A comparison of commercially available auditory brainstem response stimuli at a neurodiagnostic intensity level

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Abstract

iChirp-evoked auditory brainstem responses (ABRs) yield a larger wave V amplitude at low intensity levels than traditional broadband click stimuli, providing a reliable estimation of hearing sensitivity. However, advantages of iChirp stimulation at high intensity levels are unknown. We tested to see if high-intensity (*i.e.*, 85 dBnHL) iChirp stimulation results in larger and more reliable ABR waveforms than click. Using the commercially available Intelligent Hearing System SmartEP platform, we recorded ABRs from 43 normal hearing young adults. We report that absolute peak latencies were more variable for iChirp and were ~3 ms longer: the latter of which is simply due to the temporal duration of the signal. Interpeak latencies were slightly shorter for iChirp and were most evident between waves I-V. Interestingly, click responses were easier to identify and peak-to-trough amplitudes for waves I, III and V were significantly larger than iChirp. These differences were not due to residual noise levels. We speculate that high intensity iChirp stimulation reduces neural synchrony and conclude that for retrocochlear evaluations, click stimuli should be used as the standard for ABR neurodiagnostic testing.

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Introduction

The auditory brainstem response (ABR) is the synchronized firing of neural action potentials in response to acoustic stimulation. In normal hearing individuals, the ABR yields five to seven identifiable waveforms labeled by Roman numerals I-VII.[1,2] These waveforms are analyzed based on their latency and amplitude and are used as an objective measure of retrocochlear integrity.[3] For example, the ABR is instrumental in evaluating auditory nerve pathologies and estimating hearing threshold sensitivity in adults and infants.[4-7] Auditory system deficits result in absent, reduced, prolonged or abnormal ABR latencies and amplitudes.[7-11] The stimulus used to elicit the ABR has traditionally been brief broadband acoustic click or tone-burst stimuli. However, these stimuli do not always yield robust waveform amplitudes, especially at low intensity levels.[12-14] It has been suggested that the rapid kinetics and frequency spectrum of the broadband click results in a traveling wave that reduces neural synchrony from high-to-low frequency regions of the basilar membrane, producing significant waveform variability.[15]

As such, researchers have developed better stimuli to account for the delay properties of the traveling wave.[16-19] One stimulus, known as the chirp, accounts for the traveling wave delay by offsetting the timing of the high frequency spectrum relative to its low frequency component. In that, the low frequency component is delivered to the cochlea earlier than the higher frequencies permitting the simultaneous arrival of the stimuli across the basilar membrane.[15] This is thought to contribute to enhanced neural synchrony of afferent action potential firing and thus, more reliable latencies and larger ABR waveform amplitudes. Indeed, chirp-evoked ABRs have larger waveform amplitudes than click or tone burst when presented at low intensity level, providing a better estimation of hearing threshold sensitivity.[12,20]

However, there are conflicting results on the advantage of chirp stimulation at high intensity levels, especially for early waveforms (*e.g.*, Wave I-III; Table 1). This is confounded by the numerous types of chirp stimuli available, (*e.g.*, CE-Chirp, O-Chirp, LS-Chirp, A-Chirp, M-Chirp, *etc.*) which differ based on the magnitude, bandwidth and timing of their frequency spectrum. From a clinically perspective, this is problematic. Little evidence argues for (or suggest against) using any of the multiple chirp stimuli available for neurodiagnostic testing. In addition, manu-

facturers of commercially available evoked potential equipment further exacerbate the issue by renaming chirp stimuli that vary only slightly from typical research models. For example, the commercially available Intelligent Hearing System (IHS) SmartEP platform uses a derived linear model version of the CE-Chirp, known as the iChirp™. The conflicting results from the literature, the numerous types of chirp stimuli available and the variation from commercially available equipment leave gaps in knowledge about the appropriate stimuli to use during neurodiagnostic testing. Furthermore, the evidence suggests that some chirp stimuli may not be suitable for high intensity situations.

To address this, the current study compared the commercially available broadband iChirp stimulus to the traditional broadband click using the IHS SmartEP platform. We asked if iChirp-evoked ABR waveforms are more reliable and larger than those obtained using click stimulation? We recorded ABRs using both stimuli in normal hearing subjects at a neurodiagnostic intensity level. Using standard clinical procedures and equipment, we found that the traditional click stimulus produced more reliable latencies and significantly larger amplitudes for all waveform components of the ABR compared to the iChirp.

