Wireless Behind-the-Ear EEG Recording Device with Wireless Interface to a Mobile Device (iPhone/iPod Touch)

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***Abstract*— EEG remains the mainstay test for the diagnosis and treatment of patients with epilepsy. Unfortunately, ambulatory EEG systems are far from ideal for patients that have infrequent seizures. The systems only last up to 3 days and if a seizure is not captured during the recordings, the doctor cannot give a definite diagnosis of the patient's condition. The ambulatory systems also suffers from being too bulky and posing some constraints on the patient, such as not being able to shower during the recordings. This paper presents a novel behind-the-ear EEG recording device that uses an iPhone or iPod Touch to continuously upload the patient's data to a secure server. This device not only gives the doctors access to the EEG data in real time but it can be easily removed and re-applied by the patient at any time, thus reducing the interference with quality of life.**

I. Introduction

Epilepsy is a common neurological disorder that affects about 1% of the world population [1]. It is characterized by repeated seizures, which are caused by an abnormal neuronal firing rate at the affected brain area [2]. If the abnormal firing rate is localized in a specific part of the brain, it is called focal seizure; when spread to the rest of the brain, it is called generalized seizure. To determine the type and the focal point of a seizure an electroencephalogram (EEG) is performed [2]. EEG is the recording of the electrical activity on the scalp. Capturing a seizure with EEG is a necessary prerequisite for making a definitive diagnosis, tailoring therapy, moving toward certain kinds of solutions such as surgery, or even affixing the true rate of events.

Although EEG has been the chief modality in the diagnosis and treatment of epileptic disorders for more than half a century, the vast majority of tests are still performed in the hospital or office setting and are of brief duration. Long term recordings (from days to weeks) can be obtained but these must occur in the hospital setting. Many patients have intermittent seizures occurring very infrequently – from once a week to once every few months [3]. These patients cannot come into the hospital for weeks on end in order for an event to be captured on EEG, making an accurate and definitive diagnosis very difficult.

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Fig. 1. Examples of ambulatory EEG [4] (left) and [5] (right)

One option for the patients with infrequent seizures is to wear an ambulatory EEG system similar to the one shown in Figure 1 [4-5]. However, the ambulatory systems have many drawbacks: they only last up to 3 days, the patient must wear a backpack that contains the recording electronics all the time, the patient cannot shower since water interferes with the electrodes [6], and many avoid daily activities such as work and school while wearing the system given its cosmetic impact [7].

Some work has been done trying to reduce the form factor of the ambulatory systems by reducing the size of the electronics and storing all the data into an SD card [8-9]. With these systems, the electronics are placed on the patients head and don't require a backpack. However, these systems don't give any feedback to the patients whether the electrodes are placed correctly. So, if the patient removes the device to take a shower, there is no way of knowing if the system was reapplied correctly. [10-11] designed a wireless EEG system that gives feedback to the patient regarding the electrode connection, however, the device transmits to a receiver that needs to be attached to a computer, which poses the constraint that the patient must be within 10 meters of the computer at all times.

This paper aims to advance the ambulatory EEG space by presenting a novel wearable behind-the-ear EEG recorder that transmits the data wirelessly to an iPod Touch or an iPhone and uploads the data in real-time to the hospital's server. The iPhone also serves as the feedback interface showing whether the system was reapplied correctly. This option not only gives maximum freedom to the patient as he or she can easily carry an iPhone anywhere but also gives the doctor access to the data in real time.

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II. PROPOSED SYSTEM

The first step in the development of the system was to create a 1 channel prototype using off-the-shelf components. In order for the system to be clinically useful in the diagnosis of epilepsy, the channel count must be at least 4, so future versions of the system will have a higher number of channels [12]. The American Clinical Neurophysiology Society published a guideline on the recommended specifications for a system recording long term EEG for epilepsy, they are listed in Table 1 [13]. Usually the highest power consumption block of a system is transmitting the data wirelessly or storing it to memory. Since the amount of data is proportional to sample rate, we decided to reduce the sample rate while still exceeding the recommendations listed in Table 1 in order to minimize power consumption. As a result, the EEG was sampled at 256 Hz with a low-frequency and high-frequency response of 0.1 Hz and 100 Hz, respectively. These settings are typically what is commonly used in EEG recordings at hospitals.

