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Implementation of a Gelatin Model to Simulate Biological Activity in the Inner Ear for Electrovestibulography (EVestG) Validation

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***Abstract*—In this work, a physical model that simulates electrical activity of the inner ear has been developed. The purpose is to evaluate extraction of vestibular field potentials (FPs) in the presence of various sources of noise by a proprietary software algorithm. The ear model is constructed of gelatin as an alternative to human tissue where independently driven electrical sources are placed in gelatin to mimic various biological signals (muscle, cerebral, and vestibular). Components of system noise (recording apparatus generated noise, electrodes, etc) will be naturally superimposed on the recording, hence enables various recording conditions to be simulated. Muscle activity present in the recordings and noise generated from the recording apparatus were found to be the most dominating sources that degrade performance of FP extraction. The model can be used to provide insights towards enhancing the FP detection algorithm under various signal-to-noise ratios.**

I. Introduction

Computational modeling of electrical and mechanical behavior of human organs allows insight to the correlation between electro-physiological measurements and disease pathologies [1] [2]. Similarly, finite element modeling has been conducted [3] to investigate whether electrical activity from the vestibular organ can be recorded from the ear canal for a novel technique called Electrovestibulography (EVestG) [4]. Electrical activity from the vestibular organ is thought to be <1μV and well below the noise floor; hence a direct measurement of the vestibular field potential (FP) cannot be obtained. Therefore a proprietary software algorithm called the Neural Event Extraction Routine (NEER) [5] has been developed to extract these FP's buried in noise. A physical model of the inner ear capable of simulating electrical activity at amplitude scales observed in actual human recordings would be advantageous to quantitatively evaluate and improve the NEER algorithm. The added advantage of implementing a physical model is that various sources of noise such as background interference, bio-signal amplifier generated noise, electrode lead/skin interface noise, and noise due to skin impedances [6] will be naturally incorporated in the recordings. Hence the main objective of this work is to implement an electrical model of the ear to perform a realistic evaluation of NEER, and to identify types of noise that NEER is most susceptible to.

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II. Background

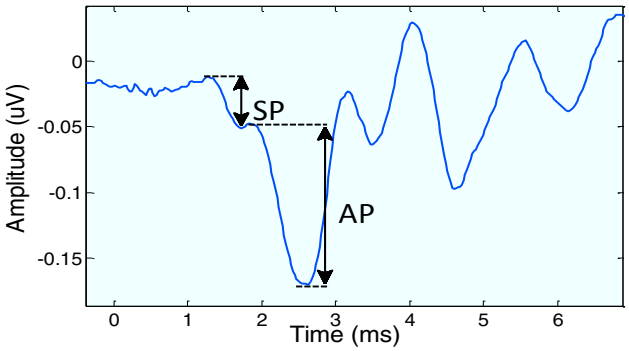

Fig. 1. Field Potential (FP)

EVestG is a variant of an established electrophysiological measurement technique called electrocochleography (ECOG) [7], where an auditory stimulus is replaced by a tilt stimulus. In extra-tympanic ECOG recordings, the cochlear response due to a sound stimulus is recorded via an electrode placed in the ear canal proximal to the tympanic membrane; Figure 1 shows a typical cochlear response due to click stimuli. Electrical activity at the onset of the stimulus is repeatedly recorded and averaged in order to reveal the small amplitude cochlear response in the presence of uncorrelated noise.

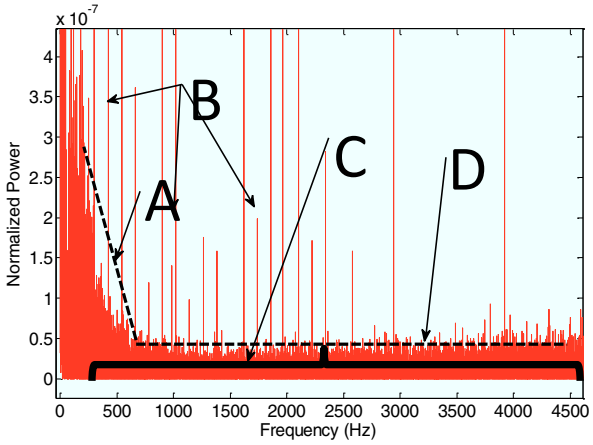

Fig.2. Gelatin Setup Block Diagram

EVestG [4], in comparison, captures spontaneous and driven FP's both at rest and when evoked by whole body tilts that occur at unknown times and time intervals. EVestG has

demonstrated potential for identifying bio-features, thought to originate predominantly from Vestibular FP's, where various bio-features have been identified that show good sensitivity and specificity in classifying control groups from some neurological disorders [8] [9].

