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DOI

[10.1121/1.1312357](https://doi.org/10.1121/1.1312357)

Publication date

2000

Published in

The Journal of the Acoustical Society of America

[Link to publication](#)

Citation for published version (APA):

Maat, A., Wit, H. P., & Dijk, P. (2000). Noise-evoked otoacoustic emissions in humans. *The Journal of the Acoustical Society of America*, 108, 2272-2280.
<https://doi.org/10.1121/1.1312357>

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Noise-evoked otoacoustic emissions in humans

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(Received 16 February 2000; revised 27 July 2000; accepted 28 July 2000)

Click-evoked otoacoustic emissions (CEOAEs) and acoustical responses evoked by bandlimited Gaussian noise (noise-evoked otoacoustic emissions; NEOAEs) were measured in three normal-hearing subjects. For the NEOAEs the first- and second-order Wiener kernel and polynomial correlation functions up to the sixth order were calculated by cross correlating the noise stimulus and the emission response. Emission components were only found in the first-order Wiener kernel. These kernels were dependent on the stimulus level, indicative of the nonlinear response of the cochlea. For each subject the frequency contents of the CEOAE and the first-order Wiener kernel were nearly identical. In the second-order Wiener kernels and higher-order polynomial correlation functions no significant contributions were identified. Apparently, odd and even order nonlinearities cannot be detected by Wiener kernel analysis. © 2000 Acoustical Society of America.

[S0001-4966(00)00911-5]

PACS numbers: 43.64.Jb, 43.64.Kc [BLM]

I. INTRODUCTION

The human cochlea is a sensitive sound transducer, which is capable of detecting sounds in a wide range of intensities and with a high frequency selectivity. This high sensitivity of the cochlea cannot easily be explained by a passive mechanism. Gold (1948) postulated a theory stating that to account for the high frequency selectivity the filters in the cochlea must be active, thus using a feedback mechanism. This mechanism will sharpen up the auditory filters, but can also oscillate if too much energy is fed into them. Gold predicted that oscillating auditory filters may provide acoustical vibrations in the inner ear, which might be transmitted into the external ear canal. About 30 years later, Kemp (1979) discovered that the ear indeed can emit sounds, which can be measured in the ear canal. The presence of these “otoacoustic” emissions was a prediction of Gold’s theory.

Since 1979, variations of otoacoustic emissions (OAEs) elicited by different kinds of acoustical stimuli have been measured and thoroughly described. It has become clear that OAEs are a phenomenon related to (nearly) normal hearing, generally absent in ears with a light to moderate sensory-neural hearing loss (Probst *et al.*, 1991). Obviously, the emission-generating mechanism is related to normal functioning of the cochlea.

Despite the fact that emission phenomena have been studied extensively during the past 20 years, the emission-generating mechanism in the cochlea is still not resolved.

However, it is clear that nonlinear mechanisms are involved in the generation of OAEs.

A general approach to system identification is Wiener kernel analysis. In Wiener kernel analysis, the system under study is described by a set of Wiener kernels (see below). A principal advantage of Wiener kernel analysis is its nonparametric nature, e.g., the behavior of the system can be described without any *a priori* knowledge of its components. On the other hand, with some additional knowledge of the system components, Wiener kernel analysis may be used to identify the component parameters (Van Dijk *et al.*, 1997b). For these reasons, we investigated the application of Wiener kernel analysis to otoacoustic emissions from the inner ear. A preliminary report was published by Maat *et al.* (1994) and comparable results obtained from one frog were described by Van Dijk *et al.* (1997a).

II. WIENER AND VOLTERRA KERNELS

Before introducing Wiener kernel analysis, we need to describe the related concept of Volterra kernels. As Volterra showed, the output $y(t)$ of a nonlinear system S , in response to a time-dependent stimulus $x(t)$ can be written as a series of independent subsystems $H_n[x(t)]$ (Marmarelis and Marmarelis, 1978)

$$y(t) = \sum_{n=0}^{\infty} H_n[x(t)]. \quad (1)$$

Here,

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$$H_n[x(t)] = \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} h_n(\tau_1, \dots, \tau_n) x(t - \tau_1), \dots, \\ x(t - \tau_n) d\tau_1, \dots, d\tau_n$$

is the n th order Volterra integral, including the n th order Volterra kernel $h_n(\tau_1, \dots, \tau_n)$. The number of subsystems, H_n , needed to describe the relation between the system input $x(t)$ and its output $y(t)$ depends on the orders of nonlinearity in the unknown system. For instance, a system consisting of a quadratic nonlinearity in combination with one or more linear filters can be fully described with the first- and second-order kernels $h_1(\tau_1)$ and $h_2(\tau_1, \tau_2)$ (Schetzen, 1989).

