BASELINE SHIFTS MEASURED IN THE HUMAN EAR CANAL PRESSURE RELATED TO DISTORTION PRODUCT GENERATION AND TWO TONE SUPPRESSION

Eric L. LePage and Narelle M. Murray, OAEricle Laboratory, Sydney, Australia. www.oaericle.com.au
John D. Seymour, National Acoustic Laboratories, Chatswood, NSW, Australia

Presented at the Mid-winter meeting of the
Association for Research in Otolaryngology
Baltimore, Maryland, USA, February 5 - 9, 2006
Session D4: Inner Ear: Mechanics I, Poster #75
This poster may be downloaded from www.oaericle.com.au

When is OAE noise not noise?
Provisional answer: Most of the time

ABSTRACT

Recently we demonstrated the results of a two-tone experiment which resulted in baseline movements of ear canal pressure, and suggestive of two-tone suppression (2TS) at the cochlear mechanical level. These "dc-shifts" evident in the otoacoustic waveform did not appear to be due to middle ear muscle effects, which could be demonstrated separately. We here show the relationship between these baseline shifts and the resulting distortion products generated. Two tones bursts were delivered as a masker type experiment -- a 25 ms long probe tone of fixed frequency (3kHz) and level (70dB SPL) plus a "masker" tone burst of 7 ms which varied over a grid from 0.5 octaves above and below the probe tone, and from 50 to 90 dB SPL. We show the pattern of baseline shifts towards rarefaction and condensation according to the masker parameters for different subjects. Also shown are how the distortion products vary with the baseline variation and separation of the primaries (i.e. the probe and masker) while both tones are present. These baseline shifts constitute "infrasonic" otoacoustic products, and, because of their relationship to the distortion products, are strongly associated with cochlear mechanical generation.

INTRODUCTION

Previous work has shown mechanical behaviour in the baseline position of the basilar membrane in guinea pig preparations analogous to, and measured simultaneously with summating potential behaviour measured at the round window [1]. Both displayed similar polarity variations with frequency - above and below the best frequency of the place. Evidently, not all measureable position shifts are interpreted as outer hair cell (OHC) motile behaviour. Mechanical measurements by Flock have observed substantial "dc-shifts" in the motion of the Hensen cells signifying the presence of hydrops [2]. Quadratic distortion products (QDP) undergo baseline shifts and these have been interpreted as operating point shifts in OHC potentials, and treated as diagnostic of hydrops [3]. Transducer function characteristics have been derived on the basis of applying an external bias [4-6]. However, the question of the extent to which such operating point shifts are themselves manifest in the ear canal pressure remains to be fully characterised [7].

Evoked otoacoustic emissions (EOAE) are an important window into cochlear mechanical behaviour and their human characteristics have been explored extensively in terms of distortion products, transient responses and stimulus frequency emissions. Mostly, emissions contain considerable "noise", particularly at low frequencies. The presence of this noise has rendered determining trends in a 13 year longitudinal study particularly difficult [8].

The working hypothesis here is that much of this measurement noise is indeed due to adaptive OHC response, hydropic response, or both, with time courses not allowed for in the usual recording paradigm.

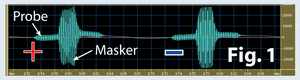
If so, it may indicate that, far from improving the characterisation of active processes, the act of signal averaging of the OAE signal may smear and obscure the dynamic nature of the regulatory processes controlling emission levels. Worse still, the usual heavy high-pass filtering of the emission signals to remove the significant low-frequency noise may be eliminating the key evidence that the forward transduction operating point is dynamically controlled by the OHC electromechanical feedback.

The experimental approach utilizes the same type of nonlinear residue extraction technique employed by Kemp [9] in transient (TEOAE) collection in comparing records obtained successively.

The preliminary findings here are presented for the data of just one subject. The other subjects show similar patterns. However, if the altogether-remarkable hypothesis that ***"most OAE noise is not noise"*** holds, then the significance of the approach should be clearly demonstrable from the data of any normally-hearing subject.

DATA COLLECTION

A standard distortion product otoacoustic emission (DPOAE) probe is sealed in the ear canal but not primarily for distortion product measurement. A two-tone masking paradigm is used; a constant 25 ms probe tone of 3 kHz at 70 dB SPL is repeated at 50 ms intervals. A masker tone of 7 ms duration is added 9 ms after the start of the probe tone. Both bursts employ 1 ms rise/fall times. The masker is varied in frequency (probe ± 0.5 oct in 1/12 oct steps), and level (probe ± 20 dB in 5 dB steps).



Each digitally-generated two-tone complex is immediately repeated, but with the repeat phase-reversed (see Fig. 1).

