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Constant RMS versus Constant Peak Modulation for the Perceptual Equivalence of Sinusoidal Amplitude Modulated Signals

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Abstract— **Neuroprosthetics using intracortical microstimulation can potentially alleviate sensory deprivation due to injury or disease. However the information bandwidth of a single microstimulation channel remains largely unanswered. This paper presents three experiments that examine the importance of Peak Power/Charge and RMS Power/Charge for detection of acoustic and electrical Sinusoidal Amplitude Modulated stimuli by the auditory system. While the peripheral auditory system is sensitive to RMS power cues for the detection of acoustic stimuli, here we provide results that suggest that the auditory cortex is sensitive to peak charge cues for electrical stimuli. Varying the modulation frequency and depth do not change this effect for detection of modulated electrical stimuli.**

I. Introduction

Neuroprosthetic devices show remarkable potential to revolutionize healthcare treatment of neural pathologies. Devices such as cochlear implants [1] and deep brain stimulators [2] demonstrate the ability of neuromodulation to treat sensory and motor deficiencies in patients. However, there are many remaining conditions that could be treated with the use of neuroprosthetics, specifically the loss of sensory input in cases such as deafness, blindness and paralysis [3]. Neuroprosthetics that stimulate the primary sensory cortices may replace the input stimuli lost in these conditions.

A major focus of contemporary research into sensory input devices is based on multichannel intracortical microstimulation (ICMS) [4-6]. ICMS of specific sensory cortical areas has been shown to effectively generate visual [7,8], somatosensory [4] and auditory [6] perceptual experiences. While these have successfully generated percepts in subjects, they still have not made the full transition to being adapted for human clinical treatment. One major obstacle is that the optimal characteristics of stimulation have not been fully explored.

Neuronal modeling shows that various types of stimulation could possibly be more effective than standard stimulation waveforms [9]. Using a high throughput rat behavioral model [10] with an implanted electrode [11] allows for more detailed exploration of the parametric space of different types of stimulation. Previously we have used this model to analyze stimulation characteristics such as the depth, waveform shape, pulse rate [12] and phase symmetry [13]. Despite these studies, there remain many different varieties of stimulation types that have yet to be examined. One type of stimulation that has potential is sinusoidal amplitude modulated (SAM) stimulation.

Amplitude modulated stimuli have proven to be important signals for the sensory processes. For example, the auditory system is attuned to amplitude modulation found in natural sounds and speech [14]. In fact, neural recordings show that the auditory system, from the auditory nerve to the auditory cortex, can phase lock to SAM stimuli [14-16]. Phase locking in response to SAM stimuli is also evident in the visual [17] and somatosensory [18] systems. Phase locking in response to SAM stimuli on the part of the sensory cortices suggests that SAM electrical stimulation may provide differential sensations and therefore may be used to deliver useful information via ICMS.

Previous research has investigated amplitude and frequency modulation of electrical stimulation. These studies show that modulating the amplitude or frequency of electrical stimulation to the sensory cortices can deliver behaviorally relevant information [19-20]. Furthermore, current neuroprosthetic devices such as cochlear implants and deep brain stimulators [2] are improved with the modulation of their electrical signals. Despite these previous findings, there has not been an extensive effort to fully explore the different parameters and resulting efficacy of SAM electrical stimulation.

Here we present results from three experiments that explore the effects of SAM stimulation on behavioral detection. An important question we sought to answer was whether a modulated signal would need to preserve the RMS value of the unmodulated signal or its peak amplitude to be equally detectable. We also examined the effect of varying the modulation depth and frequency of the electrical stimulation on detection thresholds. The different types of modulation and their basic parameters can be seen in Figure 1. To these ends, three experiments were designed. The first examined the behavioral response to acoustic SAM by varying the modulation depth and examining the RMS and peak modulation question acoustically. The second experiment examined the cortical response to electrical signals with varying modulation depths in both the RMS and Peak modulation representations. The last experiment varied the modulation frequency in conjunction with the modulation

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depth to determine if there was any effect on the conclusions from the second experiment.

