A direct approach for the design of chirp stimuli used for the recording of auditory brainstem responses

Claus Elberling^{a)}

William Demant Holding A/S, Kangebakken 9, DK-2765 Smørum, Denmark

Manuel Don

Electrophysiology Laboratory, House Ear Institute, 2100 West 3rd Street, Los Angeles, California 90057

(Received 29 April 2010; revised 21 August 2010; accepted 23 August 2010)

A recent study evaluates auditory brainstem responses (ABRs) evoked by chirps of different durations (sweeping rates) [Elberling *et al.* (2010). *J. Acoust. Soc. Am.* **128**, 215–223]. The study demonstrates that shorter chirps are most efficient at higher levels of stimulation whereas longer chirps are most efficient at lower levels. Mechanisms other than the traveling wave delay, in particular, upward spread of excitation and changes in cochlear-neural delay with level, are suggested to be responsible for these findings. As a consequence, delay models based on estimates of the traveling wave delay are insufficient for the design of chirp stimuli, and another delay model based on a direct approach is therefore proposed. The direct approach uses ABR-latencies from normal-hearing subjects in response to octave-band chirps over a wide range of levels. The octave-band chirps are constructed by decomposing a broad-band chirp, and constitute a subset of the chirp. The delay compensations of the proposed model are similar to those found in the previous experimental study, which thus verifies the results of the proposed model.

© 2010 Acoustical Society of America. [DOI: 10.1121/1.3489111]

PACS number(s): 43.64.Qh, 43.64.Bt, 43.64.Ri [BLM]

Pages: 2955–2964

I. INTRODUCTION

A. The chirp design

Chirp stimuli are designed to compensate for the time delay in the auditory periphery in an attempt to increase the temporal synchrony between the neural elements that normally are asynchronously activated by a brief stimulus such as a click. Chirps have been applied in a variety of experimental studies (for a review see e.g., Fobel and Dau, 2004, Elberling *et al.*, 2007a, and Elberling and Don, 2008), and are designed using suitable models of the cochlear-neural delay. These models attempt to describe the time delay, as a function of frequency, between an acoustic stimulus at the tympanic membrane and the neural activity in the auditory nerve or the brain stem. Due to the increased temporal synchrony, a chirp generates, in general, significantly larger compound neural responses than a click. Repeatedly this has been shown for the auditory brainstem response (ABR) by e.g., Lütkenhöner *et al.* (1990), Dau *et al.* (2000), Fobel and Dau (2004), Elberling *et al.* (2007a), Elberling and Don (2008), and Elberling *et al.* (2010).

Compensation for the time delay can in principle be obtained in two different ways: either by input compensation using the chirp ABR, or by output compensation using the Stacked ABR as described by e.g., Don *et al.* (1994). Previously we have discussed and compared these two compensation methods (Don *et al.*, 2009).

At the outset, most previous chirp experiments have focused on the delay model and used information from differ-

ent sources for its mathematical formulation. Delay models have been applied based on a linear description of the mechanical properties of the cochlea (de Boer, 1980), tone-burst ABR latencies (Neely *et al.*, 1988), stimulus-frequency otoacoustic emission latencies (Shera and Guinan, 2000), and derived-band ABR latencies (Don *et al.*, 1998); see e.g., Fobel and Dau (2004) and Elberling *et al.* (2007a).

Most of the delay models result in chirps that are independent of stimulus level. However, the tone-burst ABR latency model (Neely *et al.*, 1988) describes a change in latency as a function of frequency that is significantly dependent on level. Using this delay model, Fobel and Dau (2004) constructed a series of chirps (called the A-chirp) having progressively longer duration the lower the stimulus level. The results showed that the level-dependent A-chirp evoked ABRs with larger amplitudes than two other chirps having level-independent waveforms. In a follow-up on this interesting finding, Elberling *et al.* (2010) evaluated five different chirps (chirp 1–5), which systematically changed duration with the chirp number. In response to these chirps, ABRs were recorded at three stimulus levels in 10 normal-hearing test subjects (20 ears). The results showed a significant level effect, because at high stimulation level (60 dB nHL) the largest ABRs were evoked by the shorter chirps, whereas at low levels (20 dB nHL) the largest ABRs were evoked by the longer chirps. To explain these findings, the authors suggested that two different mechanisms influenced chirp efficiency: upward spread of excitation at higher levels, and an increased change of the cochlear-neural delay with frequency at lower levels.

The main objective of previous studies has been to construct chirps which, compared to a click, results in higher

^{a)}Author to whom correspondence should be addressed. Electronic mail: ce@demant.dk

neural synchrony and, therefore, generates larger neural responses of, for instance, the ABR. If, however, other characteristics than the cochlear traveling delay are necessary to consider (e.g., upward spread of excitation), then the delay models are inadequate either when they are based on (1) linear mechanical properties of the cochlea (e.g., implemented by [Dau et al., 2000](#), using the model by [de Boer, 1980](#)), (2) otoacoustic emission latencies (e.g., implemented by [Fobel and Dau, 2004](#), using the data from [Shera and Guinan, 2000](#)), or (3) derived-band ABR latencies (e.g., implemented by [Elberling and Don, 2008](#), using the data from [Don et al., 1998, 2005](#)). The delay model based on tone-burst ABR latencies (e.g., by [Neely et al., 1988](#)) involves both the cochlear traveling delay and any other mechanism that affects the observed latencies of the ABR, as pointed out by [Gorga et al. \(1988\)](#). However, as discussed later, it is difficult to describe the link between the level and timing of the tone-bursts and the final chirp, and therefore this delay model is difficult to apply adequately.

Another delay model can be established from latencies of ABR recordings to frequency-specific stimuli that are obtained by decomposing the broad-band click. This approach, which here is named *the direct approach*, is described in the following.

