Novel Otoacoustic Baseline Measurement Of Two-Tone Suppression Behaviour From Human Ear-Canal Pressure

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Abstract

We describe extension of otoacoustic emission technique intended to directly register change in cochlear mechanical baseline. A two tone probe/masker experiment is described in human subjects. Instead of calculating distortion products from the averaged responses, low frequency variation in ear canal pressure is obtained. The pattern of positive and negative summating/adaptive behaviour versus frequency and level of the masker is reminiscent of two-tone suppression contours. The technique largely eliminates middle ear considerations and opens up questions concerning cochlear homeostasis.

Introduction

Previous work [1] 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. 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 undergo baseline shifts and these have been interpreted as operating point shifts in OHC potentials, and treated as diagnostic of hydrops [3]. However, the question of whether "dc-shifts" occur in relation to OHC homeostasis remains.

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 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.* We have investigated whether cochlear summating responses are salvageable by using signal averaging of the ear-canal pressure.

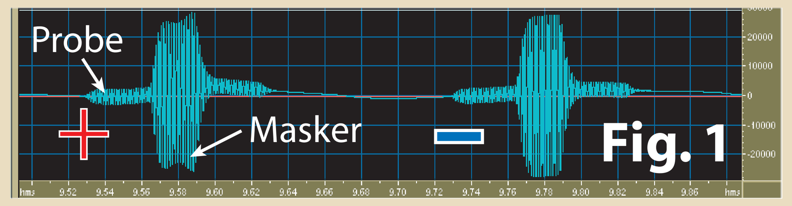
The experimental approach utilizes the same type of nonlinear/active extraction technique employed by Kemp [4] in transient (TEOAE) collection in comparing records obtained successively. *Here, instead of looking for nonlinear changes with click level, we are looking for how the system responds to the phase reversal of the probe/masker combination.*

The experiment has similarities with the experiment of Pumphrey and Gold [5] which showed that cochlear processing has memory for phase. Their experiment certainly shows memory for cochlear status, which may depend upon which direction summation occurs, and in turn depend upon stimulus phase. We explore ear canal responses from which the linear component is removed, leaving any nonlinear difference due to the summation.

Since mechanical correlates of two-tone suppression (2TS) exist [6-8] it is of interest to see if correlates can be extracted directly from ear canal pressure *without* highly filtering the responses by reduction to DPOAE behaviour accompanied by the quest to make sense of that.

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 10 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 5 levels and 13 frequencies is repeated ten times, taking 2 minutes, and the 10 response sequences averaged to eliminate external noise.