Another instructive example is a static nonlinear system [e.g., with y some polynomial of x , or $y = \exp(x)$]. Then, the Volterra kernels h_n are δ functions, and the Volterra series becomes a Taylor expansion.

In practice Volterra kernels are hard to determine. However, when the Volterra functionals are rearranged in linear combinations of H_n , H_{n-2} etc., analogous to the rearrangement of Taylor polynomials into Hermite polynomials, the so-called Wiener G-functionals are formed (Schetzen, 1989)

$$y(t) = \sum_{n=0}^{\infty} G_n[k_n; x(t)]. \quad (2)$$

Like the Volterra expansion in Eq. (1), the Wiener kernel expansion decomposes the system under study into a series of subsystems $G_n[k_n; x(t)]$. Unlike the Volterra subsystems, the Wiener G-functionals can be obtained without *a priori* knowledge of the system: For a Gaussian white-noise stimulus signal, $x(\tau)$, the G-functionals are orthogonal with respect to this stimulus (Schetzen, 1989). This implies that the Wiener kernels can be obtained independently, without knowing the highest order of nonlinearity of the system. When using a Gaussian noise stimulus, the Wiener kernels k_n are given by a set of cross-correlation functions

$$k_0 = \overline{y(t)}, \\ k_1(\tau_1) = \frac{1}{A} \overline{y(t)x(t - \tau_1)}, \quad (3)$$

$$k_2(\tau_1, \tau_2) = \frac{1}{2A^2} \overline{y(t)x(t - \tau_1)x(t - \tau_2)} - \frac{1}{2A} k_0 \delta(\tau_1 - \tau_2),$$

where

$$\overline{y(t)} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T y(t) dt$$

stands for the ensemble average of the time signal and A is the power spectral density of the Gaussian white noise.

Calculation of kernels is manageable up to the third order. Higher-order nonlinearities can be accessed in an economical way with the polynomial correlation method (De Boer, 1979; Eggermont, 1993)

$$p_n(\tau) = \frac{1}{n!} \overline{y(t) \text{He}_n[x(t - \tau)]}, \quad (4)$$

where

$$\text{He}_n[x] = x^n - \left(\frac{n}{2}\right) \frac{A}{2} x^{n-2} + 3 \left(\frac{n}{4}\right) \left(\frac{A}{2}\right)^2 x^{n-4} - \dots,$$

are Hermite polynomials. It can readily be seen that $p_n(\tau)$ is proportional to the diagonal $k_n(\tau, \tau, \dots, \tau)$ of the n th order Wiener kernel. Although the diagonals do not provide all the information present in the full kernels, for many systems the off-diagonal components of the various kernels are related (see for example the sandwich model as described in Van Dijk *et al.*, 1997b). Thus, for practical system identification, computation of the diagonals only is often sufficient, and leads to a useful description of the system (Eggermont *et al.*, 1983; Van Dijk *et al.*, 1997a).

Calculation of cross-correlation functions for responses evoked by acoustic noise stimulation has been applied in auditory research in brainstem-evoked response audiometry (Dobie and Clopton, 1980; Dobie and Wilson, 1984) and on neural responses with the reversed correlation technique (De Boer, 1967, 1968; Eggermont *et al.*, 1983). Wiener kernel analysis has been performed on anteroventral cochlear nucleus neurons (Wickesberg *et al.*, 1984) and on nerve-fiber responses of bullfrogs (Van Dijk *et al.*, 1994).