B. The direct approach

This approach uses the latencies of ABRs obtained in response to a series of frequency-specific stimuli that are formed by decomposing the click stimulus. The hypothesis behind the approach is, that if a frequency-specific stimulus generates an ABR with a latency that is delayed by x [ms], compared to the latency in response to the click, this frequency-specific stimulus, which is a sub-component of the click, should be shifted back in time by x [ms]. When similar latency adjustments are made for a number of different frequency-specific stimuli, and for all relevant levels, then theoretically, for each level, all the frequency-specific ABRs will be temporally aligned. In response to the resulting broad-band stimulus (a modified click), the neural synchrony will be increased. In this way the correct delay-compensation can be approximated for all stimulus levels.

In order to realize this approach experimentally, the frequency-specific stimuli shall have non-overlapping frequency bands and together cover the frequency range of interest. In other words, because the frequency-specific stimuli are obtained by decomposing the click, their sum reconstructs the waveform of the click. Ideally, the frequency-specific stimuli should be made not by decomposing the click but by decomposing a chirp which has an almost correct delay-compensation for the level that is investigated. Unfortunately, the correct delay-compensation is unknown and the approach needs therefore to be recursive. However, instead of an extended experiment with several recursive loops, a shortcut might be feasible if an approximately correct delay-compensation is used as a starting point.

As explained below, a pool of ABR data is available from ABRs in response to frequency-specific chirps over a large range of levels and with technical characteristics that

fulfill the requirements stated above. The delay model that is used as a starting point to generate the frequency-specific chirps is close to the one used by [Elberling and Don \(2008\)](#), which is demonstrated to provide, on the average, the best single delay-compensation for the levels 60, 40 and 20 dB nHL by [Elberling et al. \(2010\)](#).

C. The aims of the present study

The present study attempts to formulate a delay-compensation, as a function of stimulus level, for the design of new chirp stimuli. At each level, the delay-compensation will optimally synchronize the ABRs in response to frequency-specific stimuli which constitute a subset of the chirp. Available ABR latency data, which are obtained in different clinical settings, are used as a basis for developing the direct approach described above. The results will be compared with the experimental data obtained by using different chirps that systematically change duration at three levels of stimulation ([Elberling et al., 2010](#)).

II. AVAILABLE DATA

At three university clinics located in South America, in North America and in Scandinavia, ABRs were collected from normal-hearing test subjects with a beta-version of a software module running on the Interacoustics Eclipse EP25 ABR-system[®]. Besides the traditional ABR stimuli (click and tone-burst), this software incorporates a series of five clinical stimuli consisting of a broadband Chirp (called the CE-Chirp) and four frequency-specific, octave-band chirps ([Elberling et al., 2007b](#)). Details of these stimuli are given in the following.

A. Designing the clinical chirp stimuli

The broad-band CE-Chirp is designed as described by [Elberling et al. \(2007a\)](#) using a delay model based on derived-band ABR latencies (the ‘Don-data’). Mathematically this delay model is formulated as a power function

$$\tau = k \cdot f^{-d}, \quad (1)$$

where τ is the delay in seconds, f is the frequency in Hertz, and k and d are constants having the values, $k=0.0920$ and $d=0.4356$. It should be noted, that the model describes the delay between the stimulus at the tympanic membrane and wave I of the ABR because the wave I-V difference of 4.1 ms ([Elberling and Parbo, 1987](#)) is subtracted from the derived-band latencies prior to curve fitting to the power function model [Eq. (1)], see [Elberling et al. \(2007a\)](#) and [Elberling and Don \(2008\)](#).

The chirp used by [Elberling and Don \(2008\)](#) and the chirps subsequently used by [Elberling et al. \(2010\)](#), were designed from variants of the same power function model [Eq. (1)], with amplitude spectra, which were identical to that of a standard 100 μ s click and limited to the frequency range from 200 to 10 000 Hz.

Contrary to this, the new broad-band CE-Chirp, as implemented in Interacoustics EP25[®], is designed electrically to have a flat amplitude spectrum within five octave-bands ranging from 350 to 11,300 Hz (approx. -3 dB

FIG. 1. Amplitude-frequency characteristics of the filters used for the design of the broad-band CE-Chirp and the four octave-band chirps. The basic filter characteristics follow the specification for octave-band filters (class 1) given in IEC 61260 (1995). The amplitude spectra of the electrical waveforms of the stimuli are similar to the filter characteristics, whereas the acoustical spectra will be modified by the characteristics of the chosen earphone and the ear simulator in which the acoustic output is measured. See the text for further explanation.

points) and with a lower and higher amplitude-frequency roll-off corresponding to the lower part of a 500 Hz octave-band filter and the higher part of a 8000 Hz octave-band filter respectively. Four octave-band filtered versions of the CE-Chirp are also implemented with the center frequencies 500, 1000, 2000, and 4000 Hz.¹ The octave-band chirps are thus obtained by decomposing the broad-band CE-Chirp into four components that constitute a subset of the CE-Chirp. The octave-band filters used to construct the broad-band CE-Chirp and the frequency-specific chirps have amplitude-frequency characteristics in accordance with the specifications given in IEC 61260 (1995) for octave-band filters (class 1) as shown in Fig. 1, and with zero phase shifts.

The CE-Chirp and the four octave-band chirps are designed using the frequency domain method described in detail by Elberling *et al.* (2007a). This method allows the amplitude and phase of each harmonic frequency (given by the stimulus repetition rate) to be adjusted independently. By adjusting the amplitude of the harmonics the final stimulus can be designed to produce a flat, a rising, or a falling amplitude spectrum, to compensate for the amplitude response of the earphone or other parts of the sound transmission system, or to design frequency specific stimuli – such as the present octave-band chirps. By adjusting the phase of the harmonics the final stimulus can be designed to produce a specific phase spectrum – for instance to compensate for the cochlea traveling delay or to compensate for the phase response of the earphone.

