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*Selected publications in Auditory
Electrophysiology*

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Introduction

This collection consists of 22 selected papers within auditory electro-physiology written over a period of about 25 years. The papers describe a series of developments aimed at improving the quality and efficiency of recording auditory evoked potentials from the brainstem. The papers are divided into two groups: (1) the ABR recorded in the time domain, and (2) the ASSR recorded in the frequency domain.

A brief overview of each group is given below and is followed by a detailed description of each paper.

I. ABR recorded in the time domain

The quality of a recorded ABR may be described by the ratio of the amplitude of the true ABR to the amplitude of the residual background noise obtained after averaging. Both of these quantities are *unknown* and must therefore be *estimated*. One way to achieve this is described in the early paper (ref. 1) where a metric, called F_{sp} , is developed and tested. The F_{sp} depends on the signal-to-noise ratio (SNR, or rather the response-to-noise ratio) and proves useful both for the running estimation of the ABR quality as well as for ABR detection.

All clinicians have experienced how a sudden increase in the physiological background noise can disrupt a clear ABR recording. In order to deal with this problem, which arises from fluctuating background noise (for instance due to changes in the state of arousal of the patient), a specific method is developed (ref. 2). The method allows individual collected sweeps to contribute differently to the final average: sweeps collected in quiet conditions are given a higher importance than sweeps collected in noisy conditions. The method, called *weighted averaging*, is formulated in statistical terms and uses the background noise estimator developed in ref. 1.

By using the F_{sp} and the weighted averaging procedure low-level ABRs are collected in normal-hearing test subjects (ref. 3). The *ABR threshold* to clicks is evaluated and subsequently compared to the psycho-acoustic threshold for the same click stimulus. The ABR sensitivity to a click is described in detail and is shown to be dependent on the slope of the ABR-amplitude input/output function and the amplitude of the residual background noise.

By using the F_{sp} and the weighted averaging procedure low-level ABRs are collected in normal-hearing test subjects (ref. 4) and the characteristics of the *background noise* is described. By comparing *weighted averaging* to *traditional averaging* and to different strategies for *artifact rejection*, the superiority of weighted averaging is demonstrated.

The combination of the F_{sp} and the weighted averaging procedure as well as the knowledge from ref. 3 & 4, leads to the formulation of five recommendations in response to the important clinical question: "when to stop averaging"? (ref. 5). (1) *Stop when averaging has reached a point where it is possible to resolve a 'normal' response for a given stimulus condition;* (2) *Stop when an ABR with a given amplitude can be resolved;* (3) *Stop when the afforded time will be exhausted before sufficient averaging occurs;* (4) *Stop when a given residual averaged background noise level has been reached;* or (5) *Stop when a given F_{sp} or criterion of a quantitative detector has been achieved.*

All of the above is put together in a tutorial paper (ref. 9) which thus is reviewing the basic principles of tools used for detecting and assessing ABRs in the time domain.



For further improvement of broad-band ABR recordings the traditional click is replaced by a chirp (ref. 13). A chirp stimulus tries to counteract the temporal dispersion in the cochlea and thus needs to present its low-frequency energy *before* its high-frequency energy. However, the chirp has the same *power spectrum* as the click. The latency-model used to design the chirp is established from derived-band ABR latencies obtained in normal-hearing subjects (N = 81). Clinical testing in normal-hearing subjects demonstrates that the chirp ABR is 1.5 – 2.0 times *larger* than the corresponding click ABR.

Clinical testing (ref. 13) demonstrates that the *chirp ABR* compares favorably with the *Stacked ABR* when the same underlying latency model is used both to design the chirp and to align the derived-band ABRs for the formation of the individual Stacked ABR (ref. 14). A simulation study (ref. 14) indicates that the chirp ABR may replace the Stacked ABR for the detection of small tumors.

Experimental studies (ref. 15 & 16) demonstrate that Chirps that evoke the largest ABR amplitudes in normal-hearing adults have different characteristics at higher and lower levels of stimulation: at levels higher than about 50-60 dB nHL the chirp should have much shorter duration (sweeping rate) than at lower levels where a chirp based on the cochlear delay model appears to be optimal over a broad range of levels. In a specific model study (ref. 17) a new delay model is formulated based on ABR-latencies in response to octave-band chirp stimuli obtained from a large group of individuals with normal hearing.