III. MATERIAL AND METHODS

In three human subjects with normal hearing, two consecutive emission measurements were performed. A subject was placed in a soundproof booth and a custom-built coupler was connected to the subject's ear canal. This coupler consisted of a miniature electrical driver and a Sennheiser KE 13-227 microphone. The stimulus was generated by a Stanford PG535 pulse generator (100- μ s-wide rectangular electrical pulse, with a repetition rate of 8 Hz) or delivered via a Sony PCM-F1 recorder (bandlimited white Gaussian noise, 0–5 kHz). The microphone signal was preamplified with a custom-built circuit, followed by a Philips PM5170 amplifier and bandpass filter (Krone-Hite 3550, 0.3–10 kHz, 24 dB/oct). If click pulses were used as a stimulus, the microphone signal was passed through a custom-built electronic switch (to be described later) before filtering. Both the electric signal delivered to the receiver and the microphone signal were digitally recorded with a two-channel 16-bit Denon DTR-2000 audio DAT recorder, at a sampling frequency of 48 kHz. Recorded signals were transferred off-line to the disk of a NeXT computer for further analysis, using a Singular Solutions A/D 64x.

Stimuli were calibrated in a Zwislocki coupler, using a Brüel & Kjær 4133 measuring microphone connected to a Brüel & Kjær 2636 measuring amplifier. In order to avoid nonlinearities in the receiver and microphone system, noise stimuli were never above 45 dB SPL. The peak level of the click stimulus was 60 peak dB SPL (20 mPa). The long-term power spectral density measured in the Zwislocki coupler was similar for both stimulus signals at maximum levels (see Fig. 1).

For each subject the following measurement series was performed:

At first, we started with six consecutive measurements with a click stimulus. The first measurement was performed at the maximum stimulus level (60 peak dB SPL) for 2 min.

FIG. 1. Amplitude spectrum of the click and noise stimulus at maximum intensity measured in a Zwislocki coupler. The long-term spectrum of the noise stimulus (dashed line) in the coupler is similar to the long-term spectrum of the click stimulus (solid line) in the region of 0.8–5 kHz.

Then, the stimulus was attenuated 10 dB and the measurement was repeated. This was repeated until a stimulus level of 10 peak dB SPL was reached. The two weakest stimulus levels, at 10 and 20 peak dB SPL, were not identifiable by the subjects.

In CEOAE measurements, stimulus and response are both measured in the ear canal. The pressure levels of the click stimuli are three orders of magnitude higher than the response levels. To record both stimulus and response signal in the ear canal, without losing dynamic range of the DAT recorder, the first part of the measured signal (including the stimulus) was compressed with an electronic switch for the first 6 ms after stimulus onset, before being digitally recorded. The compressed signal component was recovered off-line by computer before further analysis. With this technique the dynamic range of the DAT recorder is maximally used for the stimulus and response part in the measured signal. For each stimulus level 1024 artifact-free responses were averaged in the time domain, with a time window of 85 ms.

Second, without removing the probe, six consecutive measurements were performed with bandlimited Gaussian noise as the stimulus, starting at the maximum level of 45 dB SPL and with attenuation steps of 10 dB down to –5 dB-SPL.

Finally, 2 min of recording were performed with no stimulus activity in order to analyze if spontaneous otoacoustic emissions (SOAEs) are involved. SOAEs were calculated by averaging 1024 artifact-free (Hanning) windowed (85 ms) data in the spectral domain using fast Fourier transform (FFT).

For the noise stimuli, both the cochlear response and the stimulus signal are recorded by the recording microphone, e.g.,

$$y(t) = y_{\text{stim}}(t) + y_{\text{coch}}(t) + n(t). \quad (5)$$

Here, the first term y_{stim} represents the acoustic stimulus signal present in the ear canal, due to driving the transducer with an electric signal $x(t)$. The second term $y_{\text{coch}}(t)$ is the noise-evoked otoacoustic response to acoustic stimulus y_{stim} .

The signal $y_{\text{stim}}(t)$ is linearly related to the electrical

driver signal $x(t)$. Thus, these two signals are related by a convolution

$$y_{\text{stim}}(t) = [h * x](t), \quad (6)$$

where the system function h described the response of the transducer, the ear canal, and middle ear. For simplicity, we will refer to h as the middle-ear response function.

The third term $n(t)$ is the noise produced by the subject together with the microphone noise, which are both stimulus independent.