Due to the high gain amplification used (30k) to amplify the <1µV range FP recorded in EVestG and ECOG, naturally the recording constitutes of many types of undesired interference. Figure 2 shows a power spectrum of a poor EVestG recording that illustrates most of the noise sources, such as undesired background biological activity (BBA), i.e. muscle, cerebral and cardiac activity (A), electromagnetic interference from the surrounding environment (B), and system noise (D) (a collection of signal conditioner generated noise, electrode lead/skin interface noise, and noise due to skin impedances). Note that the majority of Vestibular FP activity is presumably in the frequency band of 250Hz-5kHz (C)[4], and is not seen clearly in the power spectrum as it is buried in noise.

II. METHODS

A. An electrical ear physical model feasibility experiment

First, a pilot study was carried out to determine if a physical model of electrical activity can be simulated. A physical setup that simulates middle-inner ear electrical activity was modeled using material (gelatin) similar to human skin, such that similar coupling could be achieved when electrodes used for EVestG were inserted. In addition, the model had to be capable to generate biological-like activity in the medium, from multiple sources that when superimposed could be picked up by the recording electrodes.

Arbitrary signal pickup through bio-potential electrodes was tested by driving 2 parallel plates placed in a high concentration gelatin medium (170g gelatin per 200ml distilled water) using an arbitrary function generator. The displacement currents induced proximal to the site of the recording electrode (placed ~5cm away from the source) enabled the recording device to pick-up the arbitrary waveform generated.

During initial setup, the parallel plate electrode size was adjusted to 0.5cm and the back surface of each plate was insulated (to reduce fringing fields). The signal propagation was uniform in the frequency band up to 10 kHz.

By attenuating the generated biological signal activity (labeled 'A' in Fig. 2) down to realistic levels (~µV level), power-line harmonic pickup and system noise get inherently added at realistic proportions;, thus, they do not need to be synthetically added. Using this model, the synthetic biological activity, noise components, and FP signals, were successfully generated at amplitude scales that were characteristic of actual EVestG recordings.

B. Gelatin model construction and specifications

Stainless steel electrodes with diameters (0.5, 0.8, 1 cm^2) were made, and used as the parallel plate electrodes (PPE). The gelatin mold was a plastic container with dimensions 13 X 9 X 5 cm, where 3 sides are placed with independent signal generating electrode pairs (Fig. 3). An ear canal was created by inserting a hydrophobic nylon rod with a diameter of 5mm. All PPE's were placed in the mould, along with the rod, before pouring gelatin. Once the Gelatin was set, the rod (due to its hydrophobic properties and smooth finish) easily detaches to reveal the ear canal.

C. Hardware Setup

Tektronix AFG3022B arbitrary waveform generator units were used to drive the PPE pairs. Each channel can store 12k samples of data, and the output can be set at a desired sampling rate. Since the function generator output is not low-pass filtered, it is required to store the signal with a high sampling rate to reduce aliasing effects due to high frequency content. This necessitated the duration of the signal to be short. As a trade off, the signal was sampled at approximately 3 times the highest frequency component, and a 4^{th} order active Bessel filter was used to attenuate high frequency components.

A standard ear electrode (BioLogic TM-trode) was placed inside the molded ear canal with some conductive gel, and the reference electrode was placed on the outer surface of the gelatin body. The electrode leads were then connected to a CED1902 amplifier configured at a gain of 30k, and bandwidth of 0.1Hz-10 kHz that are normally used for EVestG recordings. The amplified signal was digitized using a CED1401 A/D converter (Fs= 41.666 kHz) and analyzed.

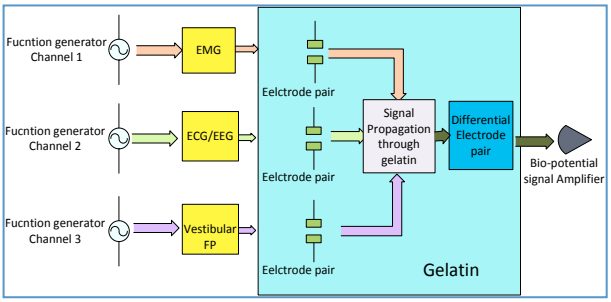

Fig. 3. Gelatin Setup Block Diagram

D. Vestibular FP waveform synthesis

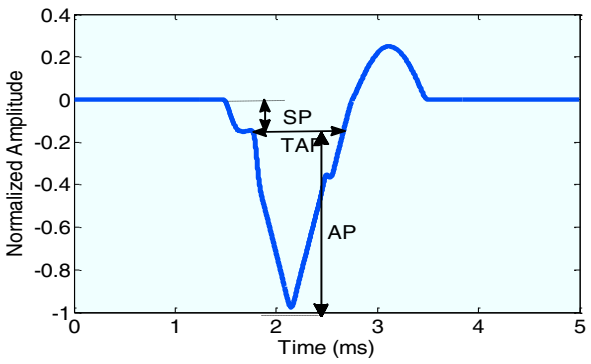

Fig. 4. Synthetic vestibular FP

A synthetic FP was created that approximated an FP seen in ECOG and EVestG recordings [11] [12] [13] (Fig. 4). The NEER algorithm is optimized to identify the AP (largest component of the FP); thus, it was sufficient to generate a

