 1 to 60 Hz. The ECG signal is represented at a signal level of 1mV over a frequency range of 0.1 to 500 Hz. As seen in this graph the Photrode™ system noise is below that of the ECG and EEG signal levels. Therefore the Photrode™ is capable of measuring low-level biopotential signals.

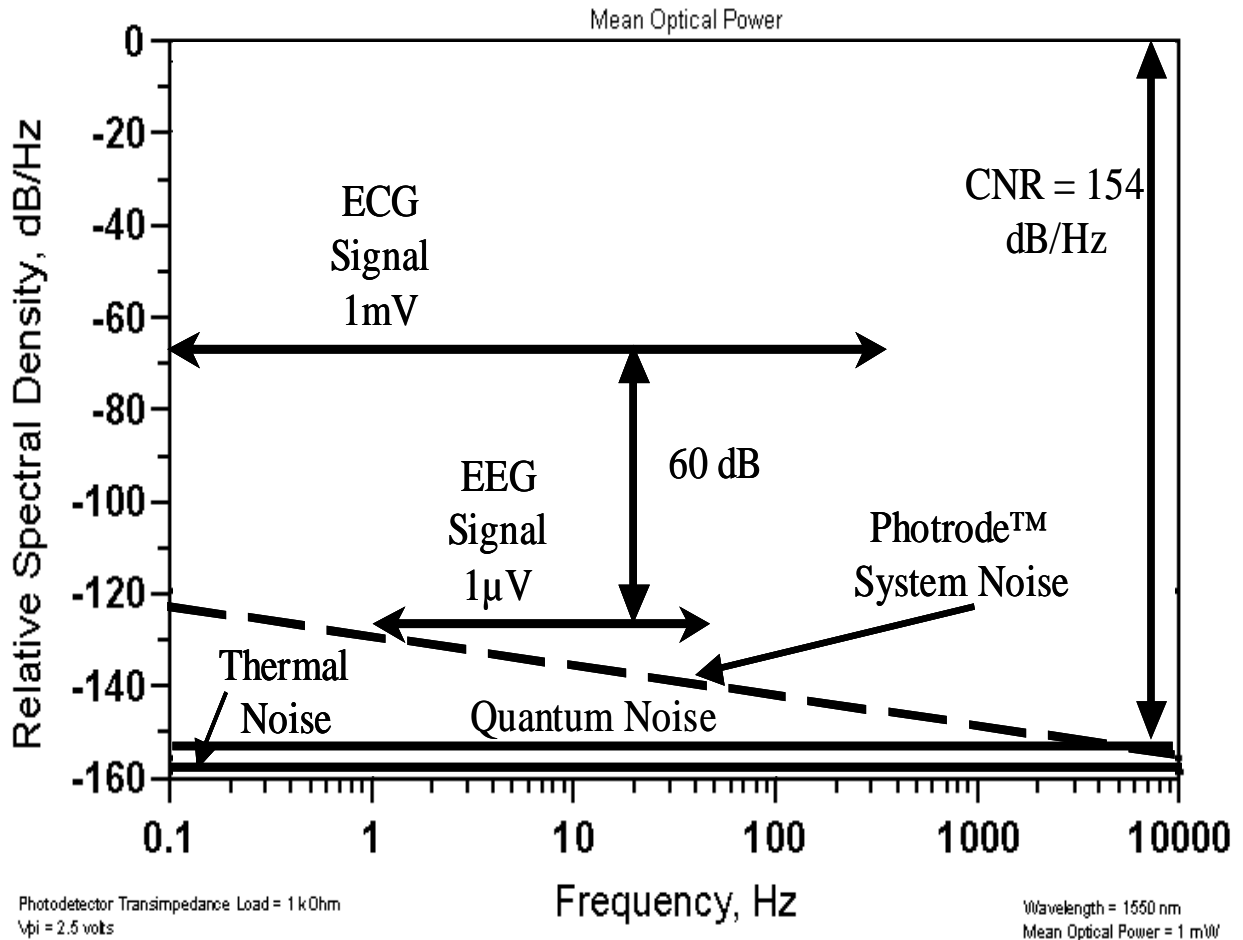


Figure 9. Signal and noise characteristics for biopotential measurements using the Photrode™

3. BIOPOTENTIAL MEASUREMENTS

The performance of the Photrode™ was characterized and compared with ECG and EEG waveforms collected using wet contact electrodes, of the typical silver-silver chloride variety. The Photrode™ signal was converted to an electrical signal, within the optical receiver, and the resulting data was acquired using a BIOPAC MP150 system simultaneously with the signals detected by conventional electrodes.