Materials and Methods

Participants

Data was obtained at Northwestern University Center for Audiology, Speech, Language and Learning (NUCASLL). Forty-three, normal hearing participants (35 females) between 18-29 years of age (average age = 22 ± 2.5 years) were recruited. ABRs were collected to obtain normative data for an IHS SmartEP platform. As a result, Northwestern University's Internal Review Board for human subject participants did not require study approval. However, before testing was performed, all procedures were explained to participants and questions regarding participation and purpose of collecting normative data were answered. Each participant read and signed a consent form explaining the procedures and their rights as participants. Personal identifiers were excluded and each individual was assigned a subject number. Personal information was kept in a secure folder on a password-protected computer in accordance with the Health Insurance Portability and Accountability act. Only testers had access to the data.

Normal hearing sensitivity was confirmed using conventional audiometry on a Grason-Stadler GSI audiostarPro audiometer. Inclusion for collecting normative data required pure tone thresholds for octave frequencies from 500-8000 Hz (via air conduction) to be ≤ 20 dBHL. Participants had air-bone gaps of < 10 dB for tested frequencies between 500-4000 Hz (bone oscillator placed behind on the right mastoid). Figure 1A shows participants average air and bone conduction thresholds. Distortion product otoacoustic emissions (DPOAEs, $2f_1$-f_2) were obtained using the Interacoustics Titan for frequencies between 500 Hz and 10,000 Hz to ensure normal outer hair cell function. Emissions were recorded twice from each participant's right ear to ensure repeatability and grand averaged. Participants were included in the current study only if they presented with normal DP Grams that exceeded the expectant noise floor ≥ 6 dB between frequencies 1000-7000 Hz (Figure 1B). Exclusion criteria included participants who self

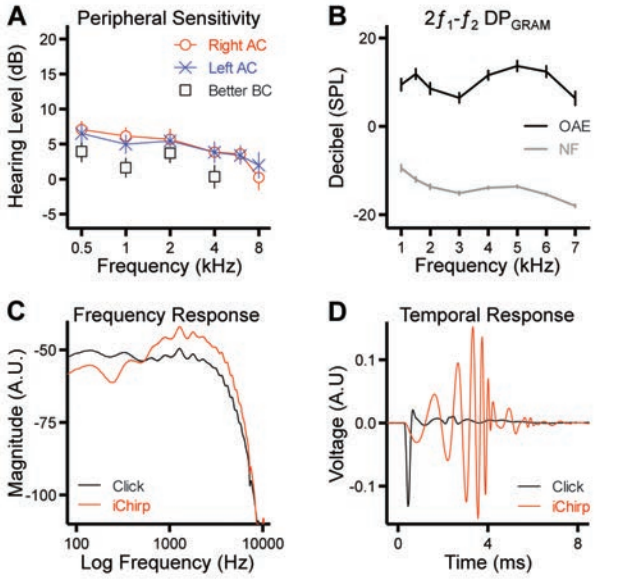

Figure 1. Population and stimulus characteristics. A) Population data (n = 43) showing normal peripheral hearing sensitivity between 0.5 and 8 kHz to air and bone conduction audiometry for both ears. AC = air conduction, BC = bone conduction. B) Population data for distortion product otoacoustic emissions for the right ear between 1 and 7 kHz. Black line represents emissions (OAE) and gray line represents noise floor (NF). Error bars = ± 1 standard deviation. C) Frequency and D) temporal characteristics of the iChirp and click stimuli (red and black lines, respectively) measured in a 2cc insert earphone adapter using a Brüel & Kjær 2230 Mediator sound level meter. Output was recorded using Audacity.

Table 1. Literature comparison of Click versus Chirp stimulation at different intensity levels for various ABR waveform components.

Study	Larger Wave V < 60 dB	Larger Wave V: >60 dB	Larger Waves I/III
Fobel & Dau (2004)	Chirp	--	Chirp: High Intensities
Chertoff *et al.* (2010)	--	--	Chirp: High Intensities, CAP
Kristensen & Elberling (2012)	Chirp	*Chirp/Click	*Chirp/Click: Level Specific
Elberling & Don (2008)	Chirp	--	--
Dau *et al.* (2000)	Chirp	--	--
Wegner & Dau (2002)	Chirp	--	--
Rodrigues & Lewis (2012)	Chirp	Click	Click

reported remarkable history of medical ear issues, such as noise exposure and a history of middle ear problems.

Stimuli

Broadband rarefaction iChirp (duration = 3.95 ms) and click stimuli (duration = 100 μs) were used in the current study. The iChirp spectral-temporal characteristics are derived from a linear model similar to the CE-Chirp, a specific type of chirp stimulus often reported in the literature. The IHS generated both stimuli with the Smart EP platform on a Dell Latitude E5500 notebook computer. Before participant testing, the output of the ER-3A ultra-shielded transducers was measured for both stimuli using a Brüel & Kjær 2238 sound level meter coupled to a 2 cc insert earphone adapter. In doing so, we confirmed that the output of both stimuli generated similar output sound pressure levels (average ΔSPL root mean square value = 1.2±0.6). Figure 1C and D shows the frequency and temporal responses for both stimuli.

