

Auditory brainstem responses elicited by embedded narrowband chirps

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Auditory brainstem responses (ABRs) have been investigated using rising frequency chirps to compensate for the dispersion along the cochlear partition in the auditory periphery. Responses elicited by the broadband chirp show larger wave-V amplitude than do click-evoked responses for most stimulation levels (Dau *et al.*, 2000). It is desirable in some clinical (objective audibility assessment) and research (cochlear latency estimation, Neely *et al.*, 1988) applications for more frequency specific responses. Traditionally, this has been accomplished using tone-burst stimuli, however these have the problem of spectral splatter associated with temporally short narrowband stimuli. Conceivably one could use narrowband chirps to synchronise a small number of auditory filters, and thereby gain frequency specificity. However, similar to the tone-burst ABRs, the stimulus duration would be very short, and therefore onset and offset effects will result in spectral splatter and thus degrade the frequency specificity. Junius and Dau (2005) showed that, by embedding a single broadband rising chirp, spectrally and temporally in two steady-state tones, the effects of spectral splatter along the cochlear partition can be minimised. Further, by ensuring that the excitation level is sufficiently low, one can keep any steady state responses in the evoked potential to a minimum. This paper presents a feasibility study in the use of embedded narrowband chirp stimuli to obtain frequency specific auditory brainstem responses, for use in clinical and research settings.

INTRODUCTION

Auditory evoked potentials are the summed response from many remotely located neurons recorded via scalp electrodes. They can be recorded from all levels of the auditory pathway, from the auditory nerve, the brainstem up to the cortex. Auditory brainstem responses (ABRs) are recorded between 1 and 7 ms after stimulus offset, and are the summed response from action potentials in the auditory nerve (AN) and postsynaptic activity in the major brainstem auditory centres.

ABRs have been used in many clinical studies on numerous applications of auditory assessment and neurodiagnosis. For example, neonatal screening, estimation of auditory sensitivity in the very young or difficult-to-test children and neurodiagnosis of AN dysfunction. The ABR is composed of major peaks in the waveform, labelled by roman numerals I-VI. Waves III and V tend to be the most robust and easy to record, and are therefore typically chosen in clinical applications. Classically, the response was assumed to reflect synchronous activation of onset-type neurons within the audi-

tory system. Whether the stimulus is an acoustic click, tone-burst, or noise-burst, the ABR was assumed to be effectively evoked by the first few milliseconds of the stimulus, and generally unaffected by further stimulation (e.g., Hecox *et al.*, 1976; Kodera *et al.*, 1977; Debruyne and Forrez, 1982; Gorga and Thornton, 1989; Van Campen *et al.*, 1997). Clicks or impulsive stimuli were used under the assumption that their wide spectral spread, inherent in transient signals, elicits synchronous discharges from a large proportion of cochlear fibers (e.g., Kodera *et al.*, 1977; Gorga and Thornton, 1989; van der Drift *et al.*, 1988a, 1988b). Click stimuli are obviously affected by cochlear dispersion, thus the tonotopic auditory-nerve single-unit activity is less synchronous with the preceding activity from basal units. This would imply that classical ABR recordings are biased towards basal higher-frequency regions of the cochlea (Neely *et al.*, 1988). Dau *et al.* (2000) developed an 'optimised' chirp stimulus to evoke maximal synchronous activation at the level of the auditory nerve. This was accomplished by compensating for the frequency dependent mechanical basilar-membrane travel time in a broadband, frequency-sweeping chirp stimulus. This stimulus was based on de Boer's (1980) model of the basilar membrane. A thorough description of the chirp stimuli is omitted here for brevity, and the interested reader is referred to Dau *et al.* (2000).