synthetic FP as shown in Fig. 4. The SP/AP ratio, commonly used in ECOG recordings, was set to be at 0.2, and the TAP size was set at 0.9ms; these values are observed in normal ECOG recordings. The constructed signal was then smoothened using a 4th order zero phase Butterworth LP digital filter.

E. Biological activity signal synthesis

Electroencephelogrpahy (EEG) activity is commonly seen in EVestG recordings. Typically the EEG band is from 0.5-40 Hz [11]. EEG activity is not the main source of EVestG signal degradation; yet it was factored in our synthetic signal generation to approach a realistic recording. Electromyography (EMG) activity in contrast is the most significant biological artifact in an EVestG recording, since it overlaps with the vestibular FP energy band (Fig. 2). EMG dominates in the frequency band 50-500Hz [4], and may be significant up to the 700 Hz in EVestG recordings.

EMG and EEG activity are complex waveforms to be synthesized; hence a slight variant of an EVestG recording obtained from a test subject was used as "synthetic" EMG/EEG data. A normal ear recording was undertaken for EVestG with the ear electrode tip positioned approximately 5mm into a 30mm deep ear canal. This was carried out to ensure that the amount of vestibular activity picked up would be significantly reduced (due to increased distance from the vestibular organ), yet EMG and EEG activity would be captured and dominate. The recording was then band pass filtered from 0.1Hz-700Hz to incorporate both EEG and EMG activity into one recording (instead of separately driving them), mainly so the proportion of EEG and EMG would be maintained at levels seen in actual recordings.

Cardiac activity was rarely seen in recordings, hence was excluded in this work.

E. Waveform Generation in artificial ear

NEER was evaluated for 3 different BBA scenarios; $5\mu V_{rms}$, $8\mu V_{rms}$ and $11\mu V_{rms}$. The $5\mu V_{rms}$ case approximates the level of background activity seen in actual EVestG recordings; in contrast, the $11\mu V_{rms}$ case represents a recording where the biological activity (including vestibular FP's) is ~2 times larger in amplitude. The noise power will be constant for all recordings; thus the proportion of noise will be smaller in the $11\mu V_{rms}$ case by 6dB. For each of these scenario's, the FP amplitude was scaled down according to (1) from -6dB to -30dB in 6dB decrements. The BBA is set to loopback to simulate continuous activity. The vestibular FP was generated at a random firing rate; where the minimum interval between FP's is set at 5ms.

The SNR of the FP Vs BBA was calculated as follows:

$$SNR = 20log_{10}\frac{V_{rms}\ of\ FP}{V_{rms}\ of\ background\ biological\ activity} \quad (1)$$

Where $V_{rms}\ of\ FP$ is calculated for the 5ms long synthetic FP created (See Fig. 4).

III. RESULTS

Fig. 5 shows the power spectrum of a collection of randomly generated FP's; this characteristic shape is not seen in an EVestG recording (Fig. 2) since the noise components (predominantly muscle and system noise) are significantly larger in comparison to the FP. The FP spectrum observed has a similar bandwidth as predicted in [4], up to ~5kHz.

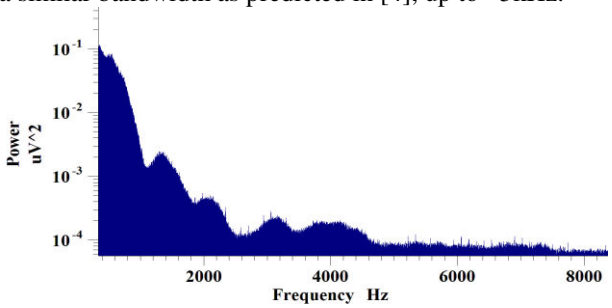

Fig. 5. Synthetic Vestibular FP power spectrum

The FP detection accuracy of NEER was evaluated for each of the variations described above. For each of the cases, four 6s long recordings from the ear model were analyzed and averaged. Fig. 6 shows the positive predictive value (PPV) Vs SNR . It is revealed that BBA has a significant impact on FP detection. With SNR decrements in 6dB results in a decrease in PPV ($p<0.01$). Secondly, for an increase in the proportion of biological activity compared to system noise, an increase in PPV is seen ($p<0.01$, $p<0.01$, $p<0.05$, *and* $p<0.17$ for SNR values -6, -12, -18, and -24dB respectively). Statisticial significance below -24dB in this case is not seen because the BBA is much larger than the contribution from system noise.