Electrophysiological recordings

Subjects were placed on a reclining masseuse table in a sound- and electrically-treated room at NUCASLL, and instructed to relax and/or sleep during ABR testing. Each participant's forehead (Fz), right (A2) and left (A1) mastoids were scrubbed with skin prepping gel and cleaned with a sterile swab (saturated with 70% isopropyl alcohol) before placement of disposable electrodes to ensure low input impedance. Overall electrode impedances were less than 7.0 kΩ and interelectrode impedances were maintained below 3.0 kΩ for all subjects. Recordings were obtained using a vertical montage from snap electrodes placed at Fz (positive), A2 (negative) and A1 (ground). Electrodes were held in place by additional surgical tape. Room lights were turned off after the participant was set up prior to recording. Stimuli were delivered via an ER-3A insert earphone to the right ear only and stimulus order was randomly presented. Stimuli were delivered at a rate of 19.3/sec and evoked responses were band pass filtered between 100-3000 Hz. Evoked potentials were amplified 10^5 and data were sampled at a rate of 50 kHz for a 12.5 ms time window (sweep). Two waveforms (2048 sweeps) were collected for each stimulus for repeatability and to obtain a grand averaged response (4096 sweeps). The grand averaged response was used for data analysis. Artifact rejection (AR) upper and lower limits were set to ±25 μV. Across the population tested, the average AR value was <1% of the grand averaged response. A typical recording session lasted approximately 45 minutes.

The IHS SmartEP platform permits real-time signal-to-noise ratio (SNR) and residual noise (RN) estimations using a split-sweep technique. In short, odd numbered sweeps were placed in buffer A and even numbered sweeps were placed in buffer B of the computers memory. The signal estimate (buffers A+B) and noise estimate (buffers A-B) were determined across a 4-9 ms time window of the 12.5 ms sweep. The starting time of 4 ms post-stimulus onset was selected to avoid any stimulus artifact during iChirp stimulation and is the default analysis window for the equipment. Before performing the SNR and RN calculations, the average of each buffer and μV conversion factor was determined. Once the averaged responses from buffer A (aveA) and buffer B (aveB) were determined, the sum and sum-squared values across the analysis window (*i.e.*, 4-9 ms) were used to calculate the SNR by the following equation:

$$EP_{SNR} = \sqrt{(S_{SS})} / \sqrt{(N_{SS})} \quad (1)$$

Where EP = evoked potential, S_{SS} = Signal sum-squared, and N_{SS} = Noise sum-squared.

The RN was estimated as a simple peak-to-peak value of the noise estimate array (buffers A-B) as shown in the equation below.

$$EP_{RN} = (\text{NoiseDataRange } (EP_A, EP_B) * \mu\text{VFactor}) \quad (2)$$

However, fast transient noise activity results in overestimation of the RN and therefore, the RN was calculated based on the standard deviation of the noise estimate array to account for 95% of the noise amplitude using the following equation:

$$EP_{RN} = 4*\sqrt{(N_{SS}\mu V/\text{datapoints})} \quad (3)$$

For more regarding IHS SmartEP platforms' calculations of SNR and RN, interested readers are referred to http://www.ihsys.com/site/

Data and statistical analyses

Waveform latencies (absolute and interpeak) and amplitudes (peak-to-trough) were marked (when identifiable) and analyzed from the grand average response for each stimulus condition. The IHS software determined latencies and amplitudes by recording the largest/smallest μV value within a 40 μs bin window of the computer cursor. Statistical analyses and graphing protocols were performed using Prism software. The second author and an additional licensed audiologist - who was unaware of the study objectives - determined inter-tester reliability of peak-to-trough amplitude identification. Each additional tester was randomly assigned twelve waveforms to identify peak-to-trough amplitudes. The inter-tester agreement coefficient (Pearson *r*) was 0.88. The standard for significant differences was defined as $P<0.05$. All graphic representations of data illustrate individual subjects and when

Table 2. Normative latency and amplitude ABR data for Click and iChirp (RE: 85 dB nHL, Grand Average = 4096 Sweeps).