3.1 Results

Figure 10 shows ECG data collected using the Photrode™ along with data collected using a standard ECG electrode. The ECG signal is from one of the authors who has a known arrhythmia. The top trace corresponds to the Photrode™, and the bottom trace represents the electrode acquired biopotential ECG data. The data on both traces have been filtered using standard software provided with the acquisition unit (BIOPAC Acqknowledge version 4.7.3). Both responses are taken simultaneously, in close proximity to one another on the chest wall, and there is excellent agreement between the two signals. The arrhythmia and the PQRST waveform of the ECG, associated with the depolarization and repolarization of the various regions of the heart, is prevalent in both traces.

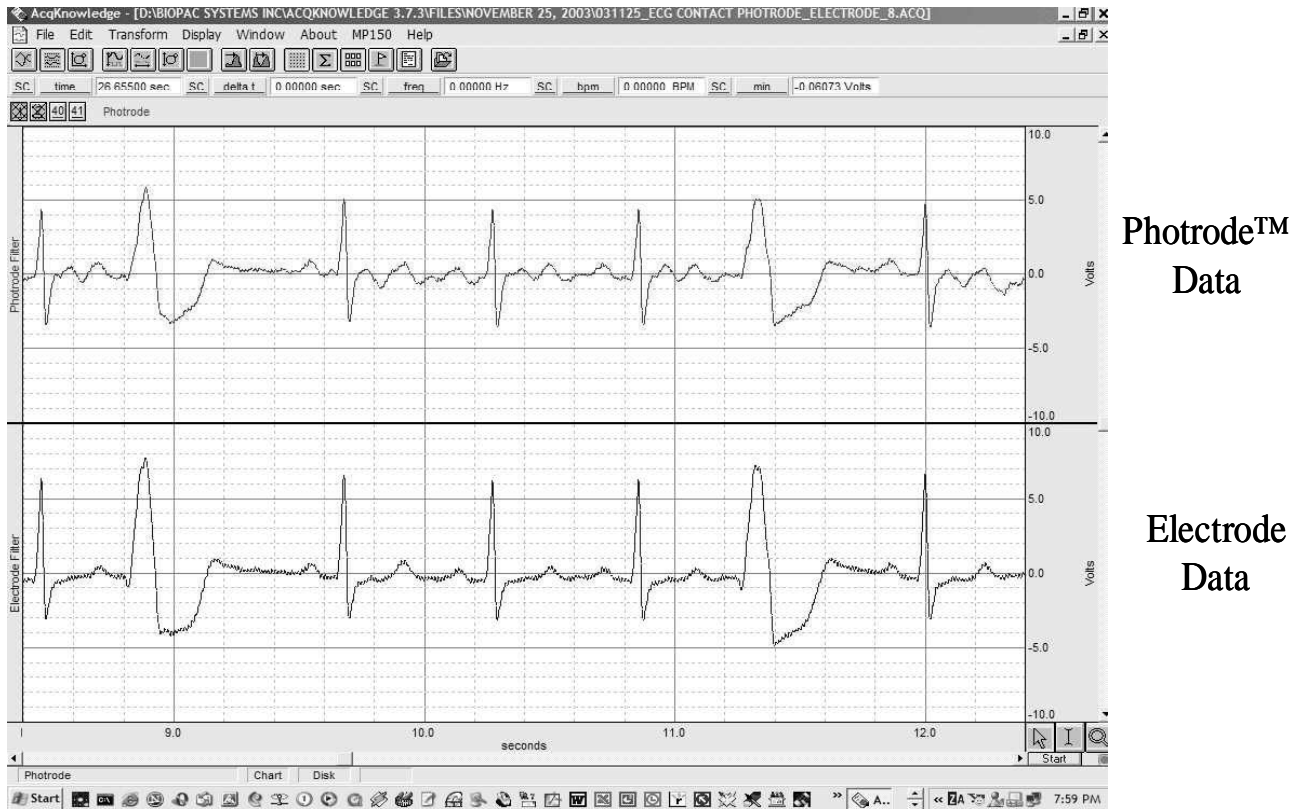


Figure 10. Photrode™ (top) vs. electrode (bottom) ECG response

Figure 11 shows the EEG response of the Photrode™ system compared to the response from standard electrodes. This data was collected from one of the authors. The electrode data was taken with a differential measurement on the C3 and C4 areas of the brain⁴, the Photrode™ data was collected on the Cz region of the brain, between the C3 and C4 areas, with a return to ground on the earlobe. The raw data are shown in traces 1 and 2, and the traces below are filtered to show various standard signals of interest. The data acquisition rate was 10000 samples per second, using the BIOPAC MP150 System. Comparing charts 3 and 7 below, the delta waveform characteristics are represented in both the electrode (#7) and Photrode™ (#3) traces and are very similar. The different placement regions of the devices, as well as the motional artifacts of the subject can account for any differences between the two traces.

