ANALYSIS OF HUMAN OTO-ACOUSTIC EMISSIONS

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1. INTRODUCTION

Oto-acoustic emissions have been reviewed, e.g., by Kemp (2007). In the present contribution, the TEOAEs (transient-evoked oto-acoustic emissions, also called click-evoked or delayed evoked) in Fig. 1 are analysed in detail.

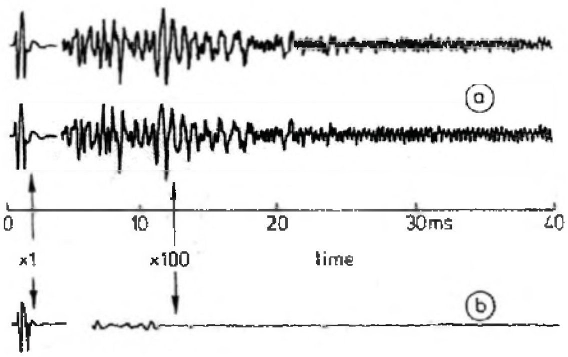

Fig. 1. Reproduction (with permission) of Fig. 16.20 of Fastl and Zwicker (2007), showing click-evoked oto-acoustic emissions from human ears; a: healthy ear of baby; b: human subject with hearing loss.

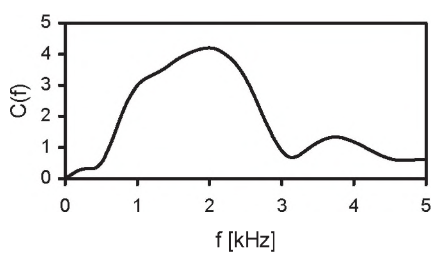

Fig. 2. Frequency spectrum of clicks shown in Fig. 1 at times from 0 to 2 ms. C(f) [in arbitrary units] is the absolute value of the complex Fourier integral defined by Eq. (8.1a) of Hartmann (1998).

In the experiment yielding Fig. 1 there was a sound source (generating the click) and a microphone (generating the three traces shown) in the closed ear canal of the subjects. The frequency spectrum of the click (time = 0 to 2 ms), derived by Fourier transformation [e.g., Eq. (8.1a) of Hartmann (1998)] from the click waveform in Fig. 1, is presented in Fig. 2. The click and the TEOAE (time = 4 to 17 ms; signal magnified, in Fig. 1, by a factor of 100) both contain frequencies from ~1 to ~2.5 kHz. The time-dependence of the instantaneous TEOAE frequency, derived from the waveform in Fig. 1a, is shown by a solid line in Fig. 3. At times later than ~14 ms there is, in Fig. 1a, a “spontaneous” 3-kHz emission, triggered by the click (see Section 2 below).

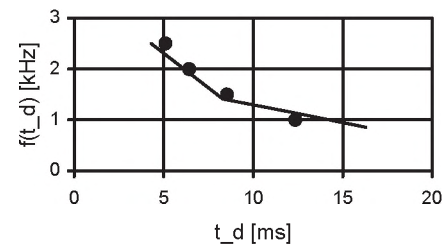

Fig. 3. Instantaneous frequency of emissions shown in Fig. 1 at times from 4 to 17 ms versus delay t_d after click centre [i.e., t_d = time – 0.7 ms]. Solid line: experimental frequency, derived from waveform in Fig. 1a. Filled circles: theoretical frequency, derived from surface-wave formulae according to Section 2 below.

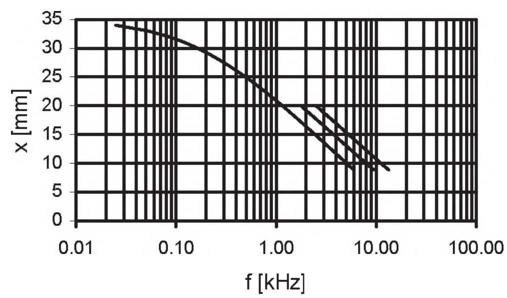

Fig. 4. Preliminary human cochlear maps; *x*: distance from base; *f*: pure-tone frequency; lower curve, 0.025–6 kHz: passive-peak map; same lower curve, 1–6 kHz: internal organ-of-Corti resonator map; middle curve, 2–10 kHz: active-peak map; upper curve, 2.5–13 kHz: basilar membrane resonator map.

2. METHODS

The derivation of the theoretical instantaneous emission frequencies represented by filled circles in Fig. 3 was based on the cochlear maps shown in Fig. 4. These maps are described in Frosch (2009, 2010a). The lowest of the three curves gives the place x [i.e., the distance from the cochlear base, measured along the basilar membrane (BM)] of the “passive peak” [BM oscillation-velocity maximum during the perception of a pure (sinusoidal) tone of frequency f, if the “active” outer hair cells (OHCs) do not function]. For $x < 20$ mm, that same lowest curve in Fig. 1 gives the resonance frequency of the local IOCR (internal organ-of-Corti resonator). The middle curve in Fig. 4 gives the location of the “active peak” (BM oscillation velocity maximum in healthy cochlea during perception of low-level pure tone). The upper curve in Fig. 4 gives, for $x < 20$ mm, the resonance frequency of the local BMR (basilar-membrane resonator).