	Wave I	Wave II	Wave III	Wave IV	Wave V	I - III	III - V	I - V
Click								
Absolute peak latency (ms)	1.51 ± 0.15	2.76 ± 0.15	3.73 ± 0.15	4.98 ± 0.18	5.51 ± 0.19	2.22 ± 0.17	1.78 ± 0.16	4.00 ± 0.22
Absolute P-T amplitude (μV)	0.39 ± 0.13	0.11 ± 0.08	0.48 ± 0.17	0.09 ± 0.08	0.67 ± 0.19			
iChirp								
Absolute peak latency (ms)	4.63 ± 0.23	5.70 ± 0.36	6.61 ± 0.25	7.60 ± 0.41	8.22 ± 0.32	1.98 ± 0.31	1.61 ± 0.28	3.59 ± 0.42
Absolute P-T amplitude (μV)	0.23 ± 0.10	0.09 ± 0.07	0.38 ± 0.18	0.09 ± 0.07	0.41 ± 0.15			
Waveform Identifiable (%)								
Click	100	70	100	40	100			
iChirp	100	33	98	21	98			

appropriate, represent the mean ± 1 standard deviation (SD) or the range of data variability. Data shown in Table 2 represents mean ± 1 SD. Paired *t*-tests were used to evaluate significant difference for waves I, III, and V amplitudes, and Pearson *r* correlation tests were used to determine signal and noise relationships. An additional reliability check was performed using SNR and RN estimates of the ABR for each stimulus recording to ensure that contaminant noise did not account for variability within and between recording sessions.

Results

Normative ABR Data for Click and iChirp

Broadband rarefaction click and iChirp stimuli were used to evoke responses and the order of presentation was randomly chosen for each participant. Two responses from each stimuli were recorded at 85 dBnHL and grand averaged. Normative data was based on the responses obtained from right ear stimulation of 43 normal hearing subjects. Figure 2A and B shows labeled peak-to-trough amplitudes of representative grand averaged waveforms from two different subjects for click and iChirp, respectively. ABRs showed variable waveform amplitudes across the population, however the range of peak-to-trough amplitude variability was similar between the two stimuli (Figure 3A and B; Table 2). Due to the temporal characteristic of the iChirp stimulus (duration = 3.95 ms; Figure 1D), the absolute peak latency of wave I occurred approximately 3 ms post stimulus onset but all interpeak latencies were within normal limits (Figure 3D; Table 2). The average variability of absolute and interpeak latencies were less for click responses (absolute latency click 1 SD = 0.16 ms; iChirp = 0.31 ms: interpeak latency click 1 SD = 0.18 ms; iChirp = 0.34 ms) however, interpeak latencies for all waveforms were significantly shorter for iChirp (waves I-III, paired t_{test} = 6.01, df = 41 P<0.0001: waves III-V, paired t_{test} = 2.09, df = 41, P=0.04: waves I-V, paired t_{test} = 6.23, df = 41 P<0.0001; Figure 3C and D; Table 2). This was most prominent for interpeak latencies between waves I-V (click Δt = 4.00 ms, iChirp Δt = 3.59 ms).

Qualitative and quantitative ABR differences to Click and iChirp

The within subject design permits direct comparison of qualitative and quantitative ABR differences to click and iChirp for individual subjects. Figure $4A_{1-4}$ shows ABRs from four randomly chosen subjects ordered by stimulus presentation. Wave I latency of the iChirp responses were normalized to wave I latency obtained from click recordings (Figure $4B_{1-4}$). The overall waveform quality was consistently poorer for iChirp compared to click. Superimposed traces show a shortening of interpeak latencies and a reduction in waveform amplitudes for iChirp. While Figure 4 shows a reduction in waveform amplitudes for some subjects using iChirp stimulation, Figure 5 shows the quantitative analysis for all subjects used in the study. Overall, we found a significant reduction in waveform amplitude for waves I, III and V for iChirp responses (wave I, paired t_{test} = 7.43, df = 42, P<0.0001: wave III, paired t_{test} = 3.05, df = 41, P<0.004: wave V, paired t_{test} = 7.96, df = 41 P<0.0001). The average reduction across all waveforms was ~34%, with waves I and V having the greatest amount of peak-to-trough amplitude reduction (41% and 39%, respectively).

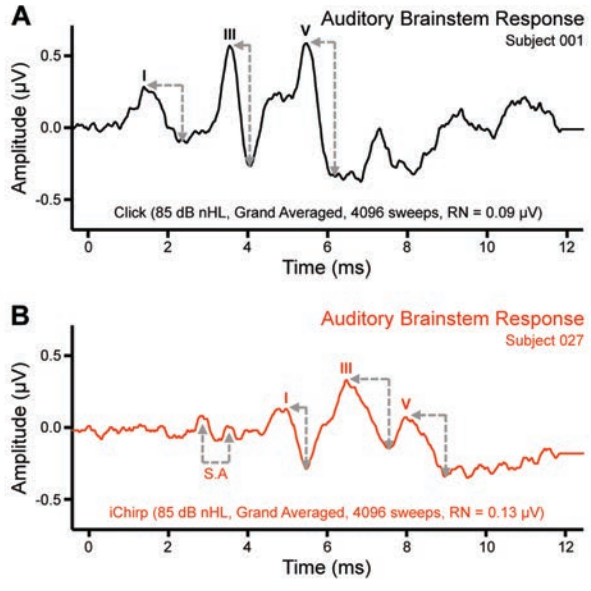

Figure 2. ABRs for Click and iChirp. Representative grand averaged (4098 sweeps) auditory brainstem responses (ABRs) recorded from two different subjects (001 and 027) using click (A, black trace) and iChirp (B, red trace) stimuli. Stimulus intensity = 85 dBnHL. Gray arrows represent selection of peak and trough components of Waves I, III, and V. RN = residual noise. In (B) upward gray arrows represent iChirp stimulus artifact (S.A.).