II. ASSR recorded in the frequency domain

Algorithms used to detect the ASSR recorded in the frequency domain are based on statistical analysis of the amplitude and phase of the harmonic frequency structure of the ASSR (Stürzebecher et al. 1999^{*)}). A detection algorithm is typically applied in such a way that for each stimulus condition multiple samples are evaluated as the data acquisition goes on. Repeated statistical testing of each run inflates the statistical power associated with a given test criterion, which therefore needs to be corrected appropriately. A new method for this correction is developed (ref. 6) using a large database of clinical ASSR recordings. This leads to a much faster detection algorithm and therefore to shortening of the necessary test time.

^{*)} Stürzebecher, E., Cebulla, M., and Wernecke, K.D. (1999). "Objective response detection in the frequency domain – Comparison of several q-sample tests," *Audiology & Neurootology*, **4**, 2-11.

An investigation demonstrates (ref. 7) that information about the ASSR is contained in the frequency domain corresponding to the first six harmonics of the stimulus repetition rate. If the information carried in the higher harmonics is included, the detection algorithm becomes much more efficient leading to the development and application of the so-called q-sample test. This algorithm is tested in normal-hearing and hearing impaired test subjects (N=57) using broad-band ASSR at low levels of stimulation. The results demonstrate that the q-sample test performs much more efficiently than the corresponding one-sample test.

For the use of the ASSR for frequency-specific hearing evaluation the classical amplitude modulated carrier only excites a narrow frequency area in the cochlea (typically 2-300 Hz), resulting in ASSRs of low amplitude. A technique is developed (ref. 8) for the design of frequency-specific stimuli that (1) excite broader cochlear areas, (2) compensate for the cochlear temporal dispersion, and (3) allow application of the q-sample test avoiding the influence from stimulus artifacts. Testing of this technique in normal-hearing subjects (N=70) confirms the efficiency of this stimulus design (ref. 9 & 10).

A systematic analysis of different cochlear models used to design an optimal chirp for the recording of ASSRs is carried out (ref. 11). A model based on derived-band ABR-latencies in normal-hearing subjects produces the most efficient chirp stimulus. This is the result of testing in normal-hearing subjects (N=49) by observing the difference in detection time of the ASSR to low-level chirps and clicks.



In order for the click to be as efficient as the chirps, the level of the click has to be increased by 20 dB or more.

Frequency-specific stimuli for both diagnostic evaluation and hearing screening are designed and tested (ref. 12). The design is based on the technique described and evaluated previously (ref. 8). However, the compensation for the cochlear temporal dispersion is now based on a more optimal model (ref. 11). For the diagnostic testing, four octave-band chirp stimuli are designed and evaluated in normal-hearing adults (N=20 ears). For hearing screening, a low-frequency and a high-frequency chirp is designed and evaluated in newborns (N=72). In both studies the stimuli are applied simultaneously and the results show that simultaneous stimulation with frequency-specific stimuli can effectively be applied in both normal-hearing adults for diagnostic testing and in newborns for hearing screening.

Detailed description of all papers

1. Elberling, C., and Don, M. (1984). "Quality estimation of averaged auditory brainstem responses," *Scand. Audiol.* **13**, 187-197.

This paper describes our early attempt to estimate the signal-to noise ratio of the averaged ABR. In the clinic, ABRs are recovered from the on-going background noise by averaging a number of sweeps. Normally, a test protocol will prescribe a fixed number of sweeps to be averaged and will recommend replications to be obtained. However, since both the ABR and the background noise differ across individual subjects both in magnitude and in other characteristics, such a test protocol can never ensure a given minimum 'quality' or signal-to-noise (response-to-noise) ratio, SNR, of the final recovered ABR.

Therefore a statistical method is developed in order to estimate the SNR of the recorded ABR during the on-going averaging process. The method calculates the F_{SP} , which is the squared ratio of the estimated magnitude of the ABR to that of the averaged background noise. The method can be employed on-line as an adaptive strategy (1) to estimate the number of sweeps necessary to obtain a given minimum SNR (quality) of the ABR recorded at supra threshold levels, or (2) to automatically detect the presence of an ABR near threshold.

