# Simultaneous acquisition of high-rate early, middle, and late auditory evoked potentials

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*Abstract*— **Auditory evoked potentials (AEPs) are typically acquired at rates that facilitate their study as segregated by epochs relative to stimulus onset: early (ABR, 1.5-15 ms), middle (MLR, 15-60 ms), and late (LAEP, $\geq$60 ms) potentials. In particular, late AEPs are often acquired with stimulus repetition rates between 0.1 Hz and 1 Hz, and are band-pass filtered to contain information only within 1-30 Hz. These low repetition rates, filtering and low SNRs eliminate much of the potential contributions of the early and middle-latency responses in AEP recordings. This study aims to demonstrate a method for acquiring whole-AEP responses at higher stimulus repetition rates of 0.5 Hz to 10 Hz, by utilizing the Continuous Loop Averaging Deconvolution (CLAD) method, increasing the bandwidth of the recordings to 1-300 Hz to include early components, and using short-duration chirps to increase synchronous firing of the cochlear and auditory pathway neurons. Such a method may facilitate diagnostic or functional assessment of single AEP recordings for detection, identification, or evaluation of early, middle and late components of auditory responses.**

## I. INTRODUCTION

Auditory evoked potentials (AEPs) have historically been studied according to three latency classifications: The auditory brainstem responses (ABR), composed of strongly neuroanatomically-correlated peaks occurring within the first 15 ms after the onset of an auditory stimulus. The middle-latency response (MLR) represents activation of the auditory thalamocortical pathways and related areas within 15-60 ms after stimulus presentation. Both ABRs and MLRs are predominantly exogenic and depend highly on the physical characteristics of the acoustic stimulus.

Late-latency AEPs (LAEP, or Cortical AEP, CAEP) are typically comprised of several characteristic peaks occurring at least 60 ms after a stimulus. Later components of the LAEP are commonly observed under different experimental conditions, some aspects of which are strongly related to exogenous conditions, and some are more endogenous in nature ([1], Ch. 11-12).

AEPs are commonly exploited for a number of diagnostic purposes, for example, the presence of peak $V$ in the ABR can be used as diagnostic of proper cochlear and early auditory pathway function ([1], Ch. 8). The ABR and MLR may also be used for non-behavioral auditory threshold detection and states of wakefulness ([1], Ch. 2), and LAEP has been utilized to diagnose schizophrenia and central auditory processing disorder, among others [1,2]. Some studies have utilized independent recordings of the ABR, MLR, and LAEP in order to compare inter-peak magnitudes and intervals between epochs for sex and gender differences [3].

The functional significance of LAEPs are still poorly understood, but the $N_1$ (negative peak, 80-120 ms) is generally thought to be a pre-attentive response within the primary and secondary association cortices, and $P_2$ (positive peak, 140-180 ms) may be related to stimulus classification, see [1,4,5] for reviews. Late AEPs can be highly endogenous and less dependent on the physical characteristics of the stimulus than its contents and relationship to its current meaning.

Generally, the primary stimuli for studying all components of AEPs have been gated pure tone bursts [1], where the recorded AEPs (for LAEPs in particular) are shown to be sensitive to parameters such as the gating function and duration, tone frequency, inter-stimulus interval (ISI), and intensity. A few studies have utilized noise, complex tones, speech syllabi, swept-tones or chirps on the ABR and MLR [1,2,6]. The effects of these variables on the LAEP have been shown to be non-linear and interactive, which has limited many studies to assessing a single variable [4].

Typical reports of the LAEP utilize ISIs of between 0.5 and 10 seconds (repetition rates of 0.1-2.0 Hz) ([1], Ch. 11). Among the reasons for a lack of studies for LAEPs at higher repetition rates is partly due to either an assumption that late potentials are adapted out prior to rates at which overlapping of adjacent stimuli begins to occur, or due to an inability to unwrap overlapping responses.

Several studies have used subtractive methods to trains of two or more stimuli to observe the effects of stimulus duration, onset and/or offset ramping functions, ISI, intensity or adaptation of the stimulus [1,7]. The Continuous Loop Averaging Deconvolution (CLAD) method utilizes designed sequences with non-uniform ISIs, known as stimulus onset-asynchrony (SOA), to recover an estimate of the transient response (to a single stimulus) from recorded overlapping responses [8,9]. This method will allow us to observe late regions of the AEP when stimulating at rates faster than has been typical to LAEP studies.

