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Abstract: Hearing thresholds for pure tones between 16 and 30 kHz were measured by an adaptive method. The maximum presentation level at the entrance of the outer ear was about 110 dB SPL. To prevent the listeners from detecting subharmonic distortions in the lower frequencies, pink noise was presented as a masker. Even at 28 kHz, threshold values were obtained from 3 out of 32 ears. No thresholds were obtained for 30 kHz tone. Between 20 and 28 kHz, the threshold tended to increase rather gradually, whereas it increased abruptly between 16 and 20 kHz.

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1. Introduction

It has been warned since the 1960s that very high-frequency noises could cause subjective effects, such as discomfort and fullness in the ears, malaise, nausea, vestibular dysfunction, tinnitus, and persistent headaches. Extraordinarily high-level ultrasounds may also induce temporary threshold shifts.[1] Although a number of damage risk criteria and maximum permissible levels such as that introduced by Health Canada[2] have been proposed since the 1960s, these tentative recommendations were based on scant experimental and survey data.[1]

Absolute thresholds for pure tones have been studied by many groups of researchers.[3–11] The absolute threshold usually starts to increase sharply when the signal frequency exceeds about 15 kHz. It reaches about 80 dB SPL at the frequency of 20 kHz.[3,6,8,11] Above 20 kHz, however, only limited data have been reported. According to recent studies,[12,13] ultrasounds seem to be inaudible as long as their level does not exceed about 85 dB SPL.

To determine thresholds at very high frequencies, stimuli have to be presented at extremely high levels. It is not easy, however, to present pure tones at a level above 80 dB SPL with a good resolution. Factors that affect the maximum measurable threshold are the resolution of the signal, performance of the D/A converter, amplifiers, and loudspeakers. In particular, sufficient linearity of loudspeakers is definitely needed.[12,14]

Henry and Fast[4] used a sound delivery system that could deliver constant stimuli up to 124 dB SPL, and reported that most listeners had detected tones up to 24 kHz. They noted that thresholds increased abruptly as the signal frequency changed from about 14 to 20 kHz. Above 20 kHz, however, thresholds increased less rapidly. In Henry and Fast's study, however, the characteristics of acoustical stimuli were not fully described. They did not specify the amount of subharmonic distortions; they only referred to harmonic distortions. Listeners in their experiment might have been responding to low-frequency distortions or noises.

Ashihara *et al.*[15] made an attempt to measure threshold of hearing for pure tones up to 28 kHz. In their study, white noise was used to mask subharmonic distortions. They could obtain threshold values from some listeners for a 24 kHz tone. They also noted that hearing threshold increased gradually for tones from 20 to 24 kHz.

These studies show that some listeners can perceive tones up to at least 24 kHz. The highest frequency examined in Henry and Fast's study was 24 kHz. Ashihara *et al.* could not obtain threshold values above 26 kHz. The highest presentation level in their study was 99 dB SPL. Therefore, it is still an open question if tones above 26 kHz would be audible or not when their level exceeded 100 dB SPL.

The purpose of the present study is to obtain thresholds for tones up to 30 kHz. A transformed up-down method combined with a two-alternative forced choice (2AFC)

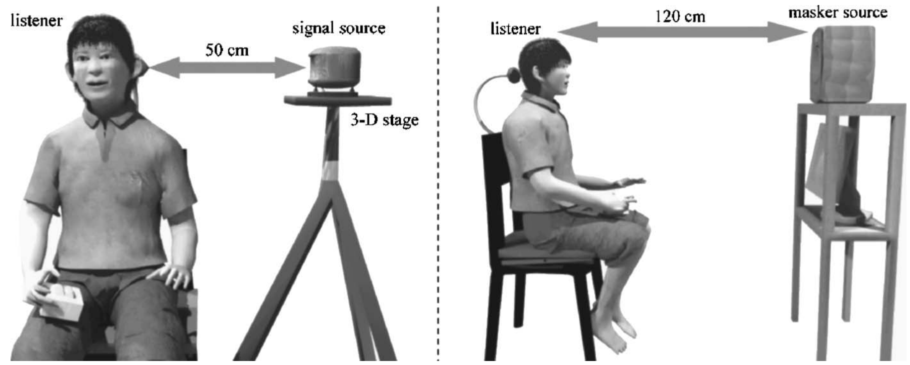

Fig. 1. Front view (left) and side view (right) of the listener. A 3D stage was adjusted so that the signal source directly faced to the entrance of the listener's ipsilateral ear and the distance between the signal source and the entrance of the listener's outer ear was 50 cm. The masking noise was presented by the masker source that directly faced to the listener's face. The distance between the masker source and the midpoint of the listener's head was 120 cm.