2. Elberling, C., and Wahlgreen, O. (1985). "Estimation of auditory brainstem response, ABR, by means of Bayesian inference," *Scand. Audiol.* **14**, 89-96.

This paper describes a method to recover the ABR by weighted averaging. The method is an effective technique to deal with the destructive effect of fluctuating, non-stationary background noise, and is based on a statistical approach called 'Bayesian inference'. The contribution of the individual sweep (or block of sweeps) is weighted inversely proportional to the level of background noise during the acquisition of the sweep.

Based on 50 sets of clinical recordings the weighted averaging method is evaluated. Weighted averaging is always as good as or better than traditional averaging, and in about 30% of the cases the weighted averaging improves the recovered ABR significantly over what is obtained by traditional

averaging. In these cases the traditional averaging would require 50% more sweeps to be averaged in order to obtain the same precision of the ABR, and the variance of the wave V latency is improved by a factor of approximately two.



3. Elberling, C., and Don, M. (1987). "Threshold characteristics of the human auditory brain stem response," J. Acoust. Soc. Am. **81**, 115-121.

This paper describes and analyzes ABRs recorded from ten normal-hearing subjects in response to 100 μ s clicks from a TDH 49 earphone at a rate of 48 pps and at levels randomly varied in 2-dB steps between 34 and 52 dB p.e.SPL (approximately 0 - 20 dB nHL). At each level, 10 000 sweeps are averaged using weighted averaging. A running estimate of the signal-to-noise ratio (SNR), F_{SP} , is used to detect the presences of the ABR. The median threshold is found at 38 dB p.e.SPL (approximately 5 dB nHL). The mean averaged background noise level is 11.3 nVrms, and the "true" ABR amplitude function crosses this value at 35.5 dB p.e.SPL (2 - 3 dB nHL), which indicates the level where the SNR = 1. By extrapolation it is found that the ABR amplitude becomes zero at 32 dB p.e.SPL. The perceptual thresholds of the click are estimated by means of a modified block up-down procedure and the median value is found at 33 dB p.e.SPL.

The slope of the amplitude function and the magnitude of the averaged background noise are the two factors responsible for the ABR threshold sensitivity which thus depends on both physiological and technical parameters. Therefore, these have to be considered together with the method of detection when the ABR is used as an indicator of the hearing sensitivity.

4. Don, M., and Elberling, C. (1994). "Evaluating residual background noise in human auditory brainstem responses," J. Acoust. Soc. Am. **96**, 2746-57.

This paper describes the nature of the residual background noise in ABR averages in normal-hearing subjects. The residual noise is estimated with the F_{sp} technique. Low-level click stimuli are presented in 2-dB steps in the range from 30 to 48 dB p.e.SPL (approximately from -2 to +16 dB nHL) and for each stimulus level, 10 000 sweeps are acquired and stored for subsequent analysis. The shortcomings of artifact rejection and traditional averaging are demonstrated. It is further demonstrated how weighted averaging can help minimize these shortcomings. Finally, it is analyzed how the number of sweeps per block influences the ability of weighted averaging to control the destructive effects of non-stationary background noise. It turns out that reducing block size from 256 to 32 sweeps per block improves the weighted averaging significantly - but with a small amount only. Minimizing the destructive effects increases the value of statistical techniques used for objective ABR detection or to control the quality of ABR recordings. It is concluded that these techniques in combination improve not only the accuracy of test interpretation but also the efficiency of clinical test time, which is becoming important for the control of medical costs.

5. Don, M., and Elberling, C. (1996). "Use of quantitative measure of ABR peak amplitude and residual background noise in the decision to stop averaging," J. Acoust. Soc. Am. **99**, 491-499.

This paper describes an objective quantitative approach to the decision of when to stop averaging in the recording of ABRs. This decision is based on (1) the knowledge of the amplitude distributions of wave V in the ABRs of normal-hearing individuals for varying stimulus levels, (2) calculated estimates of the residual background noise in the average, and (3) the use of a quantitative statistical response detector. Several reasons for terminating an averaging process are presented along with a specific protocol for each of the reasons. These protocols provide a general but consistent framework to address the issue of when to stop averaging and will thus improve the efficiency of clinical ABR testing. Furthermore, it is quite possible to automate the procedure and the decision process.