The whole sequence-grid of these "phase-reversal pairs" of 9 levels and 13 frequencies is repeated ten times, taking 2 minutes, and the 10 response sequences gathered with the intention of averaging them to eliminate external noise.

9 adult subjects (5 male, 4 female, whose audiometric and TEOAE characteristics are previously determined) are seated comfortably with head supported by a head rest.

The signals are generated and recorded at 44.1kHz by a NAL in-house built signal conditioning and recording system incorporating a Lynx 4 channel, 16 bit sound card. Sound calibrations were carried out using a 2cc coupler and B&K 2604 amplifier. All signals were processed using MATLAB™. For this data pass, the entire sampled-waveform was high-pass filtered (corner frequency 110 Hz) to remove heart beat pressure pulsations.

ANALYSIS

The sum and difference of each phase-reversal pair is computed. In Fig. 2, **Panel A** emphasizes what is common ("COM") to the pair which is primarily the delivered signal. This is represented by its envelope (Hilbert transform - blue line). The nonlinear residue ("DIF") is the red line (actually the sum of the pair of sequential presentations in Fig. 1). Its moving average (25pt gaussian-weighted) is represented by the black line. The top panel also shows the two tone stimulus segmented into five main intervals designated 1, 3, 5, 7 and 9. This presentation is confined to analysis of the activity within segment 5, during which both tones are present. Baseline pressure changes are determined from linear regressions on the time waveform to determine the *dc*-offset plus rate of change of the DIF. **Panel B** shows derivative and integral of the smoothed DIF as well as the estimated asymmetry of the DIF about the smoothed value. This is estimated by computing curves representing maxima and minima and subtracting their sum from twice the local mean value. **Panels C and D** are computed using a 2048-point Fast Fourier transform for Segment 5 of the time waveform after first applying a Hanning window. Panel C is for the raw signal while Panel D is for the DIF component. Shown are the magnitudes of the spectral peaks at the expected frequencies of the various quadratic |f1±f2| and cubic products |mf1±nf2| (QDPs, CDPs) and each of their respective second harmonics, plus the *dc* term, symbols as shown in the legend. While one would expect the DPs to reflect some of the time-determined parameters particularly the QDPs, this does not include the starting values and slopes. All the results presented are computed from the DIF component (so the primaries (f1, f2) are differences, see Panel D).

Temporal (baseline) and spectral variables defined for comparison

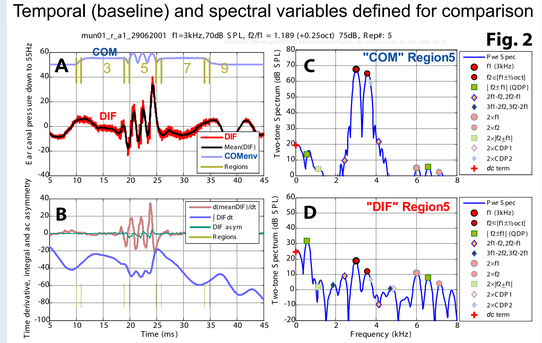


Fig. 2

RESULTS

Figure 3 shows for one subject, female normal hearing, strong transient emissions, a subset of the raw data obtained from the 2 minute sitting. The top row shows the "COM" signal (essentially the usually recorded DPOAE response) for the fixed probe and 3 levels of masker (blue) amplitude-modulated at the difference frequency f2-f1 (QDP). Below, each column shows 10 repetitions of the unaveraged responses of the "DIF" component (red) which, by linear subtraction, emphasises the nonlinear residue. At first the records appear to be significantly affected by noise, previously considered external to the processes of interest. Closer examination shows a wide variety of behaviours which are interesting in terms of cochlear homeostasis and OHC operating point control. The most important feature is that the baseline is varying quasi-chaotic, with various *dc*-levels at the onset of the masker. Secondly the asymmetry of the waveforms varies markedly from one level to the next, from one repetition to the next (in between are all other frequencies and levels). Thirdly, some waveforms are modulated at the QDP frequency leading often to a rapid baseline rise, while others the frequency is at 2xf2 and highly asymmetric, mostly with an unchanging or falling *dc* value. To average such data repetitions would smear over important dynamic behavior.