The main contribution to the microphone signal corresponds to the linear response $y_{\text{stim}}(t)$. This limits the ability to identify the cochlear response $y_{\text{coch}}(t)$. In order to reduce this problem, we first extracted the cochlear response $y_{\text{coch}}(t)$ out of the full microphone signal $y(t)$. This requires determination of the stimulus signal $y_{\text{stim}}(t)$, which can be computed from the electric stimulus $x(t)$ provided that the middle-ear response function h is known [Eq. (6)]. We estimated this response function by linear cross correlation of the full system response $y(t)$ and the electric signal $x(t)$, assuming that the first 3 ms of this cross correlation is the middle-ear response h .

Using the response function h , Eq. (6) was used to compute the signal y_{stim} , and Eq. (5) could then be used to extract the cochlear response y_{coch} from the microphone signal. Next, Wiener kernels were computed by cross correlation of the electrical signal $x(t)$ and the term $[y_{\text{coch}}(t) + n(t)]$, the cochlear response together with the subject and microphone noise.

An illustration of the effect of stimulus subtraction is depicted in Fig. 2, which gives the first 40 ms of the Wiener kernel $k_1(\tau)$ in subject EK. Trace *a* is the calculated $k_1(\tau)$ of the response without subtraction of the stimulus noise; trace *b* is $k_1(\tau)$ with subtraction of the stimulus. For comparison, trace *c* is a CEOAE from the same ear. It can be seen that the signal-to-noise ratio has been improved by using the stimulus subtraction technique. The gained improvement is on average 9 dB.

The unit for the amplitude of click-evoked responses is given in micro Pascal (μPa). It can readily be seen that the unit for the n th order Wiener kernel in Eq. (4) is equal to the unit of $y(t)$. The term $y(t)$ corresponds to the measured acoustic signal present in the ear canal [Eq. (5)], which is defined in μPa . So, Wiener kernels can be presented in the same unit as click-evoked responses.

To obtain the diagonals of higher-order kernels we calculated the polynomial correlation functions [Eq. (4)] up to order six. Similar to the calculation of the Wiener kernels, stimulus subtraction was used before calculating these polynomials.

IV. RESULTS

In Fig. 3 the first 4 milliseconds of the acoustic click and the calculated $k_1(\tau)$ for subjects EK, IE, and PE are shown. This represents the response of the probe placed in the ear canal, together with the influence of the middle ear. In each panel, the traces represent responses at the six consecutive attenuation levels used. Traces were superimposed after up-scaling to maximum stimulus level. The first 4 milliseconds

FIG. 2. Upper trace: the calculated first-order Wiener kernel $k_1(\tau)$ for subject EK. Trace *a* is the same kernel without the first 4 milliseconds on a smaller sound-pressure scale. No stimulus subtraction (see the text) was performed before calculating $k_1(\tau)$. Trace *b* represents $k_1(\tau)$ with stimulus subtraction. Trace *c* is a CEOAE from the same ear with the same time and sound-pressure scale. Traces *d*, *e*, *f* are spectra of traces *a*, *b*, *c*.

of the responses for the different stimulus levels are highly correlated (click: $r=0.98$; noise: $r=0.99$). Also the responses to clicks [panel (a)] and noise [panel (b)] are highly correlated ($r=0.98$). These results confirm linearity of the initial 3 ms of the response. As mentioned in the previous section, the initial 3 ms of the noise response [panel (b)] was used to estimate the middle-ear system function h [Eq. (6)].

In Figs. 4, 5, and 6 CEOAEs and NEOAEs (being the first order Wiener kernels) at different stimulus levels are shown for the three subjects. The first six traces are the CEOAEs at stimulus levels of 60 to 10 peak dB SPL. The next six traces are the calculated first-order Wiener kernels, $k_1(\tau)$, at 45 to -5 dB SPL. For all three subjects, emission responses became detectable at levels between 20 and 30 peak dB SPL for CEOAE measurement and between 15 and 25 dB SPL for the NEOAE measurement. At the two weakest stimulus intensities, both click- and noise-evoked responses diminish into the noise floor.

Subject EK, represented in Fig. 4, had no SOAEs. The subjects IE and PE, represented in Figs. 5 and 6, respectively, both had SOAEs as shown, respectively, in Fig. 7. IE had three emission peaks at 1415, 1511, and 1614 Hz at 5, 32, and 5 dB above noise level. PE had one emission peak at 1936 Hz at 12 dB above noise level.