The final chirp stimuli and their envelopes (calculated via the Hilbert transform) are shown in Fig. 2. In the figure, the octave-band chirps are displayed with the amplitudes by which they appear in the broad-band CE-Chirp. The zero point on the time axis corresponds to the frequency of 10 000 Hz in the underlying delay model. For the recording of ABRs, with this beta-version of the software, the zero point corresponds to the estimated time of arrival at the tympanic membrane of the 10 000 Hz component in the broad-band CE-Chirp. The zero point corresponds to the starting point (0

FIG. 2. The waveform and envelope of the broad-band CE-Chirp and the four octave-band chirps are shown. All five stimuli are plotted using the same (arbitrary) amplitude scale (in digital units, d.u.). The individual levels (in dB nHL), by which each of the octave-band stimuli contributes to the broad-band chirp at 60 dB nHL, are indicated to the right (see also Table 1). The zero point (0 ms) corresponds to the temporal location of the 10 000 Hz component of the CE-Chirp. See the text for further details.

ms) of the ABR recordings, and constitutes the temporal reference for the measurement of the ABR latency.

B. ABRs to the CE-Chirp and frequency-specific chirps

1. Subjects

The combined group of test subjects from the three different laboratories consists of 25 normal-hearing young female and male subjects. For each ear ($N=48$), the pure-tone threshold is equal to or better than 10 dB HL for the frequencies 500 to 4000 Hz and equal to or better than 15 dB HL for 6000 and 8000 Hz.

In the three laboratories the testing is carried out in accordance with approvals by the local Institutional Review Boards (IRBs). Prior to the testing, the test subjects are given an explanation about the purpose of the study and details of the test, and all remaining questions the test subjects have regarding their participation in the study are subsequently addressed. Finally, all test subjects read and sign an informed consent form.

2. Stimuli

The five chirp stimuli are presented with alternating polarity through ER-3A earphones (EAR-3A) at a rate of 27/s. The test levels are: 10, 20, 30, 40, 60, and 80 dB nHL. The five chirp stimuli are calibrated in dB nHL using the occluded ear simulator, IEC 60711 (1981), and calibration values (dB p-p.e.RETSPL) obtained from a group of 25 normal-hearing individuals in accordance with the recommendations put forward in ISO 389-9 (2009). The calibration values for the five chirp stimuli are provided by PTB

TABLE I. Calibration levels. Row (a): calibration values for the ER-3A earphone in the occluded ear simulator (IEC 60711, 1981). Row (b): electrical pp-values (mV) at the earphone terminals for each stimulus at 60 dB nHL. Row (c): values in Row (b) relative to the CE-Chirp (dB). Row (d): numerical pp-values (digital units, d.u.) of the original stimulus waveforms. Row (e): values in Row (d) relative to the CE-Chirp (dB). Row (f): Level of the octave-band stimuli relative to the CE-Chirp (dB) [=Row(e)–Row(c)]. Row (g): Level of the octave-band stimuli (dB nHL) corresponding to a chirp level of 60 dB nHL.

		CE-Chirp	500 Hz	1000 Hz	2000 Hz	4000 Hz
a	ER-3A calibrated in IEC60711					
	peRETSP (dB p.-p.e.SPL)	32.0	26.5	24.5	30.5	35.0
b	electrical p-p value at 60 dB nHL (mV)	140	118	84	98	130
c	p-p value re CE-Chirp (dB)	0.0	–1.5	–4.4	–3.1	–0.6
d	numerical p-p value (d.u.)	1000	110	216	406	673
e	p-p value re CE-Chirp (dB)	0.0	–19.2	–13.3	–7.8	–3.4
f	level re CE-Chirp (dB)	0.0	–17.7	–8.9	–4.7	–2.8
g	CE-Chirp at 60 dB nHL (dB nHL)	60.0	42.3	51.1	55.3	57.2

(Physikalisch-Technische Bundesanstalt, Braunschweig, Germany) and are shown in Table I.

3. ABR recordings

The test subjects are placed on a couch either in an ordinary, silent test room, or in a sound-treated and electrically shielded booth. The electrophysiological signal is picked up differentially between an electrode on the mid-frontal area (F_z) and an electrode on the ipsilateral mastoid (M_1 or M_2); an electrode at the lower mid-frontal area (F_{pz}) is used as ground. The electrophysiological signal is band-pass filtered from 100 to 3000 Hz (12 dB/octave). During the recording sessions an estimate of the level of the physiological background noise is continuously updated (Elberling and Don, 1984), and the ABRs are obtained by weighted averaging (Elberling and Wahlgreen, 1985). The averaging is terminated when the estimated residual background noise is 40 nV (rms) or less (Don and Elberling, 1994).

4. ABR results

Due to the following reasons ABRs are not obtained from all ears for all stimuli and levels (see Table II). Although the same test protocol is used at all three laboratories it is not required that all combinations of stimuli and level are collected in each individual test subject or ear. Therefore, only the ABRs to the broad-band CE-Chirp are obtained in all test ears ($N=48$) for all levels except the lowest one (10 dB nHL, $N=36$). However, the test time that is available for the individual test subject often limits the number of recordings that can be obtained for the octave-band chirps. Some of the laboratories give priority to the lower stimulus levels and therefore a limited number of recordings are obtained at 60 and 80 dB nHL. The limited test time also precludes reliable responses to be obtained at 10 dB nHL for the 500 and 1000 Hz octave-band chirps.

In each recorded ABR the most salient response peak (wave V) is identified and its latency measured. The hypothesis, that the latencies in each condition (stimulus and level) are Gaussian distributed, cannot be rejected by the Kolmogorov-Smirnov test (Siegel, 1956). Therefore the data in each condition are described by the sample mean and standard deviation, as shown in Table II, together with the num-

ber of ears underlying the data in each condition.² For each of the five stimuli the mean latency values are plotted as a function of level (dB nHL) in Fig. 3(a). Despite the limited number of recordings in response to the octave-band chirps at 60 and 80 dB nHL, statistical analysis suggests that the corresponding values in Table II are representative of the population of all 48 test ears.³

Each of the octave-band chirps has a timing that corresponds to its temporal location within the broad-band CE-Chirp – as shown in Fig. 2. Combined with the chosen latency reference (0 ms), which deviates from stimulus onset, the observed ABR latencies for the low frequency stimuli (500 and 1000 Hz), are much shorter than normally seen in corresponding tone-burst ABRs [see Fig. 3(a) and Table II].