However, LAEPs have been difficult to study due to large inter-subject variability, long testing durations, and lack of substantial normative data [10]. This study aims to demonstrate a method for acquiring a whole-AEP recording that exhibit characteristic waves of the ABR, MLR, and LAEP within a single recording. This is accomplished by acquiring AEP recordings at low (non-overlapping) and high rates (overlapping) and utilizing deconvolution to unwrap the overlapping components of the responses. Such a method

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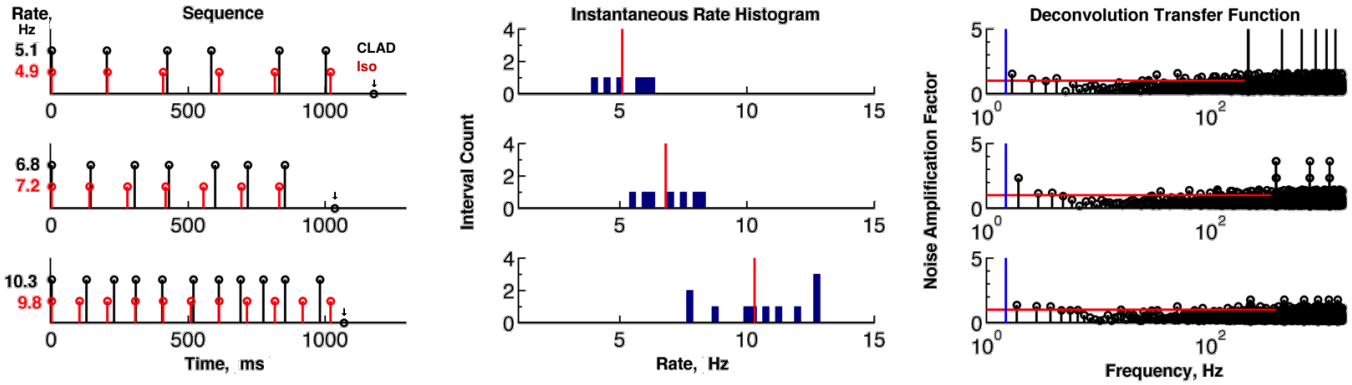


Fig. 1. Stimulus sequences designed for this study and their characteristics. The left column displays the stimulus presentation trigger raster for sequences with mean rates of 5.1 Hz (top), 6.8 Hz (middle), and 10.3 Hz (bottom) are shown with black stems. An isochronic stimulation sequence in red shown for comparison. The middle column shows the instantaneous rate histogram for each sequence, with a red line indicating the mean rate. The right column shows the deconvolution noise-amplification profile for each CLAD sequence, with NAF=1 shown as a red line (see text for details).

also allows us to retain a broadband recording of the entire AEP waveform, which may facilitate the study of interrelation between components on a per-subject basis.

## II. METHODS

### A. Subjects

Data were acquired from 7 young volunteer subjects (6 male, ages 20-29), with mean age of 23. All subjects were assessed to have normal hearing thresholds (thresholds $\leq$25 dB at .25, .5, 1, 2, 4 and 8 kHz) and no history of neurological problems. All experiments and procedures were conducted in accordance within an IRB-approved protocol.

### B. Recording

A 2-channel bioamplifier system (Intelligent Hearing Systems, Miami, FL, USA) was used to acquire continuous EEG data. Electrodes were placed on the subjects scalp and mastoids (Ch. 1: $C_z - A_2$ and Ch. 2: $C_z - A_1$), with center of the forehead as ground. Continuous EEG data were acquired at a rate of 5000 samples/sec., with a gain of 100,000$\times$ and band-pass filtered from 1-1500 Hz (6 dB/oct) prior to analog-to-digital conversion, and stored for offline analysis. Only ipsilaterally collected (Ch. 1) data will be reported in this study. Stimuli were presented using insert earphones (ER-3A with 0.89 ms acoustic delay line, Etymotic Research, Elk Grove Village, IL) to the subject's right ear, and in alternating polarity. Testing was done in an acoustically and electrically treated booth with the subject lying on a bed comfortably and watching a silent movie with captions.

### C. Stimuli

The stimulus chosen for this study is a short duration swept tone or chirp specially designed to compensate for the basilar membrane forward-delay [11]. Such chirps have been shown to elicit larger steady-state responses (ASSRs), ABR and MLR component waves [6,11,12].