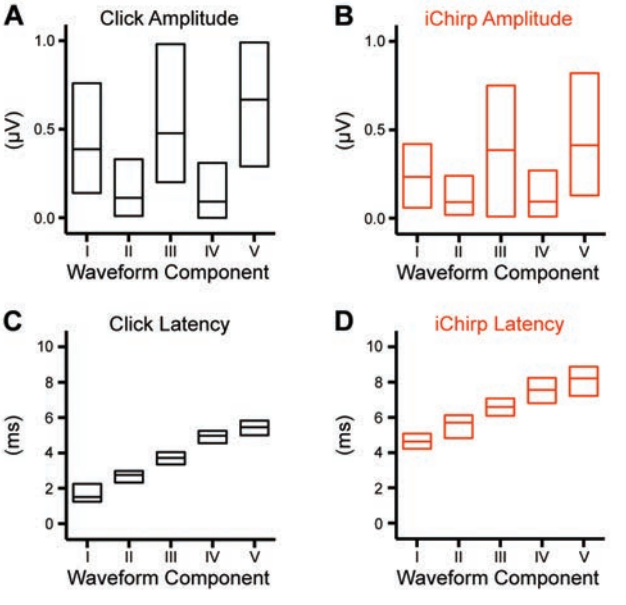

Figure 3. Normative ABR Data for Click and iChirp. Population data (n = 43) showing absolute peak-to-trough amplitudes of waves I-V for click (A, black boxes) and iChirp (B, red boxes) recorded at 85 dBnHL. Population data showing absolute latency values of wave I-V for click (C, black boxes) and iChirp (D, red boxes) recorded 85 dBnHL. Box plots represent the mean (middle line) and range of data values (top and bottom = maximum and minimum, respectively).

Signal and noise analysis of ABRs to Click and iChirp

Based on the above results, we suspected that the SNR would be smaller for the iChirp-evoked ABR. Indeed, the average SNR for the iChirp was significantly smaller (paired t_{test} = 3.69, df = 42, P<0.001), but surprisingly, the RN was not statistically different from click (paired t_{test} = 0.35, df = 42, P=0.72: Figure 6A and B). Across the population, we found a significant correlation between the evoked response and noise; recordings with high SNRs had low RN levels (and *vice versa*). This result was consistent for both stimuli (Figure 6C and D). These results suggest that the iChirp does not create unwanted physiological noise during the recordings and both stimuli produced equally low RN levels. However, there was no significant relationship discovered between the click and iChirp RN levels (Figure 6E and D). That is, a high click RN level does not result in an equally high iChirp RN level within the same subject (and *vice versa*).

Discussion

In the current study we addressed two primary questions. First, is the iChirp-evoked wave V amplitude of the ABR larger than those obtained using broadband click stimulation? Consistent with previous reports, we predicted that iChirp responses would yield a larger peak-to-trough wave V amplitude. One caveat to this prediction however is dependent on the intensity level used to elicit ABRs and the type of chirp used. It is well documented that diverse chirp stimuli are better at maintaining a larger wave V