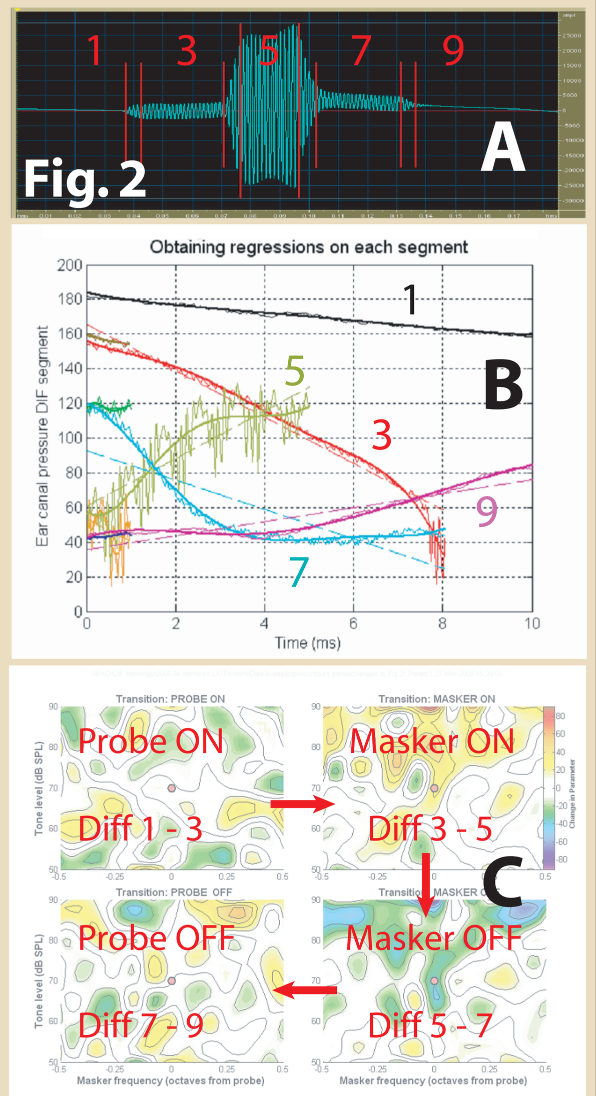


9 Subjects (young adults 5 male, 4 females whose audiometric and CEOAE characteristics are previously determined) are seated comfortably with head erect and supported by a head rest.

The signals are generated and recorded 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™. Artifact rejection, if required, ranked consistency of responses - most consistent 80% were analysed.

Analysis

The sum and difference of each phase-reversal pair is computed. The ***difference*** emphasizes what is common to the pair which is primarily the delivered signal. The ***sum*** yields the nonlinear residue. In Fig. 2, **Panel A** shows the probe and masker tones measured by the distortion product probe sealed in the ear canal, plus any baseline changes. It also shows the two tone stimulus segmented into five main intervals designated 1, 3, 5, 7 and 9 (see discussion). Baseline pressure changes are determined from regressions on the time waveform to determine the rate of change of the ***sum*** (mPa/s). **Panel B** shows for each segment polynomial curve fits of orders 1 (linear regression) and 4.



Panel C shows how the baseline slope changes from one segment to the next (i.e. segments 1 to 3, 3 to 5 etc.) for all frequencies and levels of the masker. Each transition is computed from the difference of like regression coefficients (e.g. the top left quadrant is the difference between the slopes determined from segments 1 and 3). The changes for all masker levels and frequencies is represented as a contour plot. The fixed probe is shown as the central dot. The colors represent rates of baseline shift according to the colormap shown, zero shift is white, positive- and negative-going shifts (condensation and rarefaction) are shown by warm and cool colors respectively. This z-dimension scale changes with coefficient. The contours are lines of equal rate. The clockwise ordering of the panels (see arrows) assists comparison of masker and probe datasets/offsets.

Results

Figure 3 shows (upper and lower panels respectively) an example of both difference and sum of the averaged responses for one masker frequency and level, shown for probe and masker tones for segments 3, 5 and 7. The difference of the two responses is essentially the sound in the ear canal of the 2 tone stimulus. The sum reveals virtually perfect cancellation of the probe tone when alone, leaving only the 'dc' variation. With the masker present i.e. the middle segment (5), we see five features of interest: **1)** evidence of variation of amplitude (here ~30 dB less in amplitude - while its appearance suggests intermodulation, the term is inappropriate because the pair of presentations is not simultaneous - however it does represent the nonlinear increment); **2)** segment 5 (red) presents at exactly twice the masker frequency (see Table inset); **3)** a shift in the baseline of half the 'ac' amplitude over 5 ms (about 0.1 mPa/s); **4)** asymmetry of the kind previously seen in IHC membrane potential [9] and **5)** the baseline shift for this particular set of stimuli does not subside at the end of the masker burst, but is longer lasting -- the baseline setpoint is set to a new level - remembering that this is the average of 10 such repetitions, interspersed by all the other frequencies and levels.