To detect nonlinear growth of the CEOAE and the first-order Wiener kernel, responses obtained at different stimulus

FIG. 3. (a) Six superimposed traces of click-evoked responses for the first 4 ms after click onset for subjects EK, IE, and PE. Stimulus levels are 60 down to 10 peak dB SPL. The traces were multiplied with the stimulus attenuation factor before printing. (b) $k_1(\tau)$ calculated for the same ears for noise stimulus levels of 45 down to -5 dB SPL. No stimulus subtraction was applied before calculating $k_1(\tau)$. The kernels were also multiplied with the stimulus attenuation factor before printing.

levels were subtracted after proper multiplication to cancel the linear part. In Figs. 8(a) and (b) the result is shown for the four strongest stimulus levels of subject EK; the upper trace of panel (a) and (b) is the response at maximum stimulus level minus $\sqrt{10}$ times the response at 10 dB weaker stimulus level, etc.

For subject EK, only the strongest stimulus levels [upper traces of CEOAE and $k_1(\tau)$, respectively] revealed a significant nonlinear contribution. The corresponding spectra are shown in Fig. 8(c). It is clear that for this subject both the click-evoked and the noise-evoked OAE have a similar content.

Figures 8(d) and (e) show data of subject IE. In contrast to subject EK, IE emitted three SOAEs. The SOAEs clearly contribute to the CEOAE, as can be seen by the prolonged oscillations visible in the CEOAE traces. In contrast, in the noise-evoked OAE SOAEs are suppressed by 10 dB. Nevertheless, spectral analysis still reveals their presence [panel (f)]. The suppressive effect on SOAEs in noise-evoked OAE measurements is also demonstrated in Fig. 9, which shows results for subject IE. Here, the SOAE component, visible in

FIG. 4. (a) CEOAE traces from subject EK. Stimulus levels are 60 down to 10 peak dB SPL. The sound-pressure scale for the upper four traces is multiplied with the stimulus attenuation factor in order to make comparison easier. (b) $k_1(\tau)$ calculated for the same ear for noise stimulus levels of 45 down to -5 dB SPL. The same sound-pressure scales as in (a) are used. Stimulus subtraction was applied before calculating $k_1(\tau)$.

the CEOAE measurement, was suppressed by 6 dB in the NEOAE recording.

To measure the frequency-dependent emission amplitude ratio relative to the stimulus level we computed the envelope of the emissions, using wavelet transformation, with the Morlet wavelet as basis function (Guillemain *et al.*, 1989). Next, for each clearly detectable emission frequency (two per subject) the amplitude growth was calculated. Amplitude growth functions averaged across subjects for both click- and noise-evoked OAEs are depicted in Fig. 10. Both CEOAEs and NEOAEs show a compressive emission amplitude growth, whereas the NEOAE amplitude seems to grow more linearly. This growth difference, however, is not significant ($p < 0.05$).

For all subjects the calculation of second-order Wiener kernels did not show identifiable contributions. These kernels are not depicted.

In Fig. 11(a) polynomial correlation functions, obtained from the noise measurement at the maximum stimulus intensity for subject IE, are shown. For all subjects the first-order polynomial correlation function, $p_1(\tau)$, showed emission components. But, $p_2(\tau)$ up to $p_6(\tau)$ showed no contributions (no significant difference compared to correlation functions obtained from measurements in a Zwislocki coupler). Figure 11(b) gives the corresponding spectra of the correlation func-

FIG. 5. CEOAE traces and calculated first-order Wiener kernels for subject IE. Stimulus levels and sound-pressure scales were the same as in Fig. 4.

tions (the first 4 ms were zero-padded before calculating the spectra). Only the Fourier transform of $p_1(\tau)$ (thick line) shows emission peaks.

V. DISCUSSION

A. Correlation technique

Wiener kernel analysis is a nonparametric technique to model stationary stable systems.

Strictly speaking, the technique is not designed for identification of unstable nonlinear systems as, for instance, an ear which produces SOAEs. Nevertheless, we showed that the correlation technique of the Wiener kernel analysis is suitable to describe the response of the ear to a Gaussian noise stimulus.

B. Stimulus subtraction

In click-evoked OAE measurements the first 4 ms of the response, after stimulus onset, consists mainly of the impulse response function of the probe together with ear canal and middle ear. This click artifact persists, despite the use of a nonlinear averaging technique, due to nonlinearities in the measuring system.