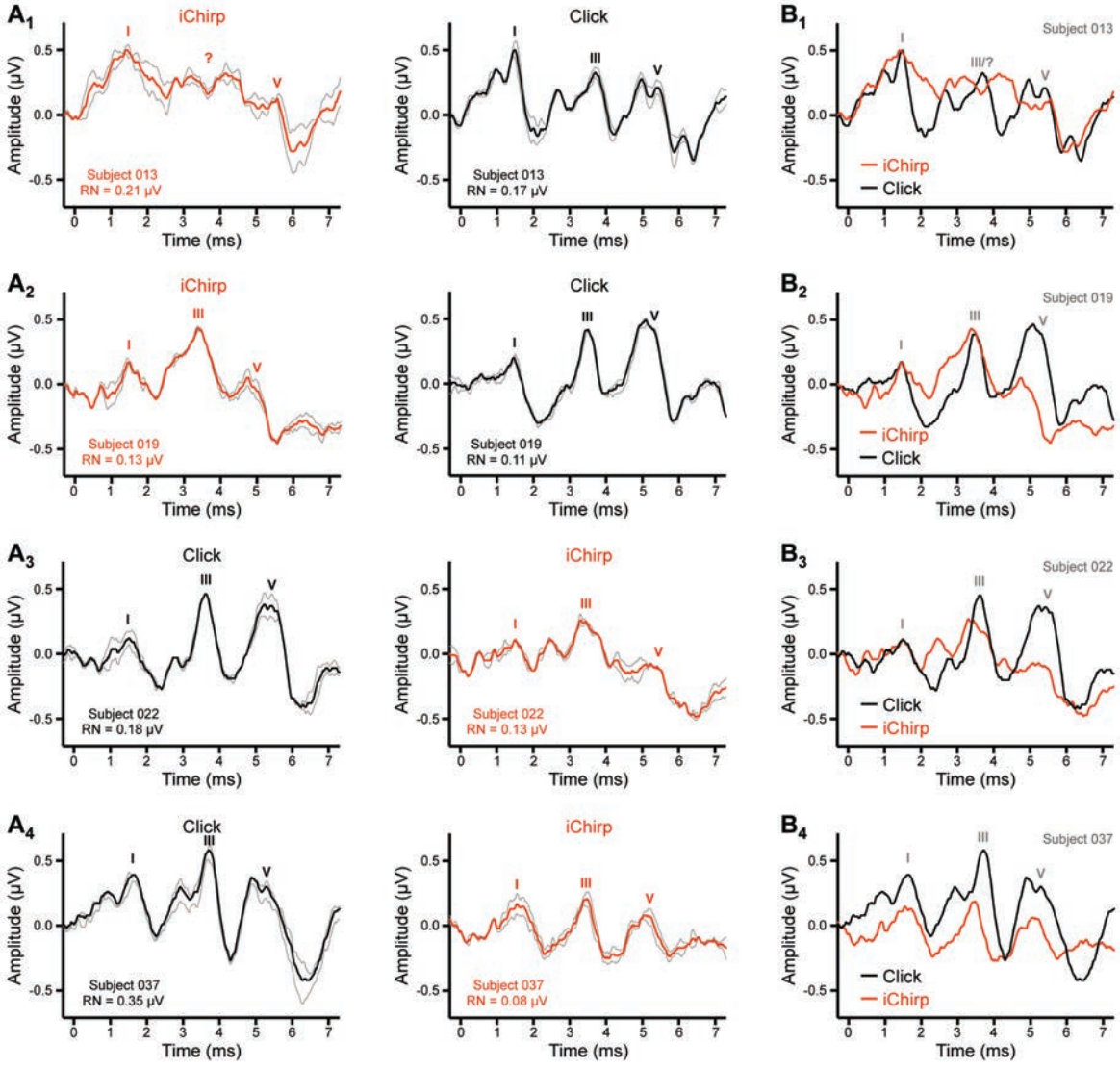

Figure 4. Qualitative Differences in ABRs to Click and iChirp. (A1-4) Representative ABRs recorded from four different subjects (013, 019, 022, 037) in the order that the stimulation paradigm was delivered. Grand averaged traces (4096) are bold. Red traces = iChirp stimulation and black traces = click stimulation. Gray traces = 2 runs of 2048 sweeps. RN = residual noise. (B1-4) Superimposed ABR traces from the subjects in (A) comparing waveform morphology differences in ABRs to click (black traces) and iChirp (red traces) stimulation (within-subject design). Stimuli artifacts (time = 0 ms) removed and iChirp wave I latency adjusted to match click wave I responses. Peak amplitudes of Waves I, III and V are labeled for qualitative comparison purposes.

amplitude than click near audiometrically confirmed behavioral thresholds, providing a more reliable objective measure of hearing sensitivity (Table 1). However, little has been reported - or conflicting results have dominated - on the usefulness of any chirp at high intensity levels (> 60 dB)[21] especially for the commercially available iChirp used in the current study.

Second, are early waveform components of the ABR (*i.e.*, waves I-III) identifiable for iChirp and if so, are their amplitudes larger and more reliable than click responses? Surprisingly, these waveforms have been largely unexplored with chirp stimuli in general (Table 1), and the few studies that have evaluated them report discrepancies in identifying these early components.[22-24] For purposes of neurodiagnostic testing, early waveforms are essential for differentiating pathophysiologies of the auditory nerve *versus* more central auditory brainstem structures.[25,26] To address these questions, we investigated differences in ABR waveform latencies and amplitudes between iChirp and click stimuli. Both stimuli were fixed at 85 dBnHL and were randomly presented to the right ears 43 normal hearing young adults.