TABLE II. ABR latency in [ms] (mean and standard deviation, SD) for the broad-band CE-Chirp and the four octave-band chirps, 500, 1000, 2000, and 4000 Hz, as a function of level in dB nHL. For each condition the number (N) of the underlying recordings (ears) are indicated. For the octave-band chirps, 500 and 1000 Hz at 10 dB nHL the mean latency values (*italics*) are estimated (see text and footnote ² for further details). The mean values are plotted in Fig. 3(a).

Stimulus level (dB nHL)		10	20	30	40	60	80
CE-Chirp	Mean	7.01	6.42	5.79	5.17	3.93	2.85
	SD	0.49	0.36	0.35	0.40	0.62	0.84
	N	36	48	48	48	48	48
4000 Hz	Mean	7.23	6.39	5.88	5.36	4.43	3.78
	SD	0.58	0.35	0.59	0.52	0.17	0.21
	N	25	27	28	29	14	14
2000 Hz	Mean	7.06	6.37	5.70	5.03	3.91	2.89
	SD	0.67	0.54	0.44	0.38	0.31	0.50
	N	21	29	29	29	14	14
1000 Hz	Mean	7.90	6.88	6.00	5.21	3.00	2.19
	SD	...	0.72	0.69	0.81	0.32	0.56
	N	...	25	27	27	13	13
500 Hz	Mean	8.00	6.19	4.87	3.90	1.36	0.74
	SD	...	1.22	1.08	1.15	0.64	0.46
	N	...	20	22	23	12	12

FIG. 3. Graphs show the ABR-latency as a function of stimulus level for each of the four octave-band chirps. (a) The x-axis refers to the level of the individual octave-band chirp in dB nHL (from Table II). The broken parts of the curves for 500 and 1000 Hz indicate where estimated values are applied. (b) The x-axis refers to the level of the broad-band CE-Chirp in dB nHL (from Table III). The differences between the longest and shortest latency are plotted for 30, 40, 50, and 60 dB nHL (Table III) together with a continuous estimate (broken curve) of the latency difference as a function of level.

For the low-frequency stimuli at high levels (>50 – 60 dB nHL) where upward spread of excitation starts to kick-in and dominate the response latencies, this is especially apparent (see the discussion by Elberling *et al.*, 2010).

III. NEW DELAY-COMPENSATION

A. Further analysis

Our objective is now to determine the ABR latencies for the octave-band chirps presented at the levels they have within the broad-band CE-Chirp. Therefore, we first have to estimate these levels (in dB nHL), and this is done as described in the following (see Table I).

- (1) At 60 dB nHL, the p-p values of the electrical waveforms of the five stimuli are measured across the terminals of the earphone during the acoustic calibration. The p-p amplitudes (mV) and the corresponding dB-values relative to the CE-Chirp are given in Table I (row b and c).
- (2) The original waveforms of the five stimuli are represented in d.u. (digital units). Numerical calculations show that when the CE-Chirp has a p-p level of 1000 d.u., the four corresponding octave-band chirps will have p-p values and dB-values relative to the CE-Chirp as shown in Table I (row d and e).
- (3) When the two sets of dB-values in Table I are subtracted from each other ($=$ row e $-$ row c), the levels of the octave-band stimuli relative to the CE-Chirp can be found. These relative dB-values are shown in Table I (row f).
- (4) For example, for a CE-Chirp at 60 dB nHL, the levels of the octave-band chirps in dB nHL correspond to those listed in Table I (row g). In other words, the sum of the 500 Hz chirp presented at 42.3 dB nHL, the 1000 Hz

chirp at 51.1 dB nHL, the 2000 Hz chirp at 55.3 dB nHL, and the 4000 Hz chirp at 57.2 dB nHL will reconstruct the waveform of the broad-band CE-Chirp at 60 dB nHL, within the frequency range corresponding to the four octave bands, i.e., from 350 to 5650 Hz.⁴ Thus, with the levels given in this example, the four octave-band chirps constitute a subset of the broad-band CE-Chirp (at 60 dB nHL), as displayed in Fig. 2.

Next we estimate the ABR latencies to the octave-band chirps corresponding to the levels they have within the broad-band CE-Chirp. This is done in the following way. The latency curve for each octave-band chirp in Fig. 3(a) is shifted by the final relative dB-value in Table I (row f). Thus, the 500 Hz curve is shifted to the right by 17.7 dB, 1000 Hz by 8.9 dB, 2000 Hz by 4.7 dB, and 4000 Hz by 2.8 dB. The shifted latency curves are shown in Fig. 3(b), and the corresponding latency values, which are read off the curves in Fig. 3(a) (rounded to the nearest 0.05 ms), are listed in Table III.⁵

In Table III the difference between the longest and shortest latency is shown for each level and plotted in Fig. 3(b) at 30, 40, 50, and 60 dB nHL. A fourth-order polynomial⁶ is fitted to all difference values and shown in Fig. 3(b) by the broken curve in the interval from 30 to 65 dB. At a chirp level around 45–50 dB nHL the four octave-band chirps produce response latencies which differ by less than 0.4 ms. This implies that the delay model, from which the CE-Chirp is designed, at these levels efficiently aligns the ABRs evoked by the different octave-band chirps. However, the further one moves away from 45–50 dB nHL, toward higher or lower chirp levels, the less adequate the underlying delay model appears to be. At higher levels e.g., 80 dB nHL, the latencies of the responses to the octave-band chirps at 500 and 1000 Hz are too short, indicating that the compensation

TABLE III. ABR latency in [ms] (mean values) for the four octave-band chirps, 500, 1000, 2000, and 4000 Hz, as a function of level of the broad-band CE-Chirp in dB nHL. For the 500 Hz octave-band chirp at a chirp level of 20 and 30 dB nHL, and the 1000 Hz octave-band chirp at a chirp level of 20 nHL, the mean latency values (*italics*) are partly based on estimated values (see text and footnote ⁵ for further details). The difference between the longest and shortest latency at each level is shown in the last row. The values are plotted in Fig. 3(b).