The chirps were generated using MATLAB (Natick, MA, USA) for an intensity of 50 dB HL over a range of 0.2-8 kHz, and calibrated using peak-equivalent reference equivalent threshold SPL (peRETSPL) in a custom 2cc coupler made of acrylic. The electroacoustic transfer function of the ER-3A was mathematically compensated for in order to be acoustically flat.

### D. Averaging, Filtering and Deconvolution

AEP recordings were obtained for several isochronic rates at 0.49, 0.98, 1.9, 4.9, 7.2, and 9.8 Hz (ISIs between 0.1 s and 2.0 s), as well as 3 CLAD optimized sequences with mean rates of 5.1, 6.8, and 10.3 Hz (mean SOA of 0.1, 0.15, and 0.2 s). Figure 1 shows the CLAD sequences designed for this study. The left column shows a stem plot for each of the stimulus triggers in black. For comparison, an isochronic stimulation pattern is shown with smaller red stems for the corresponding isochronic rates. The middle column shows the instantaneous rate histogram for the CLAD sequences in the left column, where the mean rate is indicated by a thin red line. These histograms show the rate dispersion associated with the sequence jitter required for the CLAD method. The associated deconvolution filter characteristics are shown in the right column, and are expressed in terms of

TABLE I

STIMULUS SEQUENCE PARAMETERS USED IN THIS STUDY.

| Mean Rate, Hz | Stimulus onset – asynchrony, ms | No. of stimuli | SOA min | SOA max | Mean NAF | Duration 1 sweep, sec. | No. of sweeps | Duration recording, min. |
|---|---|---|---|---|---|---|---|---|
| 5.1 | 202, 221, 161, 248, 170, 175 | 6 | 161 | 245 | 0.56 | 1.18 | 450 | 8.8 |
| 6.8 | 182, 143, 161, 125, 169, 120, 135 | 7 | 119 | 182 | 0.52 | 1.03 | 450 | 7.8 |
| 10.3 | 114, 92, 79, 84, 79, 128, 88, 128, 101, 79, 97 | 11 | 79 | 128 | 0.46 | 1.07 | 450 | 8.0 |

a noise amplification factor (NAF) profile that is unique to each sequence. The NAF essentially describes the ability of the deconvolution process to attenuate (NAF<1) or amplify (NAF>1) noise present in the convoluted signal on a per-bin basis in the frequency domain [9]. A NAF of 2 denotes a 6 dB increase in noise. CLAD sequences selected for this study have been optimized for frequencies between 2.5 Hz and 300 Hz. Isolated points where NAF>1 can be combatted with judiciously chosen digital filters, if necessary.

Table 1 provides additional details pertaining to the CLAD stimulation sequences used in this study. For each CLAD sequence, a list of the consecutive SOA comprising one sweep is provided, as well as the duration and number of sweeps acquired for each rate. The particular recording parameters, rates, and sequences were chosen as a compromise between recording duration and SNR.

Averaging was performed off-line with a rejection threshold of $\pm 50$ $\mu$V to eliminate noisy recording artifacts, and deconvolution was performed in the frequency domain according to [9], when necessary.

### *E. Analysis*

*1) Comparing to normative data:* In order to compare the recorded LAEP data with established normative data (*e.g.:* Sussman et al. [13]), data from each subject for the iso-chronic rates of 0.49, 0.98, and 1.9 Hz were band-pass filtered between 1-30 Hz with a 2nd order, zero-phase Butterworth filter to remove high-frequency information. Then, the presence of, latency, and amplitude of characteristic peaks for LAEPs were tabulated or marked as indiscernible if they were not apparent.

*2) Comparing isochronic and CLAD recordings:* Isochronic data recorded at 4.9, 7.2, and 9.8 Hz, and the deconvolved CLAD recordings with rates of 5.1, 6.8, and 10.3 Hz were low-pass filtered at 300 Hz with a 2nd order zero-phase Butterworth filter in order to match the optimized deconvolution filter bandwidth (see right column of Fig. 1). For the purposes of this paper, the similarity between isochronic and deconvolved recordings at comparable rates (*e.g.:* 5.1 Hz CLAD and 4.9 Hz isochronic) is reduced to a simple $R$ value representing the zeroth-lag normalized covariance function.