6. Stürzebecher, E., Cebulla, M., and Elberling, C. (2005). "Automated auditory response detection – statistical problems with repeated testing," *Int. J. Aud.* **44**, 110-119. Available in print from Interacoustics, item 8013289

This paper describes how sequential statistical testing, which usually is applied in an automated response detection algorithm, is time efficient but unfortunately also increases the probability of a false rejection of the null-hypothesis. Therefore, in such test situations the test criterion is normally modified by means of the Bonferroni correction. However, when dealing with dependent or partly dependent data the Bonferroni correction will lead to an over-correction and will therefore not be optimal. A new method to find the optimal test criterion is devised and tested by means of Monte Carlo simulations using real background noise data acquired from clinical ASSR-recordings.

7. Cebulla, M., Stürzebecher, E., and Elberling, C. (2006). "Objective detection of auditory steady-state responses: Comparison of one-sample and q-sample tests," *J. Am. Acad. Audiol.* **17**, 93-103. Available in print from Interacoustics, item 8013287

This paper describes how the ASSR is expected to be useful for the objective, frequency-specific assessment of hearing thresholds in small children. To detect ASSR close to the hearing threshold, a powerful statistical test in the frequency domain has to be applied. Hitherto so-called one-sample tests are used, which only evaluate the phase, or the phase and amplitude, of the first harmonic frequency (the fundamental). It is shown that higher harmonics with significant amplitudes are also contained in the ASSR spectrum. For this reason, statistical tests that only consider the first harmonic ignore a significant portion of the available information. The use of a q-sample test, which, in addition to the fundamental frequency, also includes higher harmonics in the detection algorithm leads to a better detection performance in normal-hearing and hearing impaired subjects (N = 57). The evaluation of test performance uses both detection rate and detection time.

8. Stürzebecher, E., Cebulla, M., Elberling, C., and Berger, T. (2006). "New efficient stimuli for evoking frequency-specific auditory steady-state responses," *J. Am. Acad. Audiol.* **17**, 448-461. Available in print from Interacoustics, item 8013288

This paper describes the use of the ASSR as a promising tool for the objective frequency-specific assessment of hearing thresholds in children. The stimulus generally used for ASSR recording (single amplitude-modulated carrier) only activates a small area on the basilar membrane. Therefore, the response amplitude is low. A stimulus with a broader frequency spectrum can be composed by adding several cosines whose frequency intervals comply with the desired stimulus repetition rate. Compensation for the traveling wave delay is also possible with a stimulus of this type, leading to a better synchronization of the neural response and consequently higher response amplitudes especially for low-frequency stimuli. The additional introduction of frequency offset, which minimizes the risks of detecting stimulus artifacts, enables the use of a q-sample test for the response detection, which is important particularly at the lowest frequencies. The results of investigations carried out on a large group of normal-hearing test subjects (N = 70) confirm the efficiency of this stimulus design. The new stimuli lead to significantly improved ASSRs with higher SNRs and thus higher detection rates and shorter detection times.



9. Elberling, C., and Don, M. (2006). "Detecting and assessing synchronous neural activity in the temporal domain," In: Auditory Evoked Potentials - *Basic principles and Clinical Application*. Eds. RF Burchard, JJ Eggermont, M Don. Lippincott Williams & Wilkins. ISBN 978-0-7817-5756-0. Chap. 5, pg. 102-123.

This tutorial chapter describes how the effective use of evoked potentials, EPs, depends heavily on our ability to determine their presence (detection) and to measure with sufficient precision the EPs parameters of interest (assessment). Many of the problems associated with the use and interpretation of EPs stem from the difficulties in their detection and/or assessment. The chapter presents an overview of the basic principles of tools used for detecting and assessing EPs in the time domain. Subjective and objective methods of detection and assessment are contrasted with an emphasis on some of the objective statistical methods described in the literature. The clinical value of these methods is evaluated and finally some of the misconceptions surrounding detection and assessment of EPs are pointed out.

10. Cebulla, M., Stürzebecher, E., Elberling, C., and Müller, J. (2007). "New click-like stimuli for hearing testing," J. Am. Acad. Audiol. **18**, 725-738.