- | | |
|---|---|
| Chart 1: Cz- Raw Photrode™ Data | Chart 6: Photrode™ - Beta Wave (13-30 Hz) |
| Chart 2: C3, C4 - Raw Electrode Data | Chart 7: Electrode Delta Wave (1-4 Hz) |
| Chart 3: Photrode™ - Delta Wave (1-4 Hz) | Chart 8: Electrode Theta Wave (4-8 Hz) |
| Chart 4: Photrode™ - Theta Wave (4-8 Hz) | Chart 9: Electrode Alpha Wave (8-13 Hz) |
| Chart 5: Photrode™ - Alpha Wave (8-13 Hz) | Chart 10: Electrode Beta Wave (13-30 Hz) |

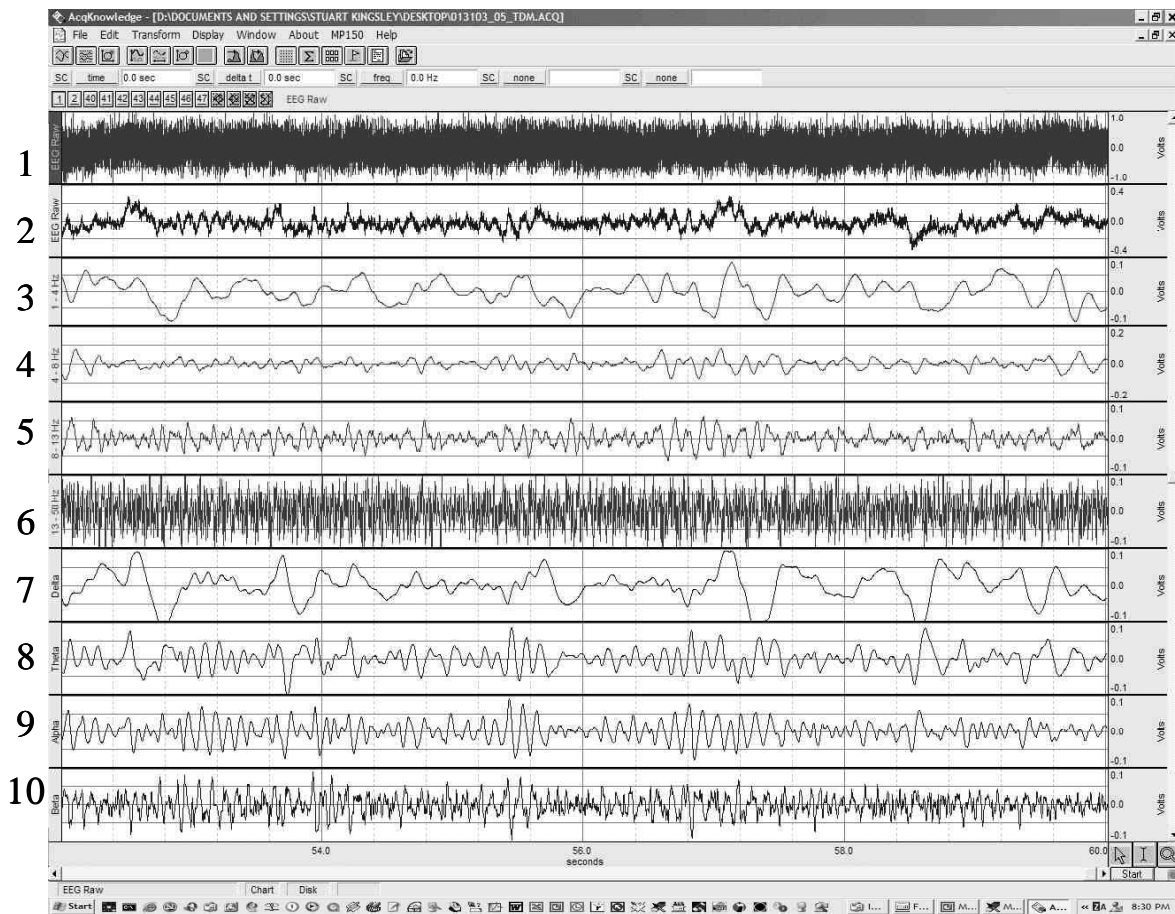


Figure 11. EEG response of Photrode™ and electrode

3.2 Application areas

Standard electrode technology relies on a low impedance contact to the skin to detect the biopotential voltage of interest. The skin, composed of many different layers of cells, has an impedance range of 200 k Ω at 1 Hz to 200 Ω at 1 MHz for 1cm² in the epidermis layer.⁵ It is in this epidermis layer that cells are constantly growing and dying – thus accounting for their different electrical characteristics. Typically, electrode impedance values range from 30 k Ω - 10 Ω , and are dependent on frequency, the electrode material, and the electrolyte used.⁶ In order for the typical electrode to maintain reliable contact, impedance <5 k Ω , the skin is often vigorously cleaned, or even abraded in order to improve the stability of the signal during collection. This can be a time-consuming, messy, and somewhat uncomfortable process, depending upon the desired biopotential. For instance, in an EEG signal as many as 24 electrodes are attached to the scalp with a collodion adhesive which hardens and must be dissolved in acetone for removal. Some subjects find this electrode removal process to be irritating, uncomfortable, and painful, particularly if they have a full head of hair. Newer electrode technology, especially in ECG acquisition, offers pre-gelled electrodes providing low impedance contact, and each electrode is surrounded by adhesive to keep the contact in place on the skin. During long-term monitoring, the gel may dry out thereby losing the low impedance contact, after which the electrode is removed and a fresh electrode is reapplied. This of course consumes the time taken by the medical professional to reapply the electrode and obtain the low impedance contact, not to mention the aggravation to the patient who must endure the removal and reattachment routine.

Since the Photrode™ is a high impedance device, low-impedance skin contact is not required. Thus, the Photrode™ can function as a non-contact or a dry contact device. Unlike conventional electrode technology, the dry contact method requires no skin preparation, no conductive gels and no adhesives. In non-contact mode, the device does not even touch the body, enabling even more flexible applications. Indeed, laboratory tests show the Photrode™ is capable of detecting an ECG signal from over the subject's shirt. These results represent a significant advance in optical voltage sensing technology and suggest the possibility of placing the ECG Photrode™ over a patient's gown, or incorporated into a soldier or police officer's body armor or underclothing. The capability of this "wear-and-forget" sensor technology is beneficial to biopotential measurement applications in future defense and security development.