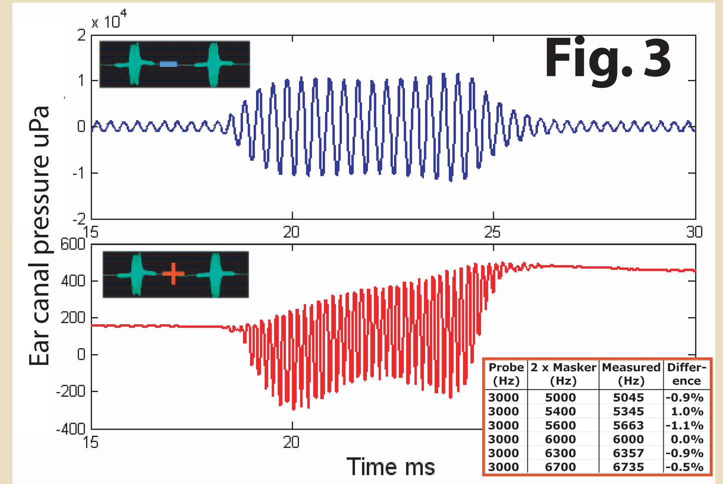


Figure 4 shows summed-pair pressure waveforms for 3 subjects, as masker frequency varies below and above the probe frequency, at 90dB SPL. The change in slope for the probe tone alone is generally closer to zero, than for the interval when the masker is present, producing positive- or negative-going summation.