## III. RESULTS

Figure 2 shows an example of an isochronic stimulated sequence at 0.98 Hz for subject S05 with detectable peaks

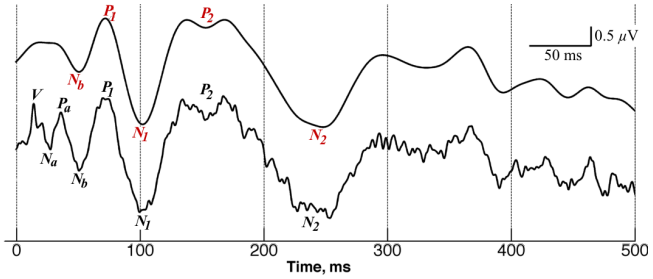


Fig. 2. Digitally filtered vs. raw EEG averaged waveforms for subject S05 at 0.98 Hz. The two traces represent the same 67 sweeps of recorded EEG (70 sec. recording duration). The upper trace has been band-pass filtered from 1-30 Hz (see text), while the lower trace has only the analog acquisition filter (1-1500 Hz).

labeled. The top trace is the output of applying a 1-30 Hz band-pass filter to the data represented in the bottom trace. The character of the latter portion of the MLR and LAEP is not diminished, however, peaks $V$ and $P_a$ are abolished or diminished significantly as a result of filtering, and the inter-peak amplitudes prior to $P_1$ are distorted.

Figure 3 shows responses recorded for the CLAD sequences (upper three traces) and isochronic recordings (lower three traces), each labeled according to mean rate of stimulation to the left. The left panel of Fig. 3 shows responses from subject S01 (with peak scoring indicated by labels or arrows), and the right panel shows the population averaged data ($N$=7). All data has been low-pass filtered at 300 Hz.

Table 2 presents a partial summary of the mean and standard deviation for the latency of the prominent AEP peaks: $V$, $N_a$, $P_1$, $N_1$, and $P_2$ as well as an average %-detected for the each peak for the 0.49, 0.98, and 1.98 Hz isochronic recordings, and the 5.1, 6.8, and 10.3 Hz CLAD recordings. The primary characteristic peaks for the ABR ($V$), MLR ($N_a$, $P_a$), and at least the $N_1$ of the LAEP are consistently identifiable in all averaged recordings. Initial comparisons between deconvolved CLAD and similar-rate isochronic recordings show high degree of correlation (R-values $\geq$0.67), but are suggestive of multiple-wrapping (data not shown), not resolvable with current methods.

We found the peak amplitude and latencies for isochronic and CLAD recordings were consistent with established literature for peak $V$, and MLR components [1]. For lower rate 0.49 and 0.98 Hz recordings, MLR and LAEP components

TABLE II

PARTIAL PEAK LATENCY DATA AVERAGED OVER THE POPULATION (N=7). * DENOTES CLAD SEQUENCE.

| Rate, Hz | SNR, dB | $R$, Corr. coef | $V$ | $\sigma$ | % | $N_a$ | $\sigma$ | % | $P_1$ | $\sigma$ | % | $N_1$ | $\sigma$ | % | $P_2$ | $\sigma$ | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.3* | 4.9 | 0.82 | 14.7 | 0.7 | 100 | 27.3 | 1.3 | 100 | 63.8 | 4.5 | 71 | 90.8 | 15.9 | 71 | 111 | 12.8 | 71 |
| 9.8 | 7.3 | | 14.9 | 0.5 | 100 | 27.7 | 1.8 | 100 | 60.9 | 2.4 | 57 | – | – | – | – | – | – |
| 7.2 | 5.5 | 0.67 | 14.7 | 0.4 | 100 | 28 | 1.4 | 100 | 65.9 | 6.5 | 86 | 96 | 20.6 | 43 | – | – | – |
| 6.8* | 3.5 | | 14.2 | 0.9 | 100 | 28 | 2.1 | 100 | 61.6 | 7.2 | 86 | 91.6 | 15.1 | 71 | 106 | 11.2 | 71 |
| 5.1* | 5.8 | 0.89 | 14.7 | 0.5 | 100 | 27 | 1.7 | 86 | 66.4 | 9.6 | 71 | 97.9 | 13.2 | 57 | 121 | 7.2 | 71 |
| 4.9 | 12.7 | | 13.9 | 2.1 | 100 | 26.8 | 1.6 | 100 | 64.6 | 4.1 | 57 | 94.4 | 19.5 | 43 | 131 | 25.4 | 43 |
| 1.98 | 9.5 | – | 14.8 | 0.5 | 100 | 26.7 | 3.8 | 100 | 71.5 | 8 | 86 | 105 | 17.3 | 86 | 155 | 23.3 | 86 |
| 0.98 | 7.1 | – | 14.8 | 0.5 | 100 | 26 | 3 | 86 | 71.7 | 7.3 | 100 | 108 | 17.6 | 71 | 158 | 21.5 | 71 |
| 0.49 | 4.5 | – | 14.2 | 0.4 | 100 | 26 | 4 | 57 | 69 | 8.4 | 100 | 108 | 17.4 | 100 | 165 | 18.5 | 100 |