Reduction in wave V amplitude to chirp stimulation at a high intensity level

The iChirp was designed to offset the time delay of the base-to-apex traveling wave that occurs along the cochlear partition.[17] In theory, delaying the high-frequency component of the stimulus - relative to its low frequency segment - permits displacement along the basilar membrane to occur simultaneously, increasing neural synchrony. This opposes normally asynchronous activity of the auditory periphery often elicited by brief, broadband stimuli, such as clicks. Since the advent of the chirp, better neural synchrony has been interpreted by the enhancement of evoked responses, typically an increase in the peak-to-trough amplitude of wave V.

Although this is true for intensity levels < 60 dB, only one recent study reported a larger wave V amplitude with chirp stimulation > 80 dB.[13] A confounding issue in this study compared to the current work, is that the authors used a different type of chirp, known as the M-Chirp (discussed further below). We report the opposite when the iChirp is used at a high intensity level. Our data in Figures 4 and 5 clearly show a significant reduction in wave V amplitude compared to click delivered at the same intensity level. This reduction was on average ~34% both within subjects and across the population tested. These findings are in agreement with Rodrigues and Lewis (2012)[24] who found that although chirp stimulation yielded larger wave V amplitudes at intensities < 60 dB, click was superior > 80 dB. Another study by Kristensen and Elberling (2012)[23] further support our findings. They reported that for all intensity levels tested, the amplitude of the ABRs to different chirp stimuli were significantly larger than click. The exception however was for intensity levels at 80 dB, where the ABR to the CE-Chirp was distorted and smaller in amplitude compared to click. It should be noted that the iChirp used in the current study is similar to the CE-Chirp reported in their study. The authors for both of these studies concluded that when chirp is used, there is a broadening of sound wave propagation along the cochlear partition at high intensity levels. This likely affects regions along basilar membrane to respond in an asynchronous manner and results in reduced amplitudes. This is clearly a limitation of the CE-Chirp at high intensity levels, and the current study using the iChirp supports this observation. Efforts are being made to overcome this limitation by constructing a short duration chirp that is *level-dependent*.[12] The level-dependent chirp (LS-Chirp) takes into account the sound wave travel time along the cochlear partition in an intensity dependent manner, providing better neural synchrony. Recently it was shown that indeed the LS-Chirp results in larger

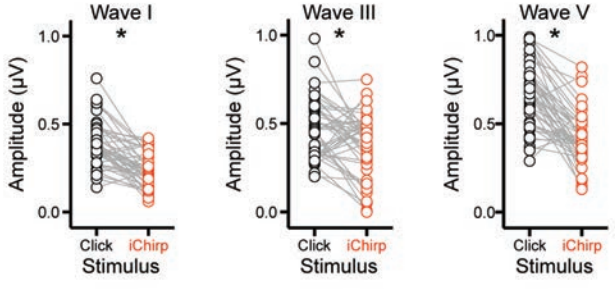

Figure 5. Amplitude differences in ABRs to Click and iChirp. Population data (n = 43) showing individual comparisons between Waves I, III, and V using click (black circles) and iChirp (red circle) stimulation. *Statistical significance (P<0.05) obtained from parametric paired t-tests.

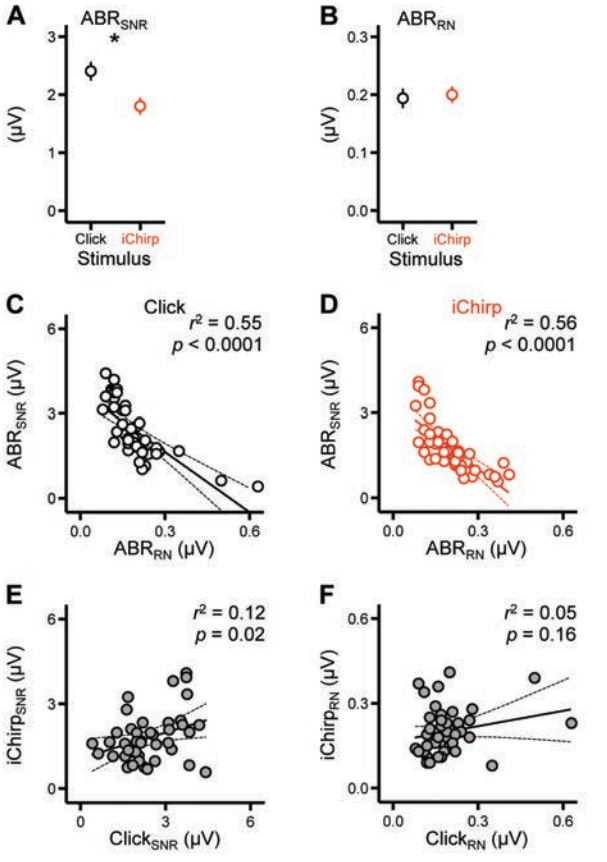

Figure 6. Signal and noise analysis of ABRs to Click and iChirp. A) Population data (n = 43) showing the average ABR signal-to-noise ratio (SNR) and residual noise (B) for click and iChirp stimulation. *Statistical significance (P<0.05) obtained from parametric paired t-tests. Population data showing the correlation analysis between the ABRSNR and ABRRN for click (C) and iChirp (D) stimulation. Population data showing the correlation analysis between iChirp (E) and click (F) residual noise levels. Statistical significance (p values) are reported and obtained from linear regression analysis (r2). Solid/dashed lines = regression slope and 95% confidence intervals, respectively.

wave V amplitudes when compared to the traditional click stimulus.[23] Until commercially available however, click stimuli should remain standard when testing at neurodiagnostic levels.