In a number of applications it would be desirable to have a more frequency specific stimulus to investigate the contribution of various neural populations to the evoked ABR. For example, if one were to investigate objective correlates of audibility, then frequency specificity is essential. Classically this would have been achieved using tone-burst stimuli as seen in Neely *et al.*'s (1988) investigation on cochlear latency estimation. In the present study, a narrowband chirp stimulus is developed, based on the Dau *et al.* (2000) broadband chirp. Simply limiting the broadband chirp in frequency and retaining the particular frequency dispersion relation would result in very short duration signals. The spectral splatter caused by such short transients would limit the frequency specificity, and thus negate the usefulness of this stimulus type. Luckily Junius and Dau (2005) investigated the relationship between evoked responses to transient broadband chirps and the responses to the same chirps embedded in tones. Embedding the narrowband chirps in tones removes the sharp onset and therefore regains our frequency specificity. This study focuses on the feasibility of using such narrowband stimuli to evoke ABRs and will look at the various stimulus parameters important for developing this as a clinical and research tool. The minimum bandwidth required to evoke a response is investigated in experiment 1, as well as a demonstration of the use of the new steady-state stimulus to quickly obtain ABRs from different locations in the cochlea (experiment 2). Wegner and Dau (2002) were similarly interested in the frequency specificity of chirp-evoked auditory brainstem responses. They used broadband chirps in the presence of high-pass masking noise at various cut-off frequencies. The study presented here differs by the use of narrowband chirps embedded in pure tones to negate spectral splatter, and remove the need for additional maskers.

MATERIALS AND METHODS

In this study, four subjects underwent experiment 1 and only a single subject underwent experiment 2. This implies that the generality of the results presented in this paper are preliminary and thus further work is required.

Experiment 1 – Investigating minimum bandwidth

To test the minimum required bandwidth to elicit a wave V response, embedded chirps were used as described by Junius and Dau (2005). The stimulus consisted of a 30 ms long lower-frequency tone, f_L , followed by the rising chirp and a 20 ms upper-frequency tone at f_U . 4 ms hanning windows were applied to the onset and offset of the stimulus time series to further minimise spectral splatter. An example waveform is shown in the top panel of Fig. 1 for $f_L = 88\text{Hz}$ and $f_U = 11,314\text{ Hz}$, corresponding to the broadband chirp used by Junius and Dau (2005) with a bandwidth encompassing 7 octaves. In this first experiment, two stimuli sets were employed: (1) The low cut-off frequency was fixed at $f_L = 88\text{ Hz}$, and the upper cut-off frequency was varied to ensure a bandwidth reduction in 1 oct. steps. (2) The upper cut-off frequency was fixed at $f_U = 11314\text{ Hz}$, and the lower cut-off frequency was varied to ensure a bandwidth reduction in 1 oct. steps. These two stimulus sets were designed to investigate the critical bandwidth at the apex and the base of the cochlea respectively.

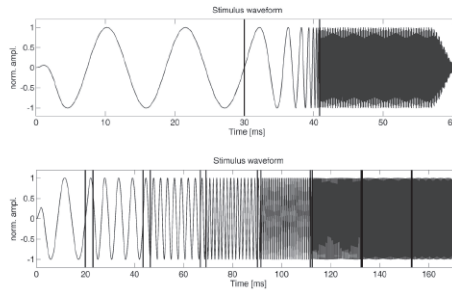


Fig. 1: (*Top*) Embedded broadband rising chirp, with lower cut-off frequency of ~ 0.09 kHz and higher cut-off frequency ~ 11.3 kHz. The vertical lines indicate the start and end of the chirp signal. (*Bottom*) Embedded narrowband rising chirp train, with lower cut-off frequency of ~ 0.09 kHz and higher cut-off frequency ~ 11.3 kHz. The vertical lines represent the start and end of the one octave rising chirps.

For ABRs evoked using click stimuli the zero time reference is the click onset. This is not as simple for the chirp stimuli as they inherently introduce a delay. This delay is bound to the dispersion relation used to compensate for cochlea travel time. All of the results shown in the next section present the ABR waveforms having compensated for this delay.