procedure[16] was employed in the present study. The hearing threshold was measured at every 2 kHz between 16 and 30 kHz. To prevent listeners from detecting subharmonic distortions in the lower frequency range, pink noise was used as a masker. To evaluate the masking effect caused by the pink noise, masked and the absolute thresholds were measured at 250 Hz, 1, 4, and 12 kHz.

2. Method

2.1 Listeners and equipment

Eight males and 8 females participated. None of them had a history of otological disease. Their ages ranged between 19 and 25 years. They were paid for their participation. Necessary information about the experiments was given to them and a written informed consent was obtained from each participant prior to the experiment. The study was approved by the Ethics Committee of National Institute of Advanced Industrial Science and Technology.

In the free-field measurement of the hearing threshold, the distance between the signal source and the listening point is recommended to be at least 1 m.[17] In the present study, however, a signal source was placed at a distance of 50 cm from the listener's ear to provide sufficient level at the listening point. A listener sat on a chair with the back of his or her head attached to a headrest in an anechoic room. The listener was instructed not to move his or her body during the measurement.

Two sound sources were used in the measurement. They were a signal source and a masker source. The signal source was either a super-tweeter (PIONEER PT-R100) or a loudspeaker (DENON SC-A33) and the masker source was a loudspeaker (DENON SC-A33). The signal source was set on a three-dimensional (3D) stage placed on either the right or left side of the listener. The stage was adjusted so that the signal source directly faced to the entrance of the listener's outer ear and the distance between the signal source and the entrance of the outer ear was 50 cm as can be seen in Fig. 1. The masker source was at a distance of 120 cm from the midpoint of the listener's head and it directly faced to the listener's face as shown in Fig. 1. A liquid crystal display was placed in front of the listener for instructions and a visual feedback.

2.2 Stimuli

Digitally synthesized sinusoids were used as signals. The signal was generated by a D/A converter (EDIROL UA-1000) at a sampling rate of 96 kHz and 16 bit resolution. The signals at 16 kHz and above were presented by a super-tweeter (PIONEER PT-R100) via a high-pass filter (PIONEER DN-100). A loudspeaker (DENON SC-A33) was used for the signals at 250 Hz, 1,

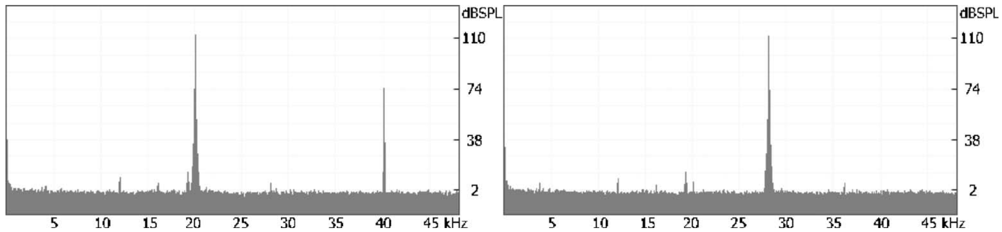

Fig. 2. Signals at the listening point. The power spectra of the signals at 20 kHz (left) and 28 kHz (right) are shown. The signals were recorded at a distance of 50 cm from the signal source when the listener was absent. Their level was 110 dB SPL. It was confirmed that there were no subharmonic distortions larger than 20 dB SPL.

4, and 12 kHz. The signal level was calibrated with a $\frac{1}{2}$ in. microphone (B&K type 4133) placed at a distance of 50 cm from the signal source when the listener was absent. The power spectra of the tones at the listening point are shown in Fig. 2. Although harmonic distortions were quite eminent at frequencies higher than the signals, subharmonic distortions in the lower frequency side of the signals were not larger than 15 dB SPL. It was confirmed that for any frequencies, subharmonic distortions never exceeded 20 dB SPL.

In the measurement of the hearing threshold, signal tones were amplitude modulated by a sinusoid of 2 Hz. They were, therefore, supposed to be heard as intermittent tones. The duration of the signal was 2000 ms.