Reduction in waves I and III to chirp stimulation at a high intensity level

The early waveform components of the ABR have important diagnostic value. For example, the latency and amplitude of wave I - which represents synchronous firing of distal afferent auditory nerve fibers - provide a foundation of comparison for many neural pathophysiological conditions. These include but are not limited to sensory/neural hearing loss, auditory neuropathy, vestibular schwanomma, Meniere's disease and recently hidden hearing loss.[25-27] Stimuli designed to enhance the early waveforms are critical for clinical decisions. It has been previously reported that there is a reduction and or absence in waves I and III when chirp is used at high intensity levels.[24] Kristensen and Elberling (2012)[23] reported that the identification of waves I and III varied immensely and were not always identifiable. Rodrigues and Lewis (2012)[24] also reported that at > 80 dB, waves I and III tended to disappear when using chirp. Our data from the current study show that although there was on average, a 41% and 29% reduction in waves I and III respectively, we were able to identify these early components in nearly all recordings using the iChirp (Table 2); albeit the overall waveform quality was consistently poorer. The discrepancy in the results between the aforementioned studies and the current one are unclear but could be explained by the type of chirp used (discussed further below). Nonetheless, reduced or absent amplitudes of waves I and III are noted limitations of the iChirp and clinicians should be aware of both its potential and shortcomings in ABR testing.

Temporal and morphological considerations

In line with reduced amplitudes is the observation of decreased reliability and poorer waveform morphology with the iChirp. Figures 3 and 4 and Table 2 show that absolute peak latencies were less reliable for iChirp [as evident from the range of occurrence (Figure 3) and the variance of responses (Table 2)]. In addition, the observation within subjects clearly shows poorer qualitative waveform morphology (Figure 4). We speculate that at high intensity levels, iChirp-evoked responses not only hinders neural synchrony but also leads to poorer temporal resolution (latency variability) and waveform quality. It should be noted that although absolute peak latency variability was higher for iChirp, interpeak latencies were shorter than click. This was most evident for interpeak latency between waves III-V and I-V, suggesting a possible *compensation* of synchronized neural activity from more central auditory brainstem structures.

Residual noise consideration

One possible confounding issue of the current study, with respect to the observed differences in ABRs to click and iChirp, is the idea that iChirp responses were more susceptible to endogenous (*i.e.*, physiological) noise. To explore this, we analyzed the SNR and RN levels of both stimuli. As expected, the SNR for click responses were significantly better than iChirp. Surprisingly, the RN levels were nearly identical for the two stimuli (Figure 6B). Although there were significant correlations between high SNR and low RN levels for both stimuli, this observation did not hold true when SNRs and RNs levels were compared between the two stimuli. In other words, a high RN level obtained from the click stimulation did not result in a high RN level for the iChirp recorded from the same subject (and *vice versa*). We conclude that the acoustic properties of the iChirp did not cause excessive physiological noise and that RN levels within stimulus recordings did not contribute to the amplitude differences seen in the ABRs.

Additional consideration

Another potential confounding issue of the current study relates to the differences between the click and iChirp spectral responses. For the current study, coupler measurements showed a marked increase in spectral energy above 800 Hz with about equal reduction below this frequency for the iChirp acoustic output (Figure 1C). These energy differences were not compensated for in the study because the overall goal was to compare stimuli using standard, commercially available evoked potential equipment. In addition, previous research has shown that variation in the chirp spectral-temporal characteristics has a profound effect across waveform amplitudes in an intensity dependent fashion.[12] It should be noted that depending on the equipment used to obtain neurodiagnostic ABRs, clinicians should be aware of the type of chirp available and the possible limitations and benefits it provides.

Conclusions

At high intensity levels, the traditional broadband click stimulus produces more reliable latencies and significantly larger amplitudes for all ABR waveforms than iChirp. We suggest that for high intensity stimulation, the low frequency component of the iChirp interferes with basal cochlear regions and impedes afferent neural synchrony, resulting in compromised ABRs. We conclude that for retrocochlear evaluations of the auditory pathway, click stimuli should be continuously used as the standard for ABR neurodiagnostic testing.

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