Chirp level (dB nHL)	20	30	40	50	60	70	80
4000 Hz	6.55	6.00	5.50	5.00	4.55	4.15	3.85
2000 Hz	6.70	6.00	5.35	4.70	4.15	3.60	3.10
1000 Hz	<i>7.80</i>	6.75	5.90	5.10	3.90	2.90	2.45
500 Hz	<i>9.50</i>	<i>7.50</i>	5.85	4.65	3.60	2.15	1.20
Latency difference	2.95	1.50	0.55	0.45	0.95	2.00	2.65

should have been smaller, leading to a chirp of shorter duration. At lower levels, e.g., 20 dB nHL, the latencies of the responses to the octave-band chirps at 500 and 1000 Hz are too long, indicating that the delay-compensation should have been larger, leading to a chirp of longer duration.

B. The final delay models

In order to quantify the qualitative description above, the latencies obtained for the 4000 Hz octave-band stimulus are used as reference, and the differences between the latencies to each octave-band chirp and the corresponding 4000 Hz octave-band chirp are calculated for the chirp levels 20, 40, 60 and 80 dB nHL. These latency differences are shown in Table IV.

The delay model [Eq. (1)], which was used to design the broad-band CE-Chirp and the corresponding four octave-band chirps, has delay values at the four center frequencies as shown in the second column of Table IV. For each of the four levels the latency differences are added to the model delay and new sets of delay values are thus obtained, as shown in the right-hand-side column for each level in Table IV. The power function model [Eq. (1)] is fitted to the new

FIG. 4. Final new delay models corresponding to the chirp levels 20, 40, 60, and 80 dB nHL. The power functions are vertically offset to have a zero delay at 10 000 Hz. For comparison, the delay model that was used to design the CE-Chirp is also shown. For each model function the change of the delay with frequency (between 5700 and 710 Hz) is indicated.

delay values (goodness of fit, R^2 , between 0.96 and 0.99) and the resulting fitting constants (k and d) are shown in the last rows of Table IV.

Before the delay models are applied, each power function is offset to have zero delay at 10 000 Hz. The final, new delay models and the delay model used to design the CE-Chirp are shown in Fig. 4. For each model, the change of the delay with frequency (between 5700 and 710 Hz) is indicated. The original delay model is located between the new estimated model functions for 40 and 60 dB nHL (visually estimated around 45–50 dB nHL), in accordance with the predictions made from the adjusted latencies in Fig. 3(b). Finally, the chirps corresponding to the new delay models are calculated by using the frequency domain method (Elberling *et al.*, 2007a), and shown in Fig. 5.

The delay models are power functions as described above in [Eq. (1)],

TABLE IV. Model delay and latency differences in [ms]. The second column shows the model delay [Eq. (1)] using the original values of k and d indicated in the bottom of the column. For each chirp level (20, 40, 60 and 80 dB nHL), columns (3, 5, 7, and 9) show the latency differences between the individual octave-band stimuli and the 4000 Hz stimulus [the values in Table III and Fig. 3(b)]. For each chirp level, column (4, 6, 8, and 10) show the new delay values (=model delay+latency difference). The new delay values are fitted to the delay model [Eq. (1)] and the new fitting constants, k and d , are shown in the bottom of each column.

Chirp level (dB nHL)	20		40		60		80	
Model								
Stimulus	delay	Lat. diff.	New delay	Lat. diff.	New delay	Lat. diff.	New delay	Lat. diff.
4000 Hz	2.48	0.00	2.48	0.00	2.48	0.00	2.48	0.00
2000 Hz	3.36	0.15	3.51	-0.15	3.21	-0.40	2.96	-0.75
1000 Hz	4.54	1.25	5.79	0.40	4.94	-0.65	3.89	-1.40
500 Hz	6.14	2.95	9.09	0.35	6.49	-0.95	5.19	-2.65
Fitting constants								
k	0.0920		0.4606		0.1285		0.0471	0.0103
d	0.4356		0.6342		0.4784		0.3589	0.1743

FIG. 5. The waveforms of the chirps designed from the new delay models in Fig. 4 are shown. For comparison the CE-Chirp is also shown. All five chirps are plotted with an amplitude scale (in digital units, d.u.), which is three times larger than used in Fig. 2.

$$\tau = k \cdot f^{-d}, \quad (2)$$

with k and d being the fitting constants. In the new delay models the values of k and d (shown in Table IV for discrete chirp levels: 20, 40, 60 and 80 dB nHL) both change with stimulus level (L). This level dependence can mathematically be described by the following approximations:

$$k = k_1 \cdot e^{k_2 \cdot L}, \quad k_1 = 1.65 \quad k_2 = -0.0625, \quad (3)$$

$$d = d_1 \cdot L + d_2, \quad d_1 = -0.00755 \quad d_2 = 0.788 \quad (4)$$

(the four constants are specified with three significant digits).

The final level-dependent delay model can now be formulated as follows:

$$\tau = k_1 \cdot e^{k_2 \cdot L} \cdot f^{-(d_1 \cdot L + d_2)}, \quad (5)$$

where τ is the delay in seconds, f is the frequency in Hertz, L is the level in dB nHL and k_1 , k_2 , d_1 , and d_2 are constants given above in [Eqs. (3) and (4)].