A low-pass filtered pink noise was used to mask distortions in the lower frequency range. When the signal frequency was 16 kHz, pink noise low-pass filtered at 12 kHz was used, otherwise pink noise low-pass filtered at 15 kHz was used. The level of the masker was fixed at 60 dB SPL at a distance of 120 cm from the masker source. The masker duration was 2500 ms, including linear onset and offset ramps of 250 ms each. The masker was generated by a D/A converter (EDIROL UA-1000) at a sampling rate of 96 kHz and 16 bit resolution.

2.3 Procedure

The threshold was measured by a three-down one-up transformed up-down paradigm combined with a 2AFC procedure. Two test intervals of 2500 ms were presented to the subject. Both intervals contained the masker but only one of them contained the signal. A silent interval between the two test intervals was 300 ms. Duration of the signal was 2000 ms. The masker always started 250 ms prior to the signal onset and ended 250 ms after the signal offset. Subjects were asked to judge which test interval contained an intermittent tone and respond by pressing a key within 8 s. A visual feedback was given immediately after every response. The level of the stimulus varied adaptively according to a three-down one-up transformed up-down method so that the threshold was estimated automatically. The level of the masker was fixed.

A single run consisted of eight reversals. The threshold value was defined as the mean level at the last four reversal points. The minimum step size was 1 dB. If the level exceeded the maximum level of presentation before eight reversals were completed, the run automatically terminated and no estimation was made. As mentioned earlier, masked and absolute thresholds were also measured for tones at 250 Hz, 1, 4, and 12 kHz. Absolute thresholds were measured without using pink noise.

3. Results and Discussion

For all ears, masked threshold values at 12 kHz and below were higher than 20 dB SPL indicating that any distortions smaller than 20 dB SPL would be masked by the pink noise. As mentioned earlier, subharmonic distortions were always lower than 20 dB SPL in the present study. It can be said that pink noise sufficiently masked distortions in the present study.

Table 1 shows hearing threshold values for tones between 16 and 30 kHz. It also shows the absolute threshold values for tones at 250 Hz, 1, 4, and 12 kHz. Because 16 listeners participated and both sides were examined for each listener, the number of the measured ears was

Table 1. Threshold of hearing for pure tones. Threshold values for tones at 12 kHz and below are the absolute threshold values, otherwise the threshold values were measured with pink noise as the masker.

Frequency (kHz)	Maximum level of presentation (dB SPL)	Minimum	Threshold values (dB SPL) median	Maximum	Number of valid data	Number of tested ears
0.25	80	0.7	7.2	20.4	32	32
1	80	−9.4	−1.6	6.2	32	32
4	80	−13.8	−5.9	7.0	32	32
12	80	−3.6	9.7	25.1	32	32
16	110	22.1	41.8	84.0	32	32
18	105	28.0	64.0	99.5	32	32
20	110	66.4	89.9	⋯	29	32
22	111	87.6	102.7	⋯	25	32
24	110	91.9	⋯	⋯	16	32
26	112	95.3	⋯	⋯	10	32
28	111	101.3	⋯	⋯	3	32
30	110	⋯	⋯	⋯	0	32

32. Threshold values were measurable for most ears at 20 and 22 kHz. They were obtained from half of the ears at 24 kHz and from about one-third of the ears at 26 kHz. Although no threshold values were obtained for a tone at 30 kHz, they could be obtained from 3 ears out of 32 at 28 kHz. Above 24 kHz, threshold values were always higher than 90 dB SPL.

Figure 3 shows the maximum, median, and the minimum values of hearing threshold. It can be seen that the hearing threshold increased abruptly as signal frequency increased from 12 to 20 kHz. The actual threshold curve is not known here for threshold values at 16 kHz and above, especially the minimum values at 16 and 18 kHz, might be affected by the masker. Still there seems to be a steep increase of threshold between 16 and 20 kHz. Above 20 kHz, however, it increased relatively slowly. This is consistent with the findings of Henry and Fast[4] and Ashihara *et al.*[15]