This paper describes how a click stimulus sets up a traveling wave along the basilar membrane, which excites each of the frequency bands in the cochlea, one after another. Due to the lack in synchronization of the excitations, the compound response amplitude is low. A repetitive click-like stimulus can be set up in the frequency domain by adding a high number of cosines, the frequency intervals of which comply with the desired stimulus repetition rate. Straight-forward compensation of the cochlear traveling wave delay is possible with a stimulus of this type. As a result, better synchronization of the neural excitation can be obtained so that higher response amplitudes can be expected. The additional introduction of a frequency offset enables the use of a q-sample test for response detection. The results of investigations carried out on a large group of normal-hearing test subjects (N = 70) have confirmed the higher efficiency of this stimulus design. The new stimuli lead to significantly higher response SNRs and thus higher detection rates and shorter detection times. Using band-limited stimuli designed in the same manner, a "frequency-specific" hearing screening seems to be possible.

11. Elberling, C., Don, M., Cebulla, M., and Stürzebecher, E. (2007). "Auditory steady-state responses to chirp stimuli based on cochlear traveling wave delay," J. Acoust. Soc. Am. **122**, 2772-2785.

Available in print from Interacoustics, item 8013297

This paper describes how chirp stimuli can be used to compensate for the cochlear traveling wave delay in recordings of the ASSR (rate: ~90/s). The temporal dispersion in the cochlea is given by the traveling time, which in this study is estimated from latency-frequency functions obtained from (1) a cochlear model, (2) tone-burst auditory brain stem response ABR-latencies, and (3) derived-band ABR-latencies. These latency-frequency functions are assumed to reflect the group delay of a linear system that modifies the phase spectrum of the applied stimulus. On the basis of this assumption, three chirps are constructed and evaluated in normal-hearing subjects (N = 49). The ASSR to these chirps and to a click stimulus are compared at two levels of stimulation viz. 30 and 50 dB nHL and at a rate of 90/s. The chirps give shorter detection time and higher signal-to-noise ratio than the click. The shorter detection time obtained by the chirps is equivalent to an increase in stimulus level of 20 dB or more. The chirp based on the derived-band ABR-latencies appears to be the most efficient of the three chirps tested here. Overall, the results indicate that a chirp is a more efficient stimulus than a click for the recording of the ASSR in normal-hearing adults using transient sounds at a high rate of stimulation.



12. Elberling, C., Cebulla, M., and Stürzebecher, E. (2007). "Simultaneous multiple stimulation of the ASSR," In: 1st International Symposium on Auditory and Audiological Research (ISAAR 2007): *Auditory signal processing in hearing-impaired listeners*. Eds. T Dau, JM Buchholz, JM Harte, TU Christensen. Centertryk A/S, Denmark. ISBN 87-990013-1-4. pg. 201-209.

Available in print from Interacoustics, item 8013321

This paper describes some characteristics of the ASSR related to the use of multiple, simultaneous, band-limited chirp-stimuli. In a diagnostic study four one-octave-band chirp-stimuli (500, 1000, 2000 and 4000 Hz) were used to measure the ASSR-threshold in normal-hearing adults (N=20 ears). The four stimuli were presented simultaneously to both ears (eight stimuli) with rates at around 90/s. The ASSRs were detected automatically (error rate 5%), and the thresholds evaluated with a resolution of 5 dB. The ASSR thresholds were compared to the audiometric pure-tone thresholds and the deviations evaluated by the group means and standard deviations. These data compare favorably well with similar data reported by others.

In a screening study a low-frequency chirp, (Lo: 180 – 1500 Hz) and a high-frequency chirp (Hi: 1500 – 8000 Hz), is used to record the ASSR in newborns (N = 72). The two stimuli are presented both sequentially and simultaneously using a rate at about 90/s and a level of 35 dB nHL. The ASSRs are detected automatically (error rate 0.1%), and stimulus efficiency is evaluated by the detection time.

The results from both studies demonstrate that simultaneous application of multiple, frequency-specific stimuli can effectively be applied without sacrificing response detection accuracy. However, in the screening study stimulus interactions are observed.

13. 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.

Available in print from Interacoustics, item 8013311

This paper describes how the temporal dispersion in the human cochlea can be compensated for by using a chirp designed from estimates of the cochlear delay based on derived-band auditory brainstem response (ABR) latencies. To evaluate inter-subject variability and level effects of such delay estimates, a large dataset is analyzed from (N = 81) normal-hearing adults (fixed click level) and from a subset thereof (different click levels). At a fixed click level, the latency difference between 5700 and 710 Hz ranges from about 2.0 to 5.0 ms, but over a range of 60 dB, the mean relative delay is almost constant.