C. Discussion

In the paper by Elberling *et al.* (2010) five chirps (chirp 1–5) are evaluated experimentally. The duration of the five chirps changes systematically with the chirp number, corresponding to a model delay (between 5700 Hz and 710 Hz) that varies as follows: 1.86, 2.56, 3.32, 4.14, and 5.04 ms. The results demonstrate that the largest ABR amplitudes are generated by chirp 5 (5.04 ms) at 20 dB nHL, by chirp 3 (3.32 ms) at 40 dB nHL, and by chirp 2 (2.56 ms) at 60 dB nHL (Elberling *et al.*, 2010, Figs. 4 and 6). With the direct approach, the present estimations of the delay-

FIG. 6. The waveforms of the octave-band chirps at 500, 1000, and 2000 Hz for the CE-Chirp (broken lines) and the Chirp 80 dB nHL (full line) are shown. All six stimuli are plotted with an amplitude scale (in digital units, d.u.), which is the same as used in Fig. 2. The zero point (0 ms) corresponds to the temporal location of the 10 000 Hz component of the CE-Chirp. See the text for further details.

compensations, which are supposed to produce maximal synchronization, are very close to the results from the previous experiment by Elberling *et al.* (2010). Thus, the largest synchronization is found at a delay-compensation corresponding to 5.25 ms at 20 dB nHL, to 3.51 ms at 40 dB nHL, and to 2.35 ms at 60 dB nHL. At 80 dB nHL, which is not tested experimentally by Elberling *et al.* (2010), a delay-compensation corresponding to 1.00 ms is found.

The present experiment is based on the suggestion that, instead of using a recursive experiment, a shortcut could be taken by using an adequate delay-compensation as a starting point. The chosen delay model is described to work reasonably well, as an average model, across the levels from 60 to 20 dB nHL (Elberling *et al.*, 2010). With this delay model used as a starting point, the present results are in agreement with the previous experimental findings, and are therefore judged to be reasonably accurate. At 80 dB nHL, however, the delay-compensation found by the direct approach deviates significantly from the delay model used as a starting point, as reflected in the striking difference between Chirp 80 dB nHL and CE-Chirp in Fig. 5. In order to evaluate the consequence of this difference, Chirp 80 dB nHL is decomposed into its subset of octave-band chirps and compared to the original octave-band chirps of the CE-Chirp (Fig. 2). For 500, 1000, and 2000 Hz, Fig. 6 shows the two sets of octave-band chirps, which are temporally located in accordance with the underlying delay models (Fig. 4), but only show subtle differences between corresponding waveforms. It is therefore probable that the delay model (CE-Chirp) also at 80 dB nHL, is a relevant starting point for the direct approach.

The direct approach demonstrates that the 500 Hz octave-band chirp, contained within the CE-Chirp, has a level that is about 18 dB lower than the level of the broadband chirp (in dB nHL). This means that 20 dB nHL is the lowest level at which the low frequency region of the cochlea (i.e., 500 Hz) is able to contribute to the broadband chirp ABR.

The derived-band latencies used to retrieve the previous delay model (Elberling *et al.*, 2007a, Elberling and Don, 2008, and Elberling *et al.*, 2010), show a large variation

FIG. 7. Estimated response latencies from ten ears to the octave-band chirps at the levels corresponding to the broad-band chirp model at 80 and 40 dB nHL. Each individual data set (i.e., the response latencies at 500, 1000, 2000 and 4000 Hz) are fitted to Eq. (1) and the fitted power functions are shown in the figure together with the new delay model at 80 dB nHL (left) and 40 dB nHL (right). The figure shows the variability across the ten ears, as well as the significant effect of level. In contrast to Fig. 4, the power functions here are not vertically offset to provide a zero delay at 10 000 Hz.

across the group of $N=81$ normal-hearing subjects (see e.g., Elberling and Don, 2008, Fig. 2). Therefore a similar variation is expected of the individual octave-band latencies relative to the new model described here. In order to present this visually the following calculations are made. From ten ears the individual octave-band latencies are estimated in the same way as described for the mean values in Figs. 3(a) and 3(b), and corresponding to the wide-band chirp levels 80 and 40 dB nHL. Each individual data set (i.e., the response latencies at 500, 1000, 2000 and 4000 Hz) are handled the same way as the mean data (Table IV) and then fitted to the power function model [Eq. (1)]. The fitted power functions are shown in Fig. 7 together with the new delay model at 80 and 40 dB nHL. The figure shows the expected variability across the ten ears, but also the significant level difference corresponding to the two different model functions.

The concept of the direct approach assumes that the ABR-latencies in response to the stimuli in the subset are independent of whether the stimuli are used alone (one at the time) or simultaneously in the broad-band chirp. During simultaneous stimulation, masking and interaction could possibly play a significant role and influence the latency of the responses to the individual stimuli. However, since the delay-compensations that are estimated in the present study are similar to those found experimentally, the difference in latency between the two modes of stimulation is probably not very large.

Unfortunately a complete data set is not available. The missing data in Table III at the lowest stimulus levels for the frequency-specific chirps at 500 Hz and 1000 Hz, are 'replaced' with values that are estimated from the fitted curves that are extrapolated visually. Consequently, the latency values for 1000 Hz at a chirp level of 20 dB nHL and 500 Hz at 20 and 30 dB nHL [Table III and Fig. 3(b)] are not measured but based, in part, on extrapolations from measured values obtained at higher levels. The magnitude of the errors introduced by using estimated instead of measured values is unknown. However, the shape of the fitted curves for 1000 Hz and 500 Hz in Fig. 3(a), indicates that the estimated values at

10 dB nHL are accurate within about ± 0.1 ms. In addition to this, of course, there is an overall uncertainty in the estimates corresponding to the observed variance (or SD) associated with the mean values in Table II.