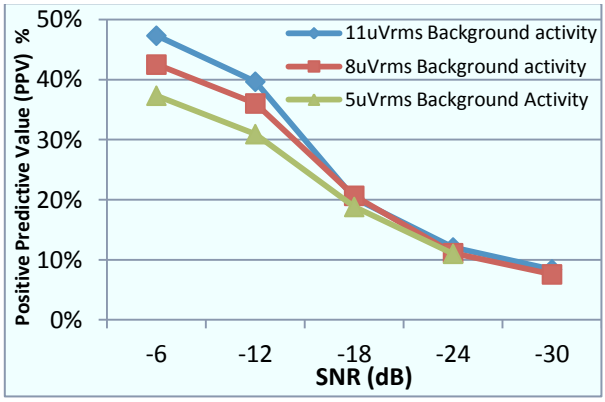

Fig. 6. NEER Field potential detection accuracy Vs SNR, and Vs increased biological activity

Apart from the vestibular FP shape, the distribution of the firing pattern is also under investigation to be used as a potential biomarker [9]. The subplots in Fig. 7 show the firing pattern obtained from NEER analysis, and compared against the actual distribution of generated vestibular FP's (red curve). An interval of at least 5ms was set between consecutive FP's. Hence a one sided normal distribution like shape is seen for the actual firing pattern. Subplots of Fig. 7 correspond to -6dB and -24dB cases, for when the background activity is $5\mu V_{rms}$.

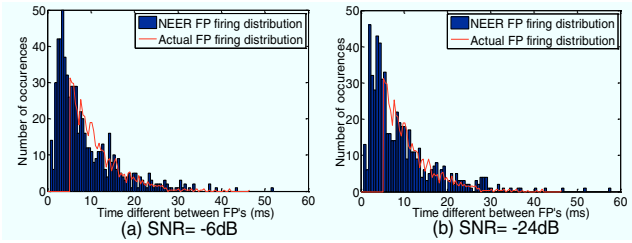

Fig. 7. Comparison of actual FP distribution Vs NEER FP distribution at varying SNR

IV. Discussion

Figure 6 data show that BBA and system noise both contribute to a degradation of FP detection rate. The SNR level in actual recordings are likely in the range -18 to -30dB, hence it can be inferred that the contribution from BBA has a more profound effect on FP detection accuracy than an increase in system noise. Minimizing background activity is not trivial since it is mostly subject dependent. The reference electrode is placed on the ipsilateral earlobe instead of the contralateral earlobe (the convention for ECOG) for EVestG, which significantly reduces the background activity pickup (from 8.1 ±2.5 μV_{rms} (N=30), to 3.1 ±0.7 μV_{rms} (N=30) *p<<0.01).* Currently test subjects are requested to keep their neck relaxed and eyes closed to reduce background activity, which needs to be further minimized to increase FP detection accuracy.

System noise can be minimized by: an application specific design of a low noise amplifier, use of low impedance electrodes (preferable matched), and proper exfoliation of skin contacts to reduce skin impedances. These aspects are currently being investigated to increase FP detection accuracy. Variations in SNR and system noise, that affect PPV, will be used to optimize NEER as well as the recording protocol currently used.

The FP firing rate and pattern are not well characterized in humans, however it is known that afferents have baseline firing rates of 50-100 spikes/sec in squirrel monkeys, and can elevate up to 300-400 spikes/sec [12][13]. Currently in NEER, FP's closer than 2 ms apart are not collected and the remaining FP's are averaged to produce the characteristic SP/AP waveform to prevent waveform artifact (due to overlap). By eliminating FP's closer than 5ms apart herein, for example, the PPV for -24dB registered at 11% will increase to ~20%. In this work, the accuracy of FP detection was investigated based on a normally distributed (one sided) firing pattern. In future work, the firing rate and pattern will be modified to be based on mammalian vestibular afferent studies, in an attempt to make our synthetic ear model mimic electrical activity similar to the vestibular organ. This will enable us to approach a more accurate analysis of FP detection rate with respect to varying signal and noise conditions. As a result of insight gained from this work, we have begun prototype testing of a new electrode/recording system that appears to produce >12dB SNR improvement for human recordings on average; suggesting an improvement to >33% detection accuracy, based on the data presented.

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