Experiment 2 – Chirp train and reverse chirp

In the second experiment, the frequency range for which single octave chirps could elicit an ABR with a clear wave V was investigated. A chirp train was developed (see bottom panel of Fig. 1) consisting of an initial 30 ms low-frequency tone lead in of

88 Hz, then the first 1 oct. chirp, then a 30 ms tone of its upper frequency of 177 Hz. This was then followed by the next chirp and its following tone, and this repeated until the whole bandwidth was covered. Table 1 shows the centre frequencies and edge frequencies for the chirps used in this stimulus. A chirp train of this type was developed so as to reduce recording time. Also presented to the test subject was a reversed time chirp train, to test for the degree of ‘improved’ synchrony accountable for the cochlear delay compensation. The reversed chirp should reduced the synchrony across channels and one would expect to observe a reduction in ABR amplitude.

Centre freq. f_C	125	250	500	1000	2000	4000	8000
Low cut-off freq. f_U	88	177	354	707	1414	2828	5657
High cut-off freq. f_L	177	354	707	1414	2828	5657	11314

Table 1: Experiment 2 chirp train centre and cut-on/off frequencies in Hz.

Stimulus generation and data acquisition

The stimuli sets were generated in MATLAB and D/A and A/D conversion made through an ADI-8 Pro 24-bit converter, the levels were set via a DT PA5 programmable attenuator, and the stimuli presented to the left ear of the test subject via an ER-2 insert earphone. A total of 4000 of each stimuli type were presented to the subjects, and repeated a second time to ensure reproducibility. All stimuli sets for both experiments were presented at 60 dB pe SPL. This was felt to be a sufficiently high level to elicit a strong ABR without being too high, which would result in an observable frequency following response artefact (see Junius and Dau, 2005).

EEG activity was recorded differentially between the vertex and the ipsilateral mastoid, with the ground electrode placed on the forehead. Silver/silver chloride electrodes were used, and inter-electrode impedance was maintained below 5 k Ω . The EEG activity was recorded on a SynAmps 5803 amplifier, providing 74 dB of gain before a low-pass filter stage (cut-off of 2 kHz), with a sampling rate of 10 kHz. After recording, the EEG-data were epoched and filtered again from 100 to 1500 Hz using a 200 tap FIR filter. The epochs were averaged using an iterative weighted-averaging algorithm (Riedel *et al.*, 2001).

RESULTS

Experiment 1 – Investigating minimum bandwidth

The results for experiment 1 for one exemplary subject are shown in Fig. 2 to illustrate the general findings. The left panel shows the results for the fixed low-frequency and variable high frequency. Each trace shows the two repeat trials and thus demonstrates excellent reproducibility except where otherwise stated. The dashed vertical lines show the zero time reference, as explained in the previous section. The top trace gives the results for the full bandwidth, 7 oct. case. The results demonstrate typical waveform peaks corresponding to a very clean ABR recording. Waves I, III, V and VI are marked for reference. Dropping from 7 to 5 octs. results in the waveforms retaining

waves III, V and VI. The traces for the 4 oct. case appears degraded, however wave V is still clear. For bandwidths below this, it is uncertain if a wave V is present. Wave V amplitude is reduced as the bandwidth becomes more and more limited, as one might expect from a smaller neural population.

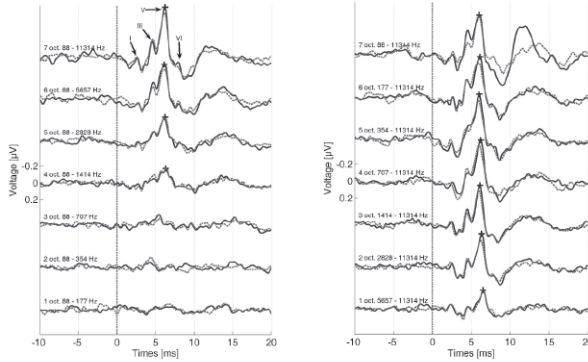


Fig. 2: Ipsilateral ABR recordings to the embedded chirps for subject ‘sv’ as a function of bandwidth; for (*left*) fixed lower cut-off frequency; and (*right*) fixed upper cut-off frequency. On each pane the top trace shows the full broadband chirp response, and each subsequent trace reduces the bandwidth by one octave, leaving only a single octave on the lower traces. Two repeat measures are shown on each trace to demonstrate reproducibility.