When an electrode is placed on the skin, a potential voltage is generated and it is dependent on the electrode material, electrolyte composition and temperature [14]. This potential voltage, commonly referred as electrode offset voltage, can be as high as 60 mV for a silver/silver chloride electrode and its frequency content is basically at DC [15]. Since EEG amplitudes can range from a few tenths of microvolts up to around a millivolt during a seizure, the system must reject the electrode offset voltage while providing the necessary gain to the EEG signal [16].

The low-noise amplifier chosen for this prototype was an INA333 low-power instrumentation amplifier from TI because it was one of the lowest noise amplifiers with low power dissipation available at this time. The input voltage noise of the INA333 is 50 nV/sqrt(Hz), so for a 256 Hz bandwidth, the total input referred noise is 800 nVrms, meeting the specification listed in Table 1. The INA333 also has an input impedance greater than 1 GΩ and a CMRR of 100 dB. Thus, all the amplifier specifications are met according to Table 1.

Since the electrode offset voltage can be as high as 60 mV, the gain of the INA333 was set to 20 in order to tolerate offset voltages as high as 100 mV for a supply of 2 V. A bandpass filter was included after the first amplifier to remove any component below 0.1 Hz and above 100 Hz, thus also removing the electrode offset voltage before going to the second amplifier. Figure 2 shows a simplified block diagram of the system. EEG amplitudes are typically less than 1 mV, so the second amplifier provides the required gain such that a 1 mV input EEG corresponds to the maximum supply voltage.

The bandpass filter also serves as the anti-alias filter before the data is digitized. The EEG signal is sampled at 2,048 Hz and digitized using a 12 bit ADC. A MSP430 microcontroller decimates the data from 2,048 Hz down to 256 Hz and transfers it to a CC2540 Bluetooth chipset that transmits the data through Low Energy Bluetooth to an iPod Touch. A custom app, which works with iPod Touch or iPhone, was developed and operates continuously receiving data from the CC2540 and uploading it in real time through WiFi to a server located at the hospital. The data is transferred using SSH and no patient identifier is included to comply with HIPPA policy. The app also plots the EEG in real time, as shown in Figure 3, which provides feedback to the patient when he or she replaces the electrodes. If the electrodes are place incorrectly (e.g. not properly attached to the skin), the app does not display any data since the amplifiers are saturated. In this case the patient would not see any of the red data plotted in Figure 3.

Table 1. Guideline from the American Clinical Neurophysiology Society for long-term epilepsy monitoring

Parameter	**Recommended Value**
Low-Frequency Response	0.5 Hz or lower
High-Frequency Response	70 Hz or higher
Noise Level	< 1 µVrms
Input Impedance	> 1 MΩ
Common Mode Rejection	> 60 dB
Dynamic Range	> 40 dB

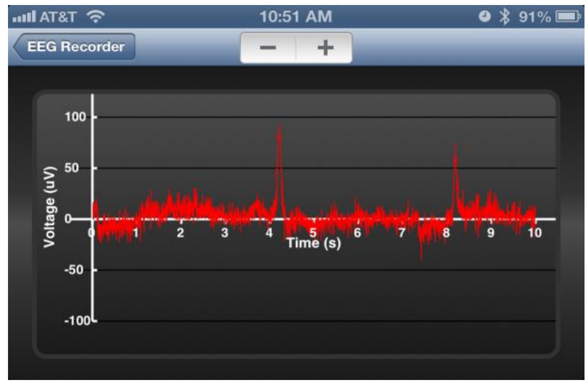

Fig. 3. 10 second segment of EEG shown in the app

Batteries typically consume a significant portion of a system's area, so power consumption was minimized in order to reduce battery' size which in turn reduces the device's area. One way to reduce power consumption is to reduce the sample rate as described earlier. Another way to reduce power is to minimize the supply voltage. In this prototype, the supply voltage was limited to 2 V by the Low Energy Bluetooth chipset (CC2540), which has a minimum recommended operating voltage of 2 V. The total power consumption of the device is 4.4 mW. Approximately 77% of the power is used to transmit the data through Low Energy