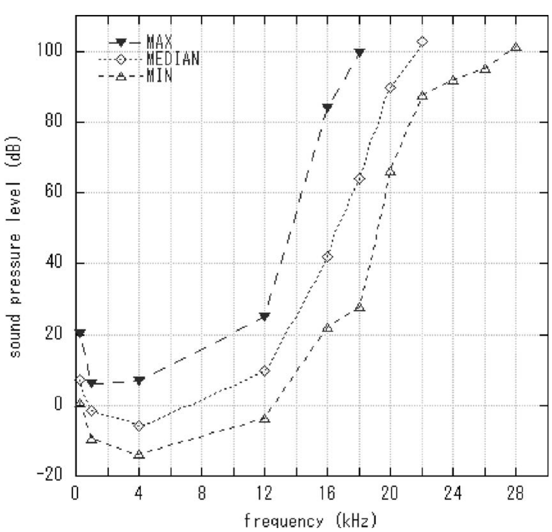

Fig. 3. Hearing threshold for tones. Hearing threshold values are shown as a function of the frequency. The minimum, median, and the maximum values are represented by open triangles, open diamonds, and closed triangles, respectively.

Although it has been repeatedly observed that the thresholds of hearing start to increase abruptly at about 14 kHz, what is responsible for this steep increase is not fully understood. Buus *et al.*[18] proposed three explanations for this steep increase of thresholds: (1) inefficient transmission of acoustic energy to the inner ear, (2) decreasing sensitivity of auditory channel tuned to high frequencies, and (3) running out of channels or the end of cochlea. Their tentative conclusion was that the abrupt increase of thresholds seemed to reflect the characteristics of the last (highest) auditory channel.

Yasin and Plack[19] suggested that the high-frequency limitation in humans would be imposed in part by the middle ear attenuation. Frequency characteristics of the middle ear have been studied and the amplitude at the stapes is known to fall off by 12–15 dB/ octave above 1 kHz.[20–23] In these studies, however, no reliable data are presented above 10 kHz, probably because the signal to noise ratio also falls off at high frequencies. Although further investigations are needed to clarify what the sharp increase of thresholds above 14 kHz represents and why the threshold curve changes its slope at around 20 kHz, the present results can be interpreted as follows.

The characteristic frequency (CF) of the last auditory channel of the cochlea is between 14 and 18 kHz as suggested by Buus *et al.*[18] The threshold curve above this frequency may reflect a combined characteristic of the upper side slope of the last auditory channel's tuning curve and the middle ear attenuation. The psychophysical tuning curve usually has a sharp dip around its CF and a shallower skirt at frequencies away from the CF. If this shallower skirt extends to the ultrasonic regions and the level of the ultrasound is sufficiently high, a part of the sound energy may activate the last auditory channel and thus the sound can be detected. The threshold, therefore, starts to increase rapidly above the CF of the last auditory channel and increase somewhat slowly at much higher frequencies.

4. Conclusion

Thresholds of hearing for pure tones between 16 and 30 kHz were measured. The maximum measurable level was more than 100 dB SPL. Although no threshold was obtained for a 30 kHz tone, it was obtained from 3 out of 32 ears at 28 kHz. The threshold values at 24 kHz and above were always more than 90 dB SPL.

The present results show that some humans can perceive tones up to at least 28 kHz when their level exceeds about 100 dB SPL. These findings would be useful for providing criteria for industrial and commercial use of ultrasounds.

The present data, however, may contain some errors. The signal level was calibrated in the absence of the listener. The actual sound pressure level of the signals at each ear is not known. Difference in size and shape of the heads and earlobes might have caused deviations that would not be negligible. Because the distance between the signal source and the listening point was not enough, a small movement of the head might seriously affect the sound pressure level. In addition, the contralateral ear canal was not sealed in the measurement. The data, therefore, may not precisely represent the actual hearing threshold values of the particular ear. Further investigations are needed to provide more accurate estimation of the hearing threshold values.