II. Materials and Methods

A. Surgical Implantation

A Sprague-Dawley rat was implanted with a silicon-substrate microelectrode array in the auditory cortex of the right hemisphere. The surgical protocol is detailed in other studies [21]. The rat received an intraperitoneal injection of ketamine hydrochloride (80 mg/kg body weight) and xylazine (5 mg/kg). This was updated with more ketamine hydrochloride (20 mg/kg) if the animal responded to a toe pinch test or the depth of anesthesia diminished.

The skull over the right primary auditory cortex was drilled through using a burr. Landmarks in the vasculature, according to known layouts [22], were used to locate the primary auditory cortex.

A linear silicone microelectrode array with sixteen iridium oxide sites (703 μm^2) was used in this experiment (NeuroNexus Technologies, Ann Arbor, MI). The electrode was activated 48 hours prior to surgery. The electrode was then inserted into the cortical mantle using microforceps (Fine Science Tools Inc., Foster City, CA). The array was positioned so that the recording sites spanned 0-1.5 mm from the surface of the brain. This was confirmed visually with a microscope. A wire was attached to one of the four implanted titanium bone screws (sizes 2-56) to create an electrical ground. Neural recordings (Tucker-Davis Technologies, Alachua, FL) were used to confirm that the electrode was in the primary auditory cortex by detecting neurological responses to click and pure tone stimuli. After placement confirmation, the array and cable were encased with silicone elastomer. UV cured dental acrylic was used to seal the craniotomy and stabilize the implant.

B. Behavioral Paradigm and Stimulation

The rats were trained on the behavioral paradigm both before and after implantation. The rats were water-deprived as motivation to complete a conditioned avoidance task. Each rat was to cease licking a water spout when a 650 ms warning tone was present. If the warning was not avoided a 1.6 mA cutaneous shock was delivered to the rat. If the warning was absent, no shock was delivered. The rats' presence on the spout was monitored during safe and warning trials. This was used to calculate a false alarm rate. If this was over 20% for a trial, the trial was not considered for analysis. The warning stimulus was acoustic before implantation and an electrical pulse afterwards. The electrical pulse trains (symmetric biphasic cathodal-leading pulses, 205 µs phase duration) were delivered using an MS16 stimulus isolator with 4 serial NC48 batteries, allowing for a +/- 96V compliance voltage (Tucker-Davis Technologies, Alachua, FL).

An adaptive paradigm was used to estimate the rats' threshold; correct detections led to a lower amplitude warning stimulus and misses led to higher amplitude stimuli.

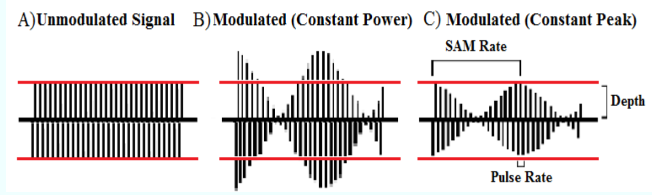

Figure 1. *Modulation types and parameters.* A) Standard unmodulated pulse train and its envelope (red lines). B) Modulated signal which preserves the RMS power/charge of the original (note original envelope). C) Modulation which preserves the Peak power/charge of the original signal

When four reversals occurred in a row, the stimulus level was considered the detection threshold.

C. Experimental Design

Four male Sprague-Dawley rat (~500g) was used in three experiments to explore the parameter space of SAM audio and electrical stimuli.

The first experiment used three rats and explored whether the auditory system is more sensitive to the peak power or RMS power of SAM acoustic stimuli. The experiment used a modulation frequency of 8 Hz and modulation depths of -100, -20, -15, -10, -5, 0 dB (0, 10, 17.78, 31.62, 56.23 and 100%). The rats were placed in a soundproof acoustic chamber and the selected stimuli were randomly presented. The detection threshold of each type of acoustic stimulus was recorded according to the RMS power in the signal. The data were then transformed to represent the peak power present in each signal for comparison.