Individual repetitions seem contaminated by considerable noise on the baseline

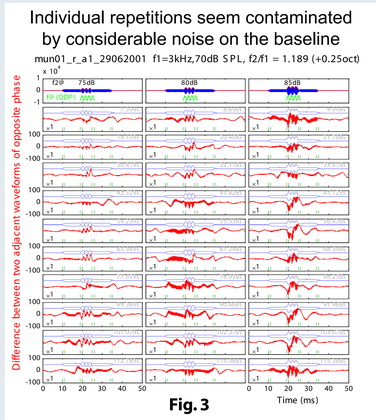


Fig. 3

A dot is placed for each repetition (#1- #10)

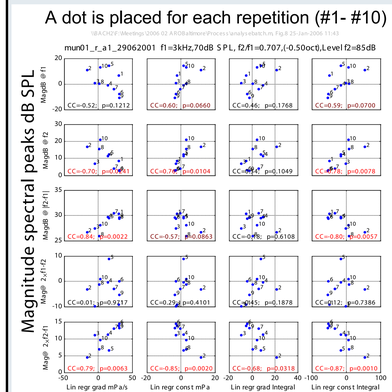


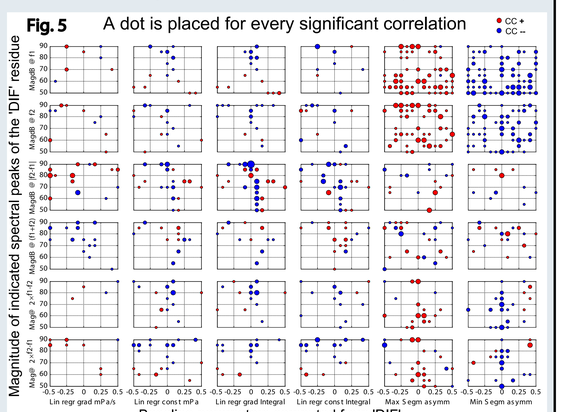
Fig. 4 Baseline parameters

Figure 4 shows the result of cross correlating the DIF parameters computed from the baseline (time) variables for just Segment 5 versus the spectral variables as shown in Fig. 2 for the same time segment. In each subplot are shown 10 points representing the values of the variables chosen for the 10 repetitions of the two tone stimulus. The four columns represent, respectively, **1)** the gradient of the DIF component, **2)** the linear regression constant (baseline starting value), **3)** the gradient of the integral of the DIF component, and **4)** its constant value. Descending subplot rows represent **1)** the DIF magnitude (dB SPL) of the f1 peak, **2)** the DIF magnitude of the f2 peak, **3)** the DIF magnitude of the |f2-f1| peak (for half the repetitions f2<f1), **4)** the DIF magnitude of the 2f1-f2, and **5)** the DIF magnitude of the 2f2-f1 peak. In each subplot, the correlation coefficient and its significance (p-val) is listed within the box with usual coloring for significance. As commented above it should not be all that remarkable that many of the cross-comparisons for the same data are highly correlated. On the other hand, *that which IS remarkable* is that these variables are correlated despite their wildly fluctuating behaviors as is indicated by the number of the repetition shown against each point. Considering that the baseline parameters do contain information which does not occur at the DP frequences, *the fact that these correlations can be high, suggests that the reason for the variation is anything but random.* The real test of significance depends on level and frequency.

Each of the subplots of **Figure 5** charts statistical outcomes for masker (f2) level versus masker frequency (oct distant) from the probe (f1) frequency. ***Every point in each box represents a significant cross-correlation between DP strength and a baseline parameter.*** i.e. 664 are significant out of a possible 4212 comparisons. The significance level of each point is represented by its size - (small p<0.05; medium p<0.01 and large p<0.001). Positive and negative correlations are red and blue respectively.

As for Fig. 4, the columns of boxes show the same selected baseline parameters, but two are added for the asymmetry of the DIF *ac* response. Asymmetry mostly occurs *not* for the rising QDP component but for the falling 2xf2 component. Each row is for one peak and the f1+f2 component is added to the list.

Fig. 5 A dot is placed for every significant correlation



Baseline parameters computed from 'DIF'

There are at least 4 interesting features: **1)** clusters with correlations of one polarity are often flanked by others of opposite polarity, **2)** high correlations still occur at low levels , **3)** in the 2 right columns the direction and asymmetry are consistent with a sigmoid curve, **4)** top right 4 boxes suggest some form of competition between the primaries; more significance for the higher level tone.

DISCUSSION

In NONE of the OAE probe data presented here has signal averaging been used to improve the signal-to-noise ratio (SNR). The variables are computed directly from the raw time signal minimally filtered as described above. The sensitivity of the technique for revealing these correlations is tied to the nonlinear ("DIF") extraction technique, which also is responsible for showing that the response to the probe signal is not always completely cancelled. Although ten repetitions of the signal sequence were collected to allow for signal averaging (as was previously used to show two-tone suppression contours on these same data [7]) this analysis has followed the realisation that these data may not be as strongly contaminated by noise as previously thought. Noise is a matter of definition. This surprising outcome cannot simply be due to the expectation that spectral parameters should correlate to time-series estimates - if this were the case all 4212 comparisons would be significant. Instead, significance occurs in clusters which have meaning for 2TS and DP generation (consistent with [7] the previous findings of triphasic pattern associated with the self-induced bias [1, 10]).