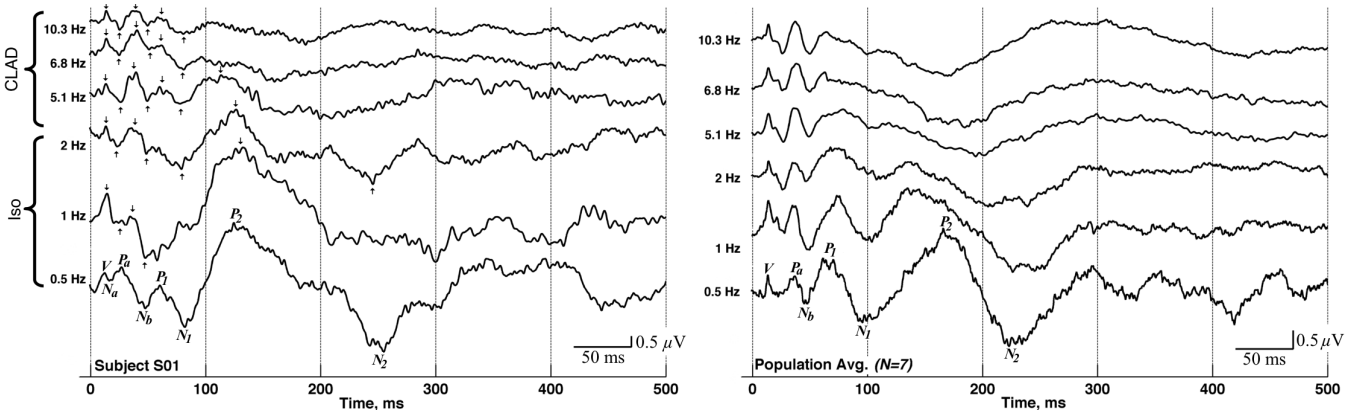


Fig. 3. Results from whole-AEP recordings, arranged according to mean stimulation rate (left of figure). The left panel shows results from subject S01, and the right panel shows the population average. All data subjected to a 300 Hz low-pass filter. Note differing amplitude scales in the left and right panels.

of $N_a$, $P_1$, $N_1$, $P_2$, and $N_2$ are also consistent with published normative data acquired from non-attending adults [5,13].

As rate increases, there is a clear trend for the $N_1$ amplitude to decrease, and a shallow negativity persists at the same latency in the 5.1 Hz and 10.3 Hz CLAD traces.

For rates above 5.1 Hz, the deconvolution procedure reveals a region of the AEP that would otherwise be lost to overlap with the subsequent stimulus. Thus, it is possible to observe that the morphology of the middle and late-latency region of the AEP is considerably modified at higher rates. For example, the negativity occurring at about 250 ms at 0.49 Hz becomes a broad positivity by the rate of 10.3 Hz. It is apparent that the brain continues to process auditory stimuli well into the late-latency epoch when stimulated at these high rates. However, the mechanisms responsible for this morphology transition are unclear.

## IV. DISCUSSION AND CONCLUSION

This study has been a demonstration of acquiring whole-AEP recordings at high-rates of stimulation and increased bandwidth. Results suggest that high quality recordings can be obtained that contains characteristic ABR, MLR, and LAEP peaks within a single recording. Additionally, rates higher than established LAEP literature appear to exhibit rate-dependence, and merits further investigation.

The cochlear delay compensated chirp stimulus appears to be capable of eliciting conventional AEP components. However, it was not within the scope of this study to differentiate between AEP morphology elicited by a chirp vs. gated pure-tone stimuli.

LAEP components are known to be especially sensitive to ISI (and SOA) [1,7], therefore additional work on the effects of jittered sequence stimulation is needed to investigate response fidelity. Also, the bandwidth limit imposed by the deconvolution filter was chosen somewhat arbitrarily, and may be adapted with additional sequence design. However, a compromise must be made between stimulation rate, recording duration and fidelity of the earlier AEP components.

Acquiring high-fidelity whole-epoch multi-component recordings at high rates is possible using deconvolution. The advantage of this method is that it may provide a reasonable compromise between early-AEP fidelity and potential diagnostic value of LAEP recordings in situations where recording duration or subject compliance is limited.

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