A similar problem occurs in Wiener kernel analysis. Then, the first-order Wiener kernel function, i.e., the first-order correlation function of the stimulus noise and the mi-

FIG. 6. CEOAE traces and calculated first-order Wiener kernels for subject PE. Stimulus levels and sound-pressure scales were the same as in Fig. 4.

crophone response, contains a large component in the first 4 ms, corresponding to the middle- and outer-ear response. There, the large component is not an artifact of nonlinearities of the measuring system, but is inherent to the linear correlation analysis.

In this work we used the first 4 ms of the Wiener kernel as an estimate of the impulse response function of the outer and middle ear. By combining the recorded stimulus signal and this impulse response function, we estimated the outer- and middle-ear contribution to the recorded ear canal sound

FIG. 7. Power spectra of SOAEs of subject PE (solid line) and IE (dashed line).

pressure. After subtraction of this contribution, we recalculated Wiener kernels, gaining an extra 9 dB signal-to-noise ratio.

C. Wiener kernels

We computed the first- and second-order Wiener kernels, and the higher-order polynomial correlation functions. Only the first-order Wiener kernel displayed emission components. The first-order Wiener kernel was dependent on stimulus level.

The level dependence of the first-order Wiener kernel reflects the nonlinear level-dependent response of the cochlea. In contrast, the absence of emission components in second-order kernel and higher-order polynomial correlation functions suggests a linear cochlear response. Thus, although the response characteristics of the cochlea depend on stimulus level, at each particular noise level it seems to respond linearly. Note that this contrasts the cochlear response to clicks, which seems to consist primarily of intermodulation distortion (Yates and Withnell, 1999).

As mentioned above, the level dependence of the first-order Wiener kernel implies a nonlinear cochlear response. In turn, this implies that the higher-order Wiener kernels must be nonzero. Apparently, the cochlea acts as an automatic gain control (AGC) system, which sets up a (nearly) linear response behavior to each particular noise level. The time constant of the AGC is probably short compared to the measuring time used in this work (120 s), explaining the linear behavior we observed for each given stimulus level. On the other hand, it is long compared to the time base we used for kernel estimation (85 ms). This can be concluded from the fact that no AGC-like contributions are evident in the higher-order kernels we calculated.

D. Comparison of CEOAE- $k_1(\tau)$

The comparison of the first-order Wiener kernels with the CEOAEs at approximately equivalent stimulus levels shows that $k_1(\tau)$ resembles the CEOAE. For the objects, for which Figs. 5 and 6 give the results, this resemblance is good. For subject PE (Fig. 6) a high frequency component is found in the first part of $k_1(\tau)$, which is not present in the CEOAE. The frequency of this component is the same as that for the SOAE of this subject. Apart from these differences, the click- and noise-evoked responses are similar.

The nonlinear residues of $k_1(\tau)$ have the same temporal characteristics as CEOAEs, showing again that there are also nonlinearities in $k_1(\tau)$ (Fig. 8). For the ear without SOAEs [Fig. 8(a)] the comparison is better than in the case with SOAE [Fig. 8(d)]. The weaker the stimulus level the smaller the nonlinear residue.

If no residues are found then, in terms of stimulus level, no nonlinearities are present, as is the case for subject EK in Figs. 8(a) and (b). Residues can also be absent if emissions have a linear behavior with respect to stimulus level. The latter is the case for subject IE, where clear emissions are found down to -40 dB re. maximum stimulus level and where nonlinear contributions [Fig. 8(d)] in the CEOAE case are practically indistinguishable from the noise floor for the

FIG. 8. (a) Nonlinear residue resulting from subtraction of traces in Fig. 4. For CEOAE first trace: $[0\text{-dB stim trace}] - \sqrt{10}[-10\text{-dB trace}]$; second trace: $[-10\text{-dB stim trace}] - \sqrt{10}[-20\text{-dB trace}]$; third trace: $[-20\text{-dB stim trace}] - \sqrt{10}[-30\text{-dB trace}]$. (b) Analog as for (a) but now for the $k_1(\tau)$ traces. (c) Spectra of the top CEOAE trace (dotted) from (a) and the top $k_1(\tau)$ trace (solid) from (b). (d) Same as (a) but now for the CEOAE traces in Fig. 5. (e) Same as (a) but now for the $k_1(\tau)$ traces in Fig. 5. (f) Same as (c) but now from (d), (e).

lower stimulus levels. For the residues in $k_1(\tau)$ the emission component around 17 ms is canceled out at lower stimulus levels, as in the CEOAE case, but an oscillation remains at the SOAE frequency. Is this oscillatory signal really an emission component that belongs to $k_1(\tau)$?