The Photrode™ was developed especially for electrophysiological measurement applications in which conventional electrodes are deemed to be unsafe, unreliable, uncomfortable, or inconvenient. Motivation for such a system includes previous research demonstrating that soldiers who have been awake for 48-72 hours rapidly lose their ability to make correct judgments.^{7, 8} Other applications of alertness monitoring include heavy equipment operators, defense, and security personnel who must be able to make decisions in order to avert possible accidents, or incidents.⁹ The optical EEG and ECG technology was initially developed for the U.S. Army Aeromedical Research Laboratory for physiological status monitoring of Army pilots; the Walter Reed Army Institute of Research, Division of Neuropsychiatry, for ambulatory alertness monitoring; and the Walter Reed Army Institute of Research, Division of Surgery, for triage applications. Subsequent research and development efforts under NIH grants have focused on the use of EEG and ECG Photrode™ technology for functional magnetic resonance imaging. Future scenarios of the battlefield envision soldiers wearing a number of sensors and devices to monitor vital signs and provide Commanders with crucial information regarding the readiness of their troops and the chances of successful missions based upon such information.¹⁰ The Photrode's™ non-invasive technology is insensitive to electromagnetic interference from other devices and from the battlefield environment making it an ideal choice for future defense and security applications, and since no electrical power is supplied to the Photrode™, safety and comfort are assured. Photrode™ technology is not limited to these applications and may be used for any type of electrophysiological measurement.

4. CONCLUSIONS

An optical technology developed for high speed telecommunications signal transmission and demanding defense and aerospace sensing applications has enabled the advancement of revolutionary medical device technology for biopotential detection. The Photrode™, which has high impedance characteristics, high bandwidth, and ultra high sensitivity, has proved to be a novel device for detection of biopotential signals. As shown, the Photrode™ is able to successfully detect ECG and EEG signals using dry contact methods, unlike conventional electrodes, which rely on low impedance, wet contact attachment to the skin. Although the Photrode™ technology has only been developed and tested for ECG and for EEG alertness analysis research, it may also be applied to other biopotential signals areas such as electromyography (EMG), and electrooculography (EOG). With such high demand application areas being important to defense and security personnel as well as those undergoing patient monitoring, the Photrode™ technology has a promising future in years to come.

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