The tone-burst ABR latencies described by Neely *et al.* (1988) constitute a model where the latency is presented as a function of frequency and level. In principle, the use of the results by Neely *et al.* (1988) also constitutes a direct approach. However, tone-bursts applied by Neely *et al.* (1988) are not obtained by decomposing a click or a chirp stimulus, and therefore, the use of this model in chirp designs poses two different problems. First, for the design of a specific chirp, what levels should be used of the different tone-burst stimuli in order to get the correct model latencies? (This is further discussed by Elberling *et al.*, 2007a). Second, what additional corrections of the latency data should be applied in order to align the timing of the tone-bursts to the timing of the corresponding frequency components in the chirp? Because the tone-bursts are not described as a subset of a click or a chirp, this delay model cannot, on the surface of it, be used by the direct approach.

In the direct approach described here, delay-compensations have been estimated to design a flat amplitude spectrum chirp (within the frequency range 350–11 300 Hz). If, for instance, a chirp was chosen with a sloping amplitude spectrum (e.g., -3 dB/octave) the estimated delay-compensations would be quite different from those presented here. The direct approach can describe the latencies as a function of frequency to be used in a delay model for the design of a chirp. However, provided that adequate band-limited stimuli are applied, the direct approach can be used to design chirps with any given amplitude spectrum.

The frequency domain method (Elberling *et al.*, 2007a) is used to design the chirp stimuli described in the present report, and, as mentioned above, the method is also well suited to compensate for the amplitude and phase characteristics of the earphone. In our previous experiments (Elberling and Don, 2008, and Elberling *et al.*, 2010) an ER-2 earphone was used. This earphone has a reasonable flat amplitude re-

sponse and a smooth phase response (and an almost flat group delay function), when measured in the occluded ear-simulator (IEC 60711, 1981). Contrary to this, the ER-3A earphone, which is used to obtain the ABR-latencies reported here, has an amplitude response that deviates significantly from being flat (especially in the frequency range above 4–5 kHz) and a rippled phase response (and therefore a rippled group-delay function). It would therefore be interesting to compare the differences between chirp ABRs recorded by the two different earphones and study the effect of introducing spectral compensation of the deviating frequency responses of the ER-3A.

IV. SUMMARY AND CONCLUSION

Chirps have been shown to evoke larger ABRs than clicks. However, the studies by [Fobel and Dau \(2004\)](#) and [Elberling *et al.* \(2010\)](#) indicate that cochlear mechanisms other than the traveling delay have to be considered (e.g., upward spread of excitation and changes in cochlear-neural delay with level) to optimize the chirp's advantage. An adequate delay model based on a direct approach that incorporates the influence of upward spread of excitation and changes in cochlear-neural delay with level is therefore proposed. This approach uses ABR-latencies from normal-hearing subjects recorded over a wide range of levels in response to frequency-specific stimuli, i.e., octave-band chirps, which are constructed by decomposition of a broad-band chirp. Decomposition means that the sum of the octave-band chirps equals the broad-band chirp and that the stimuli therefore, constitute a subset of the chirp. A pool of ABR-latencies is available from the recordings from 25 normal-hearing adults (48 ears) as a function of the level of each octave-band chirp in dB nHL. However, the direct approach needs to specify the levels by which each octave-band chirp contributes to the broad-band chirp. These levels are therefore calculated, the latency data re-specified as a function of the level of the broad-band chirp (in dB nHL), and the new model finally constructed. At different levels of stimulation, the new delay model provides estimates of the delay vs. frequency which the chirp should compensate for. These estimates are similar to those found in the previous experimental study ([Elberling *et al.*, 2010](#)). Because the results of the new model in this way are verified experimentally, within the range from 20 to 60 dB nHL, it is concluded that the new delay model, in this level range, will provide the most efficient chirp for the recording of ABRs in normal-hearing adults. It should be noted however, that the new model has not been verified experimentally at levels above 60 dB nHL. The level dependence of the new delay model is finally formulated.

ACKNOWLEDGMENTS

The authors want to thank the following individuals: Dóris Ruthi Lewis, professor, and Gabriela Ribeiro Ivo Rodrigues, PhD-student, Hearing in Children Center, São Paulo, Brazil, Todd B. Sauter, M.A., CCC-A UMass Memorial Medical Center, Worcester, MA USA, and Stefan Stenfelt, professor, Dept. of Clinical and Experimental Medicine,

Linköping University, Sweden, for providing the experimental data. The authors also want to thank Lau Crone Petersen, E.Eng., Interacoustics, Denmark, for providing the necessary electro-acoustic measurements, and finally Bue Kristensen, Director of External Affairs, Interacoustics, Denmark, for setting up the research protocol and organizing the collection of the experimental data from the clinical studies internationally. This project was supported in part by Grant No. 2R01 DC003592 (P.I. Manuel Don) from NIDCD at NIH.

¹Only four octave-band chirps, corresponding to 500, 1000, 2000, and 4000 Hz, are presently implemented in Interacoustics EP25. Recordings at other octave-bands, e.g., 8000 Hz, can therefore not be measured with this equipment. However, the latency values at the four frequencies are judged to be sufficient to obtain reliable fitting functions according to the power function model described in Eq. (1).

²In Table II, the mean values for 500 Hz and 1000 Hz at 10 dB nHL (shown in italics) are based on visually extrapolated spline-functions, which are fitted to the measured latencies at higher levels [see Fig. 3(a)]. Spline-functions refer to a wide class of functions that are used in applications requiring data interpolation and/or smoothing. The spline-functions used herein are implemented in the graphics program, Grapher 7 by Golden Software Inc. Colorado, USA.

³For each of the eight subgroups, which constitute the data for the four octave-band chirps at 60 and 80 dB nHL, the distribution of the corresponding data to the wide-band CE-Chirp is compared to the distribution of the data from the remainder of the population. For example, for the 14 ears that constitute the data at 4000Hz/80 dB nHL the distribution of the data in response to the CE-Chirp are compared to the distribution of the data from the remainder 34 individuals (=48–14). In none of the eight comparisons the two distributions deviate significantly from each other (Mann-Whitney U test, [Siegel, 1956](#), $p < 0.05$).