SOAEs can be synchronized by external tones with frequencies close to the SOAE frequency (Van Dijk and Wit, 1990). Also, a click pulse may synchronize SOAEs (Wit *et al.*, 1981; Moulin *et al.*, 1993). This results in strong emission components in CEOAE measurements at SOAE frequencies, as can be seen in Figs. 5, 6, and 9. The presence of the SOAE component in $k_1(\tau)$ may imply that the SOAE is influenced by, and thus correlated to, the noise. However, a

SOAE emission component may also persist in the computed Wiener kernel if it is completely unaffected by the noise: due to the finite measuring time, its presence in the microphone system results in a corresponding component in the kernel.¹

FIG. 9. CEOAE and first-order Wiener kernel $k_1(\tau)$ for subject IE. For the CEOAE the click stimulus level was 50 peak dB SPL and for $k_1(\tau)$ a stimulus level of 35 dB SPL was used.

FIG. 10. Emission amplitude ratio with respect to the stimulus intensity (bars: 1 s.d.). The dotted line depicts linear amplitude growth.

FIG. 11. Polynomial correlation functions obtained from the recordings at maximum stimulus level for subject IE based on the data depicted in Fig. 5. (a) The first-order polynomial correlation function $p_1(\tau)$ up to the correlation function of the sixth order, $p_6(\tau)$. Polynomial correlation functions are proportional to the diagonals of Wiener kernels. (b) Spectra of the polynomial correlation functions.

E. Clinical aspects

Compared to other evoked-emission measurement, a possible advantage of NEOAE measurement for clinical application is that relatively small peak amplitudes are needed in order to obtain a considerable stimulus power. Thus, an emission measurement can be conducted at high stimulus level, without driving the measuring system into saturation. This may be useful when testing patients with mild to moderate hearing losses (conductive or sensory-neural).

F. Conclusion

We demonstrated that OAEs can be found with Wiener kernel analysis using Gaussian white noise as stimulus. The emissions, which were only visible in the first-order Wiener kernel, were consistent with the CEOAE data. The amplitude of $k_1(\tau)$ depended nonlinearly on the stimulus level, similar to the level dependence of CEOAE amplitudes. Apparently, in response to noise the cochlea acts as an automatic gain control system. For such a system, the response is stimulus-level dependent, but at each particular stimulus level it responds linearly.

ACKNOWLEDGMENT

The research of Bert Maat was supported by the Groningen Graduate School for Behavioral and Cognitive Neurosciences (BCN).

¹If we assume that an ear produces a strong SOAE and the stimulus is too weak to synchronize the SOAE. Then, the SOAE is independent of the stimulus and can, strongly simplified, be described as the function $y_s(t) = B(t)\cos(\omega_0(t+t_0))$. Here, the term $B(t)$ is the amplitude and ω_0 is the frequency of the SOAE. The first-order Wiener kernel calculated of $y_s(t) + y_{\text{other}}(t)$ will then be $k_1(\tau) = B/T \cos(\omega_0\tau + \phi(\omega_0)) + k_{1-\text{other}}(\tau)$. Here, $k_{1-\text{other}}(\tau)$ describes the non-SOAE activity of the ear, T is the averaging time, and $\phi(\omega_0)$ an arbitrary phase. The first part $k_1(\tau)$ is a periodic sinusoidal function on the stimulus noise level. Its amplitude is dependent on the measurement time and will reduce with factor $1/T$. The stimulus noise in $k_1(\tau)$ reduces with factor $1/T^2$, so the sinusoidal oscillation will become visible at kernel-noise level. As strong SOAEs are known as sinusoidal oscillations (Bialek and Wit, 1984) this could explain the existence of the SOAEs in $k_1(\tau)$ at low stimulus levels.

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