The second experiment similarly explored whether the auditory cortex is more sensitive to the peak charge or the RMS charge of SAM electrical stimulation. One implanted rat was used for this experiment. The deepest site with the lowest thresholds for modulated pulse trains was selected for the trials (~1000 µm depth). The pulse train was modulated at a single arbitrary modulation frequency of 32 Hz and six modulation depths: -100, -20, -10, -5, 0 dB (0, 10, 31.62, 56.23 and 100%). The carrier frequency of the pulse train was 254 Hz. The rat was randomly presented with the six modulation depths for a total of ten trials. The detection threshold (nC) for each signal was recorded in terms of RMS charge and then transformed into terms of peak charge amplitude for comparison.

The third experiment sought to explore the parameter space for SAM electrical stimuli and determine whether they affected the conclusions of the second experiment. The SAM stimuli selected for this trial had modulation depths: -100, -20, -15, -10, -5, 0 dB (0, 10, 17.78, 31.62, 56.23 and 100%) and modulation frequencies: 2, 16, 48 Hz at a pulse rate of 254 Hz (see Figure 1). All of these stimuli were randomly presented to the implanted rat each day for a total of eight trials and the detection thresholds (nC) were recorded in terms of RMS charge. The data was then transformed to represent peak charge present in the signal for comparison.

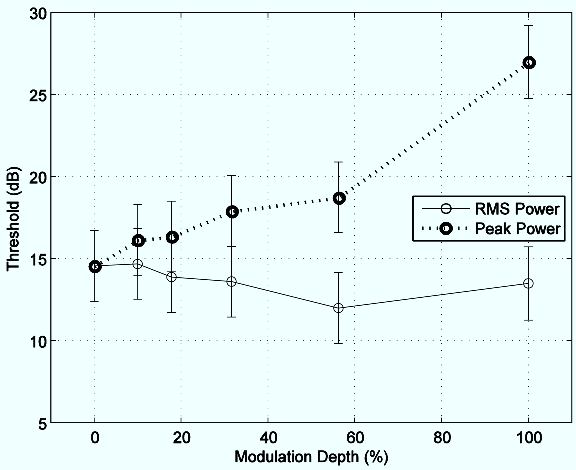

Figure 2. *RMS versus Peak Power for detection of acoustic cues*. The data show the acoustic detection threshold for the six modulation depths. The data is represented in both the RMS and peak power threshold measurements. Error bars indicate 95% CIs.

D. Statistical Analysis

All of the experiments were analyzed using SAS version 9.2 (Cary, NC). The detection thresholds from each experiment were collected and analyzed using a MANOVA with each trial and rat serving as a block. Pairwise comparisons for the different factors were performed using Tukey's test (α=0.05) and 95% confidence intervals (CI) for the comparisons were calculated. The factors for the first and second experiments were the six different modulation depths. The factors for the last experiment were the five different modulation depths and the three modulation frequencies.

III. Results and Discussion

A. SAM Acoustic Stimuli

The data from Figure 2 present the auditory system's response to acoustic SAM stimuli. The data was recorded as the constant RMS power modulation, but it was transformed to also represent the peak power modulation detection threshold. A number of trends are clear. For the peak power, the first four modulation depths are not significantly different from each other. However the detection threshold at 100% modulation is significantly different from the others, showing an upward trend. This indicates that peak power modulation is less easily detected at higher modulation depths. Additionally, the RMS power data shows that none of the modulation depths are significantly different from each other. The implication of this data is that, for acoustic stimuli, equal RMS modulated stimuli have a perceptual equivalence or are detected equally well. Restated, when the auditory system detects SAM acoustic stimuli, RMS power, not peak power, is the important factor.

B. SAM Electric Stimuli

This experiment was designed to examine the ability of the auditory cortex to detect SAM electrical auditory stimulus. Like the previous experiment, the experiment sought to determine whether perceptual equivalence to the unmodulated signal was due to the stimulus having the same RMS or peak charge. As seen in Figure 3, the curve that measures the detection threshold in terms of the RMS charge of the signal decreases monotonically with higher modulation depths, with each point being significantly lower than the last (with the exception of the 17.32% modulated data point). This seems to indicate that for modulated stimuli with constant RMS values higher modulation depths are more detectable.