Modeling experiments demonstrate that the derived-band latencies depend on the cochlear filter build-up time and on the unit response waveform. Because these quantities are partly unknown, the relationship between the derived-band latencies and the basilar membrane group delay cannot be specified. A chirp based on the above delay estimates is used to record ABRs in 10 normal-hearing adults (20 ears). For levels below 60 dB nHL, the gain in amplitude of chirp-ABRs to click-ABRs approaches two, and the effectiveness of chirp-ABRs compares favorably to Stacked-ABRs obtained under similar conditions.



14. 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**, (2).
Available in print from Interacoustics, item 8101158

This paper describes how the Stacked ABR - at the output of the cochlea - attempts to compensate for the temporal dispersion of neural activation caused by the cochlear traveling wave in response to click stimulation. Compensation can also be made - at the input of the cochlea - by using a chirp stimulus. Previously it has been demonstrated that the Stacked ABR is sensitive to small tumors that are often missed by standard ABR latency measures. Because a chirp stimulus requires only a single data acquisition run, whereas the Stacked ABR requires six, the evidence justifying the use of a chirp for small tumor detection is evaluated. The sensitivity and specificity are compared of different Stacked ABRs formed by aligning the derived-band ABRs according to (1) the individual's peak latencies, (2) the group mean latencies, and (3) the modeled latencies used to develop the chirp. Results suggest that for tumor detection with a chosen sensitivity of 95%, a relatively high specificity of 85% may be achieved with a chirp. Thus, it appears worthwhile to explore the actual use of a chirp because significantly shorter test and analysis times might be possible.

15. 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.
Available in print from Interacoustics, item 8013374

This paper describes how the ABR amplitude is dependent of Chirp duration (sweeping rate) and stimulus level. A standard Click and five Chirps of different durations are presented at three levels of stimulation (20, 40 and 60 dB nHL) in 20 normal hearing adult ears. It is found that all the Chirps (except the longest one at 60 dB nHL) always produce larger ABR amplitudes than the Click. It is also found that the shorter Chirps are most efficient at higher levels whereas the longer Chirps are most efficient at lower levels. The paper concludes that two mechanisms appear to be involved: (1) upward-spread-of-excitation at higher levels, and (2) an increased change of the cochlear-neural delay with frequency at lower levels. The observed changes in ABR amplitude and latency from the different chirp stimuli are consistent with this conclusion.

16. Cebulla M., and Elberling, C. (2010). "Auditory brain stem responses evoked by different chirps based on different delay models," J. Am. Acad. Audiol. **21**, 452-460.
Available in print from Interacoustics, item 8101157

This paper describes a similar experiment as the one above (ref. 15). However, relative to ref. 15, recordings are obtained from 50 normal-hearing adults, the five Chirps have slightly different durations, the stimulus levels are limited to 30 and 50 dB nHL, the frequency bandwidth of the stimuli is limited to 8 kHz, and some of the recording characteristics (e.g. HP-filter cut-off) have other values. Despite these differences the main experimental findings are the same as in ref. 15, but the effect of chirp duration on

ABR amplitude is not as prominent as seen in ref. 15. The main reason for this result is probably the limited range of stimulus levels that has been used in this study.



17. Elberling, C., and Don, M. (2010). "A direct approach for the design of chirp stimuli used for the recording of auditory brainstem responses," J. Acoust. Soc. Am. **128**, 2955-2964.

Available in print from Interacoustics, item 8013377

This paper describes a novel approach to find the delay for each frequency component in order to design a family of chirps that optimally synchronizes all response components from across the cochlea (or brainstem) at all levels of stimulation. ABR latencies in response to octave-band chirp stimuli are collected from 48 normal-hearing adults and are used to formulate a latency-frequency model as a function of stimulus level. The delay compensations of the proposed model are similar to those found in the experimental studies described above (ref. 15 and 16).

18. Kristensen, S.G.B., and Elberling, C. (2012). "Auditory brainstem responses to level-specific chirps in normal-hearing adults," J. Am. Acad. Audiol. **23**, 712-721.