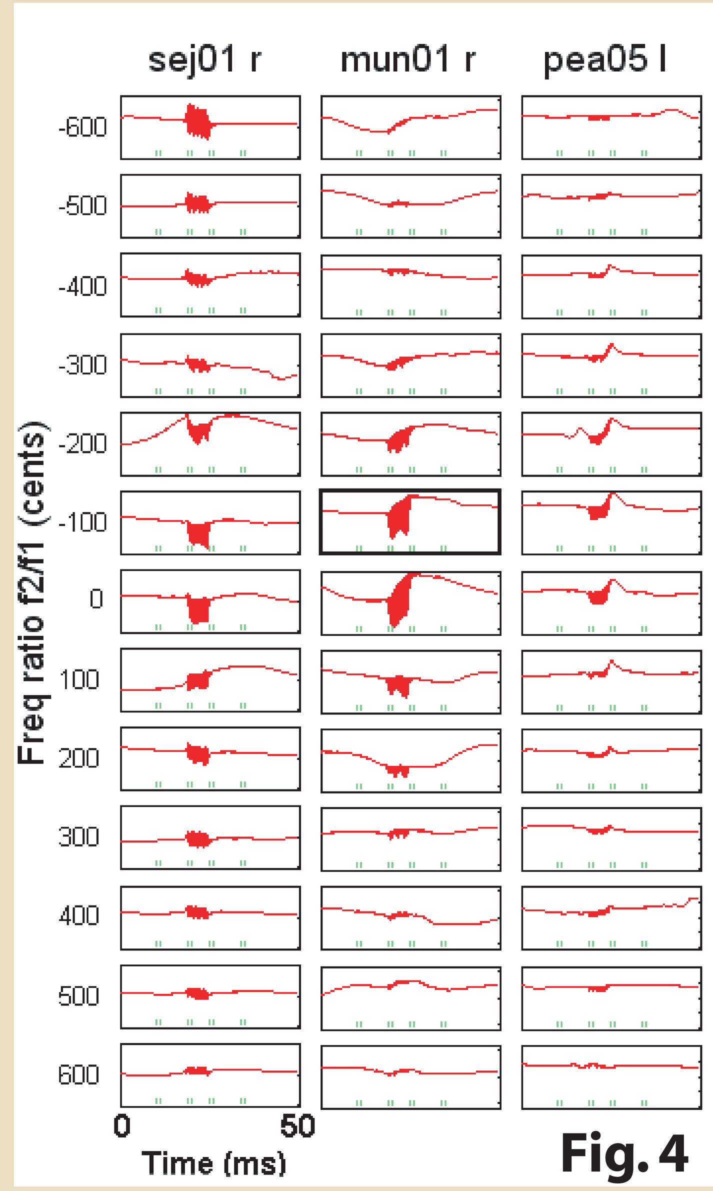
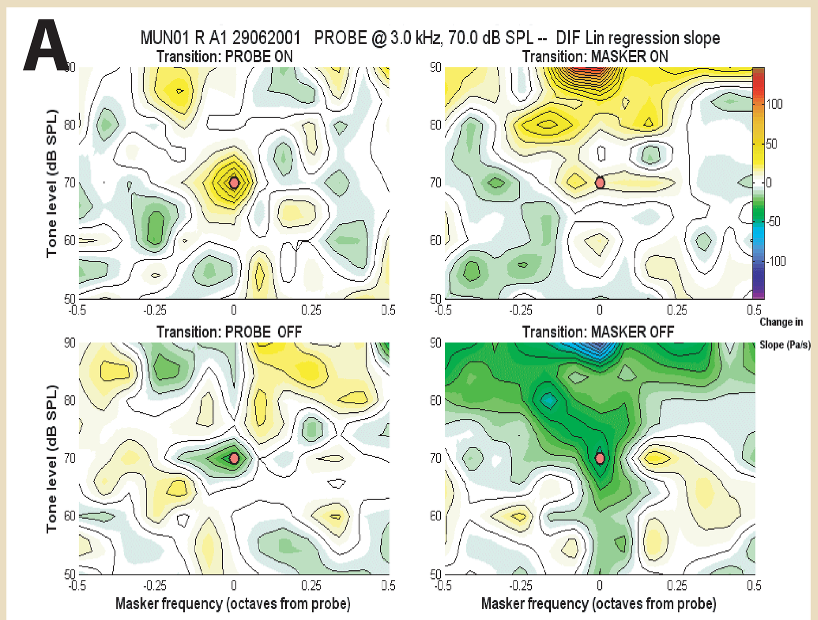
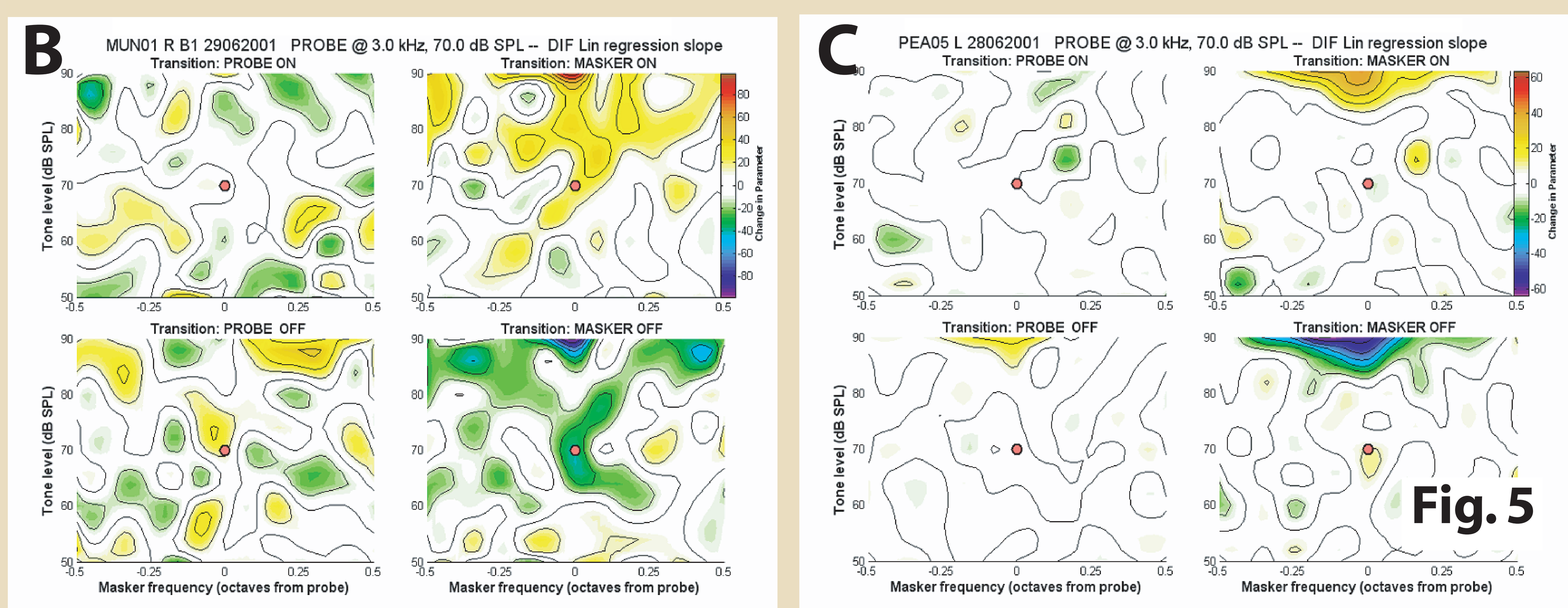