The data was also transformed to represent the threshold in terms of the peak charge present in the stimulation. The curve does not decrease monotonically like the constant RMS charge; in fact none of the points are significantly different from each other. This indicates that perceptual equivalence between the unmodulated and modulated electrical stimuli is determined by peak charge.

The conclusion is that the auditory cortex relies more upon the maximum charge present in the electrical stimulation rather than the RMS charge present. The RMS modulation detection threshold values were decreasing, or becoming more detectable, because modulating with a constant RMS requires a higher peak charge in the signal. Interestingly, the behavioral response of the auditory cortex to electrical stimulation is the opposite of the peripheral auditory system's response to acoustic stimulation, where RMS charge was important

C. Modulation Frequencies of SAM Electrical Stimuli

This experiment was designed to see if the conclusions from the second experiment were still valid when the modulation frequencies of the SAM electrical stimulation were varied. The results are depicted in Figure 4. A range of frequencies from 2 – 48 Hz was selected for analysis. Despite the wide range selected there does not seem to be any effect. None of the data points are significantly different from each other in terms of detection threshold, due either to modulation frequency or modulation depth. This further

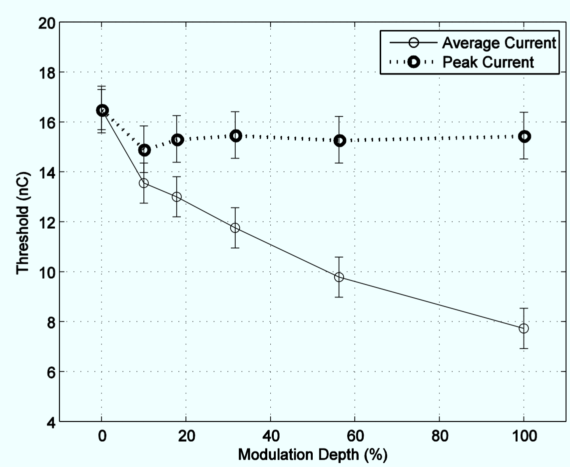

Figure 3. *RMS versus Peak Charge for detection of ICMS of the auditory cortex.* The lines depicted above compare the electrical detection threshold data for the six modulation depths. The data is represented in both the RMS and peak power threshold measurements. Error bars indicate 95% CIs

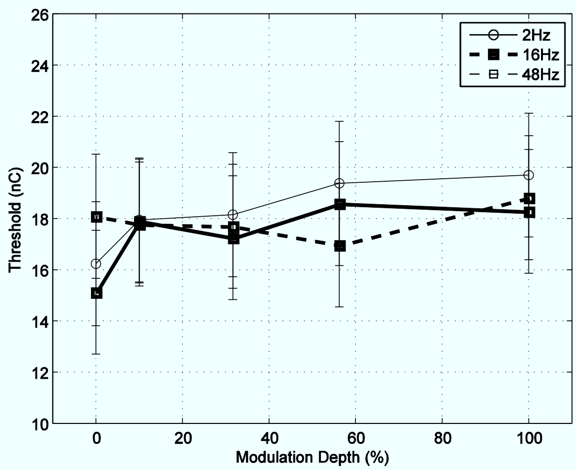

Figure 4. *Varying the Modulation Frequency and Depth of electrical stimulation.* Effect of varying the Modulation Depth and Frequency on the threshold. Error Bars indicate 95% CI.

reinforces the conclusions from the previous experiment, by eliminating modulation frequency as a factor for detection. These results imply that, as before, the modulated signals with the same peak charge were perceptually equivalent to the unmodulated signal. In summary, equivalent detection in the electrical stimulation arena seems to be driven by the peak charge present in the signal rather than modulation depth or frequency.

IV. Conclusion

This study examined the parameters of SAM stimulation and whether modulation which keeps the RMS or peak constant is more relevant to detection. The acoustic response appears to detect a signal based on its RMS power, while the electrical response detects a signal based on the peak charge present. The perceptual equivalence of the respective types of modulation is unchanged by varied modulation frequencies or depths. This study has demonstrated that the peak charge is the important factor for cortical detection of electrical SAM stimulation. These findings enable further experiments to determine the modulation detection threshold of ICMS of auditory cortex.

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