Available in print from Interacoustics, item 8101161

This paper describes an experimental verification of the proposed level-specific model (ref. 17). The study compares the CE-Chirp with the LS-Chirp (and the standard Click) by recording the ABR from both ears in 10 normal-hearing, young adults (N = 20 ears). Both chirps have an electrical amplitude spectrum which is flat from 350 to 11.300 Hz (the IA CE-Chirp). The ER-3A earphone is used and the recordings are obtained with the Eclipse using a 30 nV background noise stop criteria and weighted averaging. The ABR amplitude, latency, and waveform are evaluated. The results clearly demonstrate the advantage of the LS-Chirp over the CE-Chirp at levels above 60 dB nHL.

19. Rønne, F.M., Dau, T., Harte, J., and Elberling, C. (2012). "Modelling auditory evoked brainstem responses to transient stimuli," J. Acoust. Soc. Am. **131**, 3903-3913.

This paper describes the development of a quantitative auditory model based on a 'humanized' non-linear auditory-nerve model of Zilany and Bruce (2007). The model is able to account for the change in tone-burst evoked ABR latency with frequency, but underestimate changes in both click and tone-burst latency values with stimulus level. However, the model correctly predicts the non-linear ABR amplitude behaviour in response to different chirp stimuli (ref. 15, 16 & 17) and thus supports the hypothesis that the ABR generation strongly is influenced by the non-linear and dispersive processes in the cochlea.

20. Elberling, C., Kristensen, S.G.B., and Don, M. (2012). "Auditory brainstem responses to chirps delivered by different insert earphones," J. Acoust. Soc. Am. **131**, 2091-2100.

Available in print from Interacoustics, item 8029368

This paper describes a research project which compares the ABRs in 11 normal-hearing young adults (N = 22 ears) in response to the Click, the CE-Chirp and the LS-Chirp (ref. 17) at a broad range of stimulus levels. The stimuli are delivered by two different insert earphones, the ER-3A and the ER-2. The ER-3A has an amplitude response that rolls off at about 4 kHz, whereas the ER-2 has an amplitude response which is flat all the way up to and beyond 10 kHz. The recordings are obtained with the Eclipse using a 30 nV background noise stop criteria and weighted averaging. For both chirps it is found that the ABRs at lower levels (i.e. below 60 dB nHL) are significantly larger with the ER-2 than with the ER-3A earphone, and further it is demonstrated that this finding most likely is due to the large differences between the amplitude-frequency responses of the two earphones.



21. Elberling, C., Don, M., and Kristensen, S.G.B. (2012). "Auditory brainstem responses to chirps delivered by an insert earphone with equalized frequency response," J. Acoust. Soc. Am. **132**, EL149-154.
Available in print from Interacoustics, item 8101159

This paper describes the design and testing of a modified LS-Chirp – called the LSY-Chirp – which acoustically produces a chirp with an equalized amplitude spectrum when delivered by the ER-3A insert earphone. ABRs are recorded from one ear of 20 normal-hearing, young adults (N = 20 ears) in response to a standardized Click, the LS-Chirp, and the LSY-Chirp, and are obtained with the Eclipse using a 30 nV background noise stop criteria and weighted averaging. The results confirm the expectation that the LSY-Chirp generates significantly larger ABR amplitudes than the LS-Chirp at levels below 60 dB nHL.

22. Gøtsche-Rasmussen, K., Poulsen, T., and Elberling, C. (2012). "Reference hearing threshold levels for chirp signals delivered by an ER-3A insert earphone," Int. J. Aud. **51**, 794-799.
Available in print from Interacoustics, item 8101160

This paper describes a reference study in which the behavioural thresholds to chirp stimuli are measured in a large group of normal-hearing individuals. The test group consists of 25 young adults (N = 50 ears) and the measurements are in compliance with the recommendations given in the ISO 389-9 standard. The test signals are the CE-Chirp and the four octave-band chirps, which are presented at two repetition rates, 20 and 90 stimuli/s, and using the ER-3A insert earphone. The calibration values are reported in dB p.e. SPL in the occluded-ear simulator. The results are similar to those from another investigation (PTB-study) and the values from the two, independent studies are therefore relevant for a future extension of the existing ISO 389-6 standard, which presently provides reference calibration values for standardized click and tone-burst stimuli delivered from various earphones.