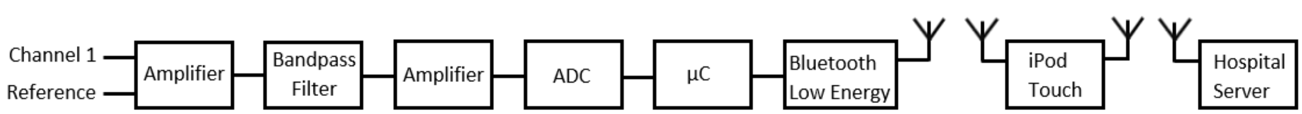

Fig. 2. System Block Diagram

Fig. 4. System Prototype

Bluetooth, the microcontroller consumes 18% to decimate the data from 2,048 Hz down to 256 Hz, and the remaining 5% is used by the analog front end (amplifiers, filter, and ADC). The system runs from a zinc-air battery A675P, which has a capacity of 550 mAh, and lasts approximately 6.8 days. A zinc-air battery was chosen because it has the highest energy density due to the fact that the cathode reactant is air and not included inside the battery [17]. Therefore, for the same capacity, a zinc-air battery has a smaller form factor than other battery types. The end result is a smaller battery and a smaller device.

The package to house the system was designed in SolidWorks and created using a 3D printer. The package, shown in Figure 4, measures 6.0 cm by 6.4 cm and sits behind the patient's ear as shown in Figure 5. The package was made symmetrically so that it can be used either on the left or right ear. The circular shape is semi flexible to conform better to the ear and to help secure the device. The PCB was made in a circular shape, as shown in Figure 6, to conform to the package.

The prototype requires two electrodes in order to measure EEG, as shown in Figure 5. One electrode is placed at the temporal lobe or the area of interest and the other is placed at the mastoid (reference electrode). An actual ground electrode is not needed because the package itself serves that purpose. The bottom part of the package was coated with silver conductive epoxy (MG Chemicals 8331) so that when it makes physical contact with the ear, it sets the body to our voltage reference.

Fig. 5: Device and electrodes placement

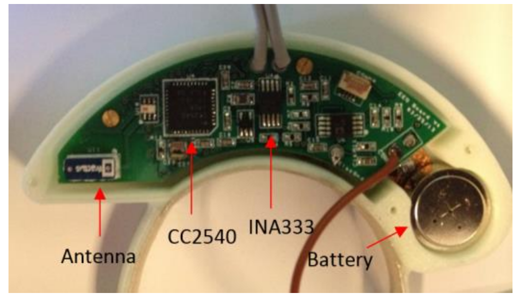

Fig. 6. Front of the PCB

The electrode chosen for this device is a 1'' silver/silver chloride wet gel electrode (MVAP Huggable electrode) that is easily attached and removed. After application to the skin, the gel takes about one day to dry, increasing the electrode impedance and degrading the signal quality. So, the patient must replace the electrode daily in order to maintain signal quality. The electrode attaches to the electrode connector shown in blue and yellow in Figure 4. Since we used standard connectors, other electrodes can also be used.

III. SYSTEM TESTING

This device is currently being tested on patients at Massachusetts General Hospital located in Boston, MA. So far, the device has been tested on 2 patients and over 100 hours of EEG has been recorded. Figure 7 shows a 10 second EEG segment recorded from a patient with electrodes placed at T4 (right temporal) and right mastoid. The EEG shown in Figure 7 has normal background rhythms with some ECG artifacts. In contrast, Figure 8 shows EEG from the same patient taken during a seizure. The top and bottom graphs represent the data from our device and the hospital's EEG recording machine, respectively. The data clearly shows high-amplitude (100 μV) 7 Hz waves that are an indication of a seizure. The data from our device does not match perfectly the data from the hospital's machine because our reference is located at the right mastoid while the hospital used A2 as the reference.