The right panel of Fig. 2 shows the results for the fixed upper and variable lower-frequency case. The top trace corresponds to identical stimulus condition as for the top trace of the left panel. The dashed curve corresponds well with these previous set of results, however the solid curve does not. This trace represents the only case where reproducibility was called into question. It is believed this trace is corrupted by post-auricular muscle activity (PAM). As the later traces did not show this effect it was deemed unnecessary to investigate further. However this corrupted trace still shows key ABR features such as a strong wave V. Reducing the bandwidth has the effect of reducing the wave V amplitude as previously. However, a clear wave V is seen all the way down to a single octave bandwidth.

In comparison, the fixed-low frequency very narrowband embedded chirps did not elicit a clean wave V in the ABR. The fixed-high frequency narrowband embedded chirps demonstrated clear wave V peaks in the ABR for all the bandwidths tested.

Experiment 2 – Chirp train and reverse chirp

The results for the rising chirp trains in experiment 2 are shown in the left panel of Fig. 3. The single octave chirp responses have been identified and aligned vertically on the Figures for clearer viewing. Distinct wave-V peaks can be seen down to a centre frequency of 1 kHz, with ambiguous results at centre frequencies below this.

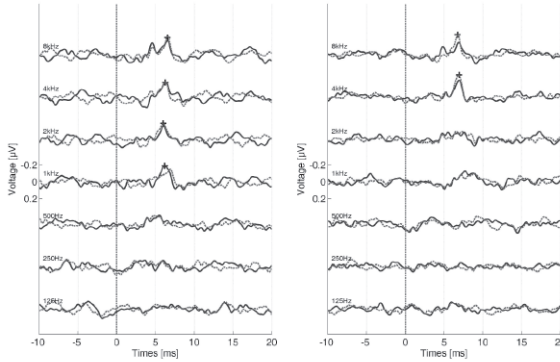


Fig. 3: Ipsilateral ABR recordings to the embedded chirps with a bandwidth of one octave for subject ‘sv’. (*left*) Rising chirp train and (*right*) Falling chirp train. Two repeat measures are shown to demonstrate reproducibility. The ‘+’ symbols mark the location of the wave-V peaks.

The right panel of Fig. 3 shows the results for the reversed, falling, chirp train. The expected outcome from this experiment would have been a reduction in amplitude in the resulting wave-V (if at all present), due to the reduced synchrony in the neural populations due to cochlear dispersion. It can be seen that this is the case except for centre frequencies of 8 and 4 kHz, where the wave-V amplitude appears similar to the rising chirp case.

DICUSSION AND CONCLUSIONS

Experiment 1 demonstrated that it was possible to record ABRs evoked from narrow-band chirps embedded in steady state tones. The minimum bandwidth, required to evoke a clean wave-V peak, depended on the frequency range of the chirp. The left panel of Fig. 2 shows that a chirp spanning the range 88-707 Hz does not evoke a clear ABR waveform. This was further demonstrated in experiment 2, showing that it was possible to record single-octave wide chirp-evoked ABRs at high centre frequencies, down to around 1 kHz (Fig. 3, left). Below this, no discernable wave V peak could be seen. The question is whether similar ABR recordings could be expected from the apex and the base.

The bandwidths for the experiments here were defined in terms of octaves (i.e. logarithmically) to ensure a fixed distance along the basilar membrane being excited as a function of centre frequency. The inner hair-cell density in human cochleae is approximately 87 IHC/mm (Uleřlová *et al.*, 1987), and does not vary systematically along the cochlea length. Around 10-30 type I afferent AN fibres form a single synaptic connection with each IHC. Again there does not appear to be any systematic variation with cochlea length. Tsuji and Liberman (1997) demonstrated in guinea pigs, that the tuning of individual AN fibres, measured in Q_{ERB} , increases gradually with characteristic frequency (CF) throughout the cochlea. Shera *et al.* (2002) demonstrated, with Q_{ERB} values derived from objective otoacoustic emissions and a new behavioural approach,