⁴However the sum only *approximates* the waveform of the broad-band CE-Chirp because the linear attenuation functions of the octave-band filters do not add up exactly to a unity gain function (or attenuation function) in the range 500–8000 Hz.

⁵In Table III, the mean values for 500 Hz at 30 and 20 dB nHL and for 1000 Hz at 20 dB nHL (shown in italics) are based in part on the extrapolated values in Table II.

⁶This is found by systematically increasing the order of the polynomial until the residual variance became lower than 0.1%.

Dau, T., Wagner, O., Mellert, V., and Kollmeier, B. (2000). "Auditory brain-stem responses with optimized chirp signals compensating basilar membrane dispersion," *J. Acoust. Soc. Am.* **107**, 1530–1540.

de Boer, E. (1980). "Auditory physics. Physical principles in hearing theory I," *Phys. Rep.* **62**, 87–174.

Don, M., and Elberling, C. (1994). "Evaluating residual background noise in human auditory brain-stem responses," *J. Acoust. Soc. Am.* **96**, 2746–2757.

Don, M., Elberling, C., and Maloff, E. (2009). "Input and output compensation for the cochlear traveling wave delay in wide-band ABR recordings: Implications for small acoustic tumor detection," *J. Am. Acad. Audiol.* **20**, 99–108.

Don, M., Kwong, B., and Tanaka, C. (2005). "A diagnostic test for Meniere's disease and cochlear hydrops: Impaired high-pass noise masking of auditory brainstem response," *Otol. Neurotol.* **26**, 711–722.

Don, M., Ponton, C. W., Eggermont, J. J., and Kwong, B. (1998). "The effects of sensory hearing loss on cochlear filter times estimated from auditory brainstem response latencies," *J. Acoust. Soc. Am.* **104**, 2280–2289.

Don, M., Ponton, C. W., Eggermont, J. J., and Masuda, A. (1994). "Auditory brainstem response (ABR) peak amplitude variability reflects individual differences in cochlear response times," *J. Acoust. Soc. Am.* **96**, 3476–3491.

Elberling, C., Callø, J., and Don, M. (2010). "Evaluating auditory brainstem responses to different chirp stimuli at three levels of stimulation," *J. Acoust. Soc. Am.* **128**, 215–223.

Elberling, C., Cebulla, M., and Stürzebecher, E. (2007b). "Simultaneous multiple stimulation of the ASSR," in *1st International Symposium on Auditory and Audiological Research (ISAAR 2007): Auditory Signal Pro-*

- cessing in *Hearing-Impaired Listeners*, edited by T. Dau, J. M. Buchholz, J. M. Harte, and T. U. Christensen (Centertryk A/S, Denmark), pp. 201–209.
- Elberling, C., and Don, M. (1984). “Quality estimation of averaged auditory brainstem responses,” *Scand. Audiol.* **13**, 187–197.
- Elberling, C., and Don, M. (2008). “Auditory brainstem responses to a chirp stimulus designed from derived-band latencies in normal-hearing subjects,” *J. Acoust. Soc. Am.* **124**, 3022–3037.
- Elberling, C., Don, M., Cebulla, M., and Stürzebecher, E. (2007a). “Auditory steady-state responses to chirp stimuli based on cochlear traveling wave delay,” *J. Acoust. Soc. Am.* **122**, 2772–2785.
- Elberling, C., and Parbo, J. (1987). “Reference data for ABR’s in retrocochlear diagnosis,” *Scand. Audiol.* **16**, 49–55.
- Elberling, C., and Wahlgreen, O. (1985). “Estimation of auditory brainstem responses, ABR, by means of Bayesian inference,” *Scand. Audiol.* **14**, 89–96.
- Fobel, O., and Dau, T. (2004). “Searching for the optimal stimulus eliciting auditory brainstem responses in humans,” *J. Acoust. Soc. Am.* **116**, 2213–2222.
- Gorga, P. M., Kaminski, J. R., Beauchaine, K. A., and Jesteadt, W. (1988). “Auditory brainstem responses to tone bursts in normally hearing subjects,” *J. Speech Hear. Res.* **31**, 87–97.
- IEC 60711 (1981). “Occluded-ear simulator for the measurement of earphones coupled to the ear by ear inserts,” International Electrotechnical Commission, Geneva, Switzerland.
- IEC 61260 (1995). “Electroacoustics – Octave-band and fractional-octave-band filters,” International Electrotechnical Commission, Geneva, Switzerland.
- ISO 389-9 (2009). “Acoustics - Reference zero for the calibration of audiometric equipment-Part 9: Preferred test conditions for the determination of reference hearing threshold levels,” International Organization for Standardization, Geneva, Switzerland.
- Lütkenhöner, B., Kauffmann, G., Pantev, C., and Ross, B. (1990). “Verbesserung der Synchronisation auditorisch evozierter Hirnstammpotentialle durch Verwendung eines die cochleären Laufzeitunterschiede kompensierenden Stimulus (Increased synchronization of the auditory brainstem response obtained by a stimulus which compensates for the cochlear delay),” *Arch. Otolaryngol.* **2**, 157–159.
- Neely, S. T., Norton, S. J., Gorga, M. P., and Jesteadt, W. (1988). “Latency of auditory brain-stem responses and otoacoustic emissions using tone-burst stimuli,” *J. Acoust. Soc. Am.* **83**, 652–656.
- Shera, C. A., and Guinan, J. J. (2000). “Frequency dependence of stimulus-frequency-emission phase: Implications for cochlear mechanics,” in *Recent Developments in Auditory Mechanics*, edited by H. Wada, T. Takasaka, K. Ikeda, and K. Ohyama (World Scientific Press, Singapore), pp. 381–387.
- Siegel, S. (1956). *Nonparametric Statistics for the Behavioural Sciences* (McGraw-Hill, London), pp. 1–312.