IV. CONCLUSION

We have presented a behind-the-ear EEG recording device that uses an iPhone or iPod Touch to continuously upload the patient's data to a hospital server, giving doctors real time access to the data. This device is one step forward in the design of smaller and better ambulatory EEG systems. It is able to give patients significantly less restriction by eliminating the need of wearing a backpack or being within 10 meters of a laptop. The electrodes are also easily replaceable, enabling the patient to remove and reapply the device for daily activities, such as taking a shower. This new system offers patients suffering from infrequent seizures a more convenient way of monitoring their seizures, giving doctors more accurate information for the diagnosis and treatment options.

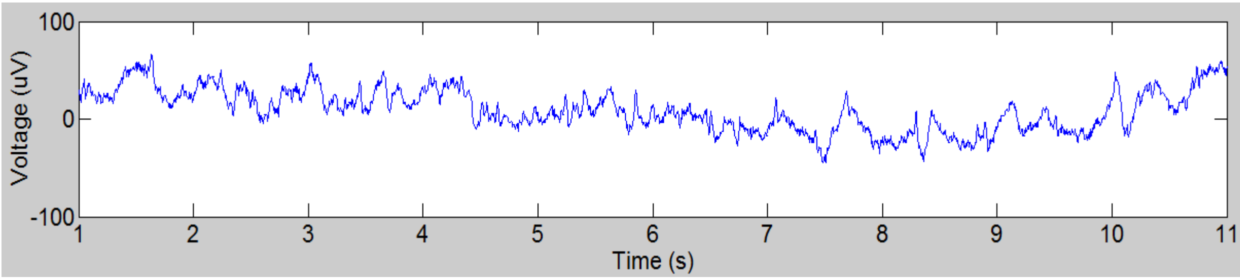

Fig. 7. 10-second normal EEG segment

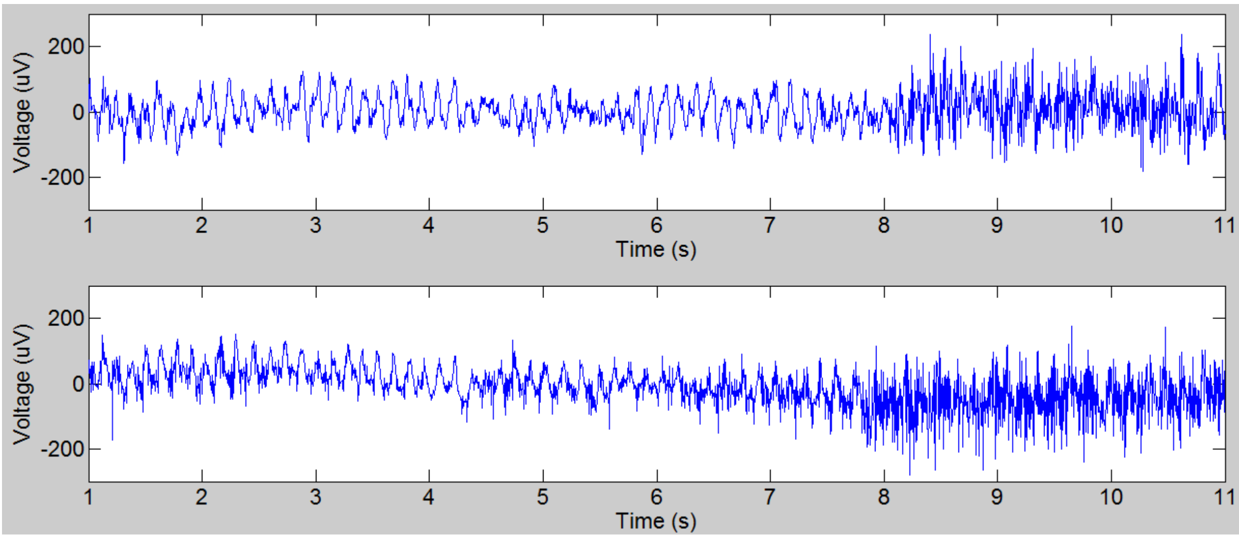

Fig. 8. 10-second raw EEG segment recorded during a seizure from one of the patients using our device (top) and hospital recorder (bottom)

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