Figure 5 compresses these trends using contour plots of masker level vs masker frequency, the z-dimension is the rate of shift of ear canal baseline pressure. Composite panels A and B are for the one subject and show no obvious patterns for just the transition from no stimulus to PROBE ON, nor for PROBE OFF (left panels). However, adding MASKER ON produces a positive-going baseline shift pattern above the probe level, while turning the MASKER OFF produces summation in the negative-going direction. Comparison of panels A and B indicate the level of reproducibility of the linear regression measures carried out in the same session -- and also seen in later sessions. Panel C for another subject, only shows such summation for relatively high masker levels (>80 dB SPL, see discussion re stapedius reflex and timing issues).



For these preliminary data, increasing masker levels rising above the probe tone level appears to increase the frequency range for which masker onset produces condensation; same applies for masker offset-produced rarefaction.



Discussion

Low frequencies are normally filtered from clinical recordings on the basis they are primarily noise or that no useful information exists outside of the auditory passband that is not already contained in emissions. This approach benefits from multiple measures for external noise reduction, to attempt to eliminate breathing noise, internal body noises and cardiac pressure pulses (up to 80 dB SPL) in the ear canal. The possibility that these data (particularly the high level shifts) are due to stapedius reflex [10] seems remote since each whole experiment was scrutinised, and replayed unaveraged, for signs of stapedius response. The data did not show an obvious pattern in the Probe-ON and -OFF transitions - which is expected because there is no reference condition. However, the Masker-ON and -OFF seems more robust which can be attributed to using the Probe-only condition as a reference. This transition is repeatable.

The post-processing of the data, after averaging, is, for this first pass, timed to stimulus segmentation. This schema does not allow for delays of physiological origin. It might well be that some active OHC, medial-efferent, or hydropic-type phenomena may result in delayed transitions which will affect the computed slopes, seriously underestimating them. This is suggested in the data shown for subject pea05L (Figs 4 and 5C).

Since the baseline shifts are occurring at infrasonic frequencies, the responses captured here are not "emissions" in the audio-frequency sense. Rather they may be more reminiscent of electro-mechanical adaptation in the cochlea shown via its effect upon DPOAE behaviour [11,12]. There is not room here for showing the DPOAE generated, yet it is clear that the baseline behaviour may be important for understanding the origin of the intermodulation. It is not impossible that the f_2-f_1 component [3] may, in more basic terms, be characterised as a baseline-shift. **There is similarity of these contours and neural 2TS contours, further supporting a basilar membrane-bias origin for two-tone masking effects.** If these ear-canal baseline shifts are related to summating phenomena and fatigue [15] it might account for the variability seen.

Intriguingly, these results lead to questioning what is the nature of the "phase-memory" responsible for the Pumphrey-Gold effect [5]. Could such storage take the form of operating point which is sensitive to phase change, such as the phase switching used by them and us here?

Conclusions

It has been worthwhile to question whether the only 'vehicle' for extracting information about active processes is otoacoustic emissions within the auditory passband, or alternately whether it is possible to directly access cochlear homeostatic processes as baseline shifts in ear-canal pressure and not be completely hi-pass filtered by the middle ear. The preliminary data suggest that the approach is worth following since such changes may underpin DPOAE generation and two-tone suppression. If baseline changes are readily measured in the ear canal it bypasses some of the controversial issues as to whether they exist at the basilar membrane level. Lastly, the experiment leads to questioning the nature of mechanisms responsible for why Gold concluded that there must exist a highly tuned mechanical oscillator, with low damping.

Acknowledgements

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