Interpretation of Fig. 1b: The OHCs in the basal half of the cochlear channel were damaged; cochlear travelling waves generated by the click were "passive", were not significantly reflected, and were extinguished by friction after having passed their passive-peak place.

Interpretation of Fig. 1a: Any strong component of the click frequency spectrum (Fig. 2) caused the OHCs in the corresponding IOCR resonance region to feed "actively" mechanical energy into the travelling wave, to thus give rise to the "active peak" for that component, and also to generate a backward travelling wave, which carried some of the mechanical energy generated by the OHCs back towards the stapes.

The "spontaneous" 3-kHz emission in Fig. 1a is attributed to feedback-generated BMR oscillations involving *evanescent liquid sound-pressure waves* [Frosch (2010a, 2010b)]. Conjectured place of the *submerged* BMR generating the 3-kHz emission: x = 16.6 mm; local BMR frequency according to Fig. 4 (valid for oscillations without cochlear liquid): 4.2 kHz. Resonance frequency of that same local BMR if it is submerged in cochlear liquids and generates evanescent waves: 3.0 kHz.

Formulae for theoretical TEOAE delay $t_d(f)$ *:*

$$t_d(f) = 2\tau_{\text{sw}} + \tau_{\text{rise}}, \tag{1}$$

where τ_{sw} = surface-wave group travel time, from $x = 0$ to $x_{\text{IOCR}}(f)$, according to box-model short-wave formula,

$$\tau_{\text{sw}} = \frac{4\rho \cdot \omega}{\alpha \cdot S_0} \cdot \left(\frac{1}{e^{-\alpha \cdot x} - \eta} - \frac{1}{1-\eta} \right); \tag{2}$$

see Chapter 44 of Frosch (2010a). In Eq. (2), ρ is the cochlear-liquid density; the constants S_0 and α define the BM stiffness, $S(x) = S_0 \cdot e^{-\alpha \cdot x}$; $\omega \equiv 2\pi \cdot f$ is the angular frequency, and $\eta \equiv M \cdot \omega^2 / S_0$ is a dimension-less frequency-dependent quantity; M is the BM surface mass density. The following constants were used:

$$\rho = 10^3 \frac{\text{kg}}{\text{m}^3}; S_0 = 10^{10} \frac{\text{N}}{\text{m}^3}; \alpha = 300\text{m}^{-1}; M = 0.1 \frac{\text{kg}}{\text{m}^2}. \tag{3}$$

The quantity $\tau_{\text{rise}} = Q/(\pi \cdot f) \approx 1.3/f$ in Eq. (1) is the rise time of the forced oscillations of the IOCRs, which have a quality factor of $Q \approx 4$.

Theoretical delay of start of 3-kHz emission in Fig. 1a:

$$t_d = \tau_{\text{sw}}(f_{\max}, x) + \Delta t + \tau_{\text{sw}}(3\text{kHz}, x), \tag{4}$$

where $f_{\max}$ = 2.5 kHz = highest strong component of click spectrum (Fig. 2); the lower-frequency components have shorter τ_{sw}; $x = 16.6\,\text{mm}$ = place of BMR generating the 3-kHz emission; $\Delta t \approx 1\,\text{ms}$ = time after passage of $f_{\max}$-component at which liquid is sufficiently quiet for generation of evanescent waves [Frosch (2010a), (2010b)].

3. RESULTS

The theoretical TEOAE delays $t_d(f)$ for f =1.0, 1.5. 2.0, and 2.5 kHz derived from Eqs. (1)–(3) are represented by filled circles in Fig. 1 and are seen to agree fairly well with the solid line representing the experimental delays derived from the TEOAE waveform in Fig. 1a.

The theoretical TEOAE delays according to Eqs. (1)–(3) were found to agree not only with Fig. 16.20 of Fastl and Zwicker (2007) [reproduced in our Fig. 1], but also with the many experimental TEOAE delays presented in their Fig. 3.20.

The BMR place $x = 16.6\,\text{mm}$ inserted into Eq. (4) yields a theoretical delay of $t_d = 13\,\text{ms}$ (corresponding to time ≈ 14 ms) for the start of the 3-kHz emission, in agreement with Fig. 1a. As mentioned in the text above Eq. (1), the without-liquid BMR frequency at that place is 4.2 kHz.

4. CONCLUSIONS

The measured dependence of the click-evoked otoacoustic-emission (OAE) delay on instantaneous frequency is consistent with the hypothesis that these emissions are generated by the outer hair cells (OHCs) which feed energy into the forward travelling cochlear surface wave.

The place of these OHCs is the place of that internal organ-of-Corti resonator (IOCR) having a resonant frequency equal to the considered click-component frequency; above ~1 kHz, that place is basal of the "characteristic place" (=low-level active-peak place) by ~0.5 octave distance (~2.3 mm), and basal of the corresponding basilar-membrane resonator (BMR) by ~1 octave distance (~4.6 mm).

The "spontaneous" OAEs are hypothesized to be due to BMR oscillations which involve evanescent (standing) liquid sound-pressure waves and so have a frequency ~0.5 octave below the local without-liquid BMR frequency; these oscillations are thought to be generated by feedback from a local IOCR having a resonance frequency region ranging up to exceptionally high frequencies.

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