These data test the hypothesis that clinical algorithms used to improve the SNR may actually obscure vital behavior necessary to fully characterise the active processes. The "noise" previously deemed to be external to the process being characterised (e.g. strength of the 2f1-f2 DP) is instead intimately related to it, albeit in ways which are not fully understood. While we have no complete description of what is causing the wild variations seen in the raw data, this analysis merely compares aspects of the time course not directly contained in DPOAEs, with the way they are normally extracted by standard Fourier analysis.

It is suggested that the responses to the masker tone burst are caught in various states which suggest that operating point is changing over the whole range of the transducer function. Very often it is in a linear central region, or alternately saturated above and below this mid point. Subsequent baseline movement appears to be controlled by processes invoked when saturation result in strong asymmetry of the *ac* waveform. These data further support the notion of two opposing active mechanical processes [10] required to maintain the OP.

If there is any merit to this approach it may explain the basis of mechanical variability [11] and hysteresis [12] in our guinea pig data -- not to mention our difficulties with comparing TEOAEs over many years in the same subjects.

CONCLUSIONS

1) We continue to question whether the only 'vehicle' for extracting information about active processes is OAEs within the auditory passband, or alternately whether it is possible to directly access cochlear homeostatic processes remotely from ear-canal pressure. Since their discovery, it has been assumed that OAEs are only auditory-band signals and that huge levels of noise contamination required extensive processing. **2)** *The remarkable feature of the study is that very high correlations have been found between baseline "noise" in the unaveraged signal and the magnitude of DPOAEs, particularly the QDP.* **3)** These data further support the existence of a 'self-induced' bias [1] due to OHC activity (which is interacting with any externally-applied low-frequency bias [4-6]). **4)** The outcome leads directly to questioning, *"What is signal and what is noise?"* in OAEs. **5)** These findings help explain difficulties in managing the huge variability in clinical OAE data, particularly longitudinal data [8]. **6)** The notion of studies needing many subjects and complex designs to show significance stems from preconceptions of 'noise'.

Acknowledgements

These data were collected as part of projects HLPR98.1 & HLPR98.2 at the National Acoustic Laboratories, which received approval from the Research and Human Ethics Committees.

References

1. LePage, E. L. Frequency-dependent self-induced bias of the basilar membrane and its potential for controlling sensitivity and tuning in the mammalian cochlea. J Acoust Soc Am. 1987; 82:139-154.
2. Flock, A. and Flock, B. Hydrops in the cochlea can be induced by sound as well as by static pressure. Hear Res. 2000 Dec; 150(1-2):175-88.
3. Sirjani, D. B.; Salt, A. N.; Gill, R. M., and Hale, S. A. The influence of transducer operating point on distortion generation in the cochlea. J Acoust Soc Am. 2004 Mar; 115(3):1219-29.
4. Patuzzi, R. and Moleirinho, A. Automatic monitoring of mechano-electrical transduction in the guinea pig cochlea. Hear Res. 1998 Nov; 125(1-2):1-16.
5. Bian, L.; Chertoff, M. E., and Miller, E. Deriving a cochlear transducer function from low-frequency modulation of distortion product otoacoustic emissions. J Acoust Soc Am. 2002 Jul; 112(1):198-210.
6. Lukashkin, A. N. and Russell, I. J. Dependence of the DPOAE amplitude pattern on acoustical biasing of the cochlear partition. Hear Res. 2005 May; 203(1-2):45-53.
7. LePage, E. L.; Murray, N. M., and Seymour, JD. Novel otoacoustic baseline measurement of two-tone suppression behaviour from human ear-canal pressure. Presented at: "Auditory mechanisms: processes and models", The ninth "Mechanics of Hearing" workshop; OHSU, Portland, OR. 2005 Jul 23-2005 Jul 28.
8. LePage, E. L. and Murray, N. M. (in preparation). 2006.
9. Kemp, D. T. Evidence of mechanical nonlinearity and frequency selective wave amplification in the cochlea. Arch Otorhinolaryngol. 1979; 224(1-2):37-45.
10. LePage, E. L. Functional role of the olivo-cochlear bundle: a motor unit control system in the mammalian cochlea. Hear Res. 1989 Apr; 38(3):177-98.
11. LePage, E. L. and Johnstone, B. M. Short-term vulnerability and variability of the basilar membrane nonlinearity. J Acoust Soc Am. 1981; 70:58.
12. LePage, E. L. Hysteresis in cochlear mechanics and a model for variability in noise-induced hearing loss. In: A. Dancer, D. Henderson R. J. Salvi and R. P. Hamernik. Noise-Induced Hearing Loss. St.Louis : Mosby Year Book; 1992; pp. 106-115.