that cochlear filters in humans seem to vary compressively with CF. This is contrary to the classical view (see Moore, 1986) of fixed Q values at least in the base of the cochlea. The findings from the Shera *et al.* (2002) study suggest a re-examination of the relation between the cochlear map, and the spatial correlate of the critical bands, is necessary. Further evidence from Allen (1996) suggests that the spatial correlate of the ERB, known as the equivalent rectangular spread (ERS), depends on the width of the basilar membrane, and therefore varies with position. For the study here, this would imply that at low CF a greater number of fibres would contribute to generating the ABR response, and one would expect increased wave V amplitude. This is contrary to the experimental observations. However, at low frequencies, where greater temporal synchrony is expected, the rate functions are much shallower and the summed activity would be smoothed compared to the higher frequencies. It is thus not fully clear what these observations have with the experimental data presented here.

The chirp dispersion characteristics were based on the linear cochlear model of de Boer (1980), not the individuals themselves. Therefore the timing based in the model may be incorrect for this test subject. However, even with a non-optimal synchronisation, one would expect some ABR waveform even if it was smaller in amplitude. Further work modelling ABR generation needs to be carried out to test this hypothesis.

When defining the stimuli sets for experiment 2, the criterion was a single octave to ensure equal sections of the cochlea being excited. Due to the logarithmic mapping of frequency to place on the basilar membrane, and the dispersion relation used in the chirp to compensate for it then a single octave at the lower frequencies often meant that the chirp waveform did not have a full cycle. It is not immediately apparent what this may imply, however this can be investigated by defining the stimulus in terms of a fixed number of cycles and allowing the bandwidth to vary.

The chirp used in these experiments was arbitrarily chosen as the broadband chirp described in Dau *et al.* (2000). The instantaneous frequency of this chirp changes slowly at low frequencies relative to the changes at high frequencies, therefore its magnitude spectrum is dominated by the low frequencies (see Fig. 1, Dau *et al.*, 2000). With that in mind, one might have expected to observe higher ABR wave V peaks at lower frequencies. Again this would point to the opposite of the experimental observations.

It is possible that simple level differences at low stimulus levels account for the lack of an ABR, i.e. due to middle-ear filtering. Future experiment stimuli should be calibrated in terms of sensation level rather than peak equivalent sound pressure level to remove this ambiguity. Experiment 2 was also carried out at the higher stimulus level of 70 dB pe SPL, though the results were not shown here for brevity. In this case a reproducible wave V peak was observed for centre frequencies as low as 500 Hz. Calibrating in terms of sensation level may go some way to explaining the results observed in this study.

The results for the falling chirp stimuli are interesting. The fact that there is no reduction in wave-V amplitude at high centre frequencies compared with the rising chirp,

calls into question the effect of synchronisation between neural populations for these narrow bandwidths. Would simply using a tone burst stimuli produce the same results? Future work and a more detailed comparison will to be carried out to try and understand this dichotomy. In order to address the various issues raised here, it is felt that an evoked-response model needs to be developed, that accounts for the new physiological understanding of the tonotopic mapping and cochlear dispersion.

All of this discussion has been based on the results of a very small set of experimental data from this preliminary study. The scope of this study will be broadened to include a much larger pool of test subjects.

SUMMARY

The paper presents some preliminary findings in the use of embedded narrowband chirps to record ABRs. It is desirable in some clinical (objective audibility assessment) and research (cochlear latency estimation, Neely *et al.*, 1988) applications for more frequency specific responses. In this study it was shown that single octave-wide narrowband chirp evoked ABRs could be obtained for centre frequencies 8, 4, 2 and 1 kHz. Below this no reproducible ABR waveform could be recorded. There are a number of potential experimental and theoretical concerns that may account for this; from simple sensation/presentation level; to a theoretical difference in the way ABRs are generated in the auditory periphery. This study does not offer evidence yet as to the cause, merely highlights and documents the work carried out so far and this potential avenue for future research into auditory physiology.

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