References and links

[1]B. W. Lawton, "Damage to human hearing by airborne sound of very high frequency or ultrasonic frequency," Contract Research Report 343, Health and Safety Executive (HSE books, Suffolk, 2001).
[2]Health Canada, "Guidelines for the safe use of ultrasound. II. Industrial and commercial applications," Minister of National Health and Welfare, EHDTR-158, Canadian Communication Group, Ottawa, 1991.
[3]S. A. Fausti, R. H. Fray, D. A. Erickson, B. Z. Rappaport, E. J. Cleary, and R. E. Brummett, "System for evaluating auditory function from 8,000-20,000 Hz," J. Acoust. Soc. Am. **66**, 1713–1718 (1979).
[4]K. R. Henry and G. A. Fast, "Ultrahigh-frequency auditory thresholds in young adults: Reliable responses up to 24 kHz with a quasi-free-field technique," Audiology **23**, 477–489 (1984).
[5]D. M. Green, G. Kidd, Jr., and K. N. Stevens, "High-frequency audiometric assessment of a young adult population," J. Acoust. Soc. Am. **81**, 485–494 (1987).
[6]P. G. Stelmachowicz, K. A. Beauchain, A. Kalberer, and W. Jesteadt, "Normative thresholds in the 8- to 20-kHz range as a function of age," J. Acoust. Soc. Am. **86**, 1384–1391 (1989).

[7]K. Betke, “New hearing threshold measurements for pure tones under free-field listening conditions,” J. Acoust. Soc. Am. **89**, 2400–2403 (1991).
[8]H. Takeshima, Y. Suzuki, M. Kumagai, T. Sone, T. Fujimori, and H. Miura, “Threshold of hearing for pure tone under free-field listening conditions,” J. Acoust. Soc. Jpn. (E) **15**, 159–169 (1994).
[9]T. Poulsen and L. A. Han, “The binaural free field hearing threshold for pure tones from 125 Hz to 16 kHz,” Acust. Acta Acust. **86**, 333–337 (2000).
[10]M. Sakamoto, M. Sugawara, K. Kaga, and T. Kamio, “Average thresholds in the 8 to 20 kHz range in young adults,” Scand. Audiol. **27**, 169–172 (1998).
[11]K. Kurakata, K. Ashihara, K. Matsushita, H. Tamai, and Y. Ihara, “Threshold of hearing in free field for high frequency tones from 1 to 20 kHz,” Acoust. Sci. & Tech. **24**, 398–399 (2003).
[12]K. Ashihara, “Audibility of complex tones above 20 kHz,” *Proceedings Internoise 2000* (Nice, 2000).
[13]K. Ashihara, “The higher limit of the audible area for complex sounds,” *Proceedings of the 15th Triennial Congress of International Ergonomics Association*, pp. 524–537 (Seoul, 2003).
[14]K. Ashihara and S. Kiryu, “Audibility of components above 22 kHz in a complex tone,” Acust. Acta Acust. **89**, 540–546 (2003).
[15]K. Ashihara, K. Kurakata, T. Mizunami, and K. Matsushita, “Hearing threshold for pure tones above 20 kHz,” Acoust. Sci. & Tech. **27**, 12–19 (2006).
[16]H. Levitt, “Transformed up-down methods in psychoacoustics,” J. Acoust. Soc. Am. **49**, 467–477 (1971).
[17]ISO 8253-2, “Acoustics - audiometric test methods. - 2 Sound field audiometry with pure tone and narrow-band test signals,” International Organization for Standardization, Geneva Switzerland, 1992.
[18]S. Buus, M. Florentine, and C. R. Mason, “Tuning curves at high frequencies and their relation to the absolute threshold curves,” in *Auditory Frequency Selectivity*, edited by B. C. J. Moore and R. D. Patterson (Plenum, New York, 1986).
[19]I. Yasin and C. J. Plack, “Psychophysical tuning curves at very high frequencies,” J. Acoust. Soc. Am. **118**, 2498–2506 (2005).
[20]M. Kringlebotn and T. Gundersen, “Frequency characteristics of the middle ear,” J. Acoust. Soc. Am. **77**, 159–164 (1985).
[21]M. S. Vlaming and L. Feenstra, “Studies on the mechanics of the normal human middle ear,” Clin. Otolaryngol. **11**, 353–363 (1986).
[22]R. L. Goode, K. Nakamura, K. Gyo, and H. Aritomo, “Comments on ‘Acoustic transfer characteristics in human middle ears studied by a SQUID magnetometer method’ [J. Acoust. Soc. Am. **82**, 1646–1654 (1987)],” J. Acoust. Soc. Am. **86**, 2446–2449 (1989).
[23]H. Kurokawa and R. L. Goode, “Sound pressure gain produced by the human middle ear,” Arch. Otolaryngol. Head Neck Surg. **113**, 349–355 (1995).