Hearing threshold for pure tones above 20 kHz

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Abstract: Hearing thresholds for pure tones from 2 kHz to 28 kHz were measured. A 2AFC procedure combined with a 3-down 1-up transformed up-down method was employed to obtain threshold values that were less affected by listener’s criterion of judgment. From some listeners, threshold values of 88 dB SPL or higher were obtained for a tone at 24 kHz, whereas thresholds could not be obtained from all participants at 26 kHz and above. Furthermore, thresholds were also measured under masking by a noise low-pass filtered at 20 kHz. At frequencies above 20 kHz, the difference of threshold values between with and without the masking noise was a few decibels, indicating that the tone detection was not affected by subharmonic components that might have appeared in the lower frequency regions. The results of measurement also showed that the threshold increased rather gradually for tones from 20 to 24 kHz whereas it increased sharply from 14 to 20 kHz.

Keywords: Threshold of hearing, Masked threshold, Subharmonic distortion, Ultrasound

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1. INTRODUCTION

There are some industrial and commercial appliances that radiate ultrasounds. Included are drills, ultrasonic washers, intruder alarms, ultrasonic animal repellers[1], automatic door-openers, TV converters[2], and dental turbines[3]. The frequency of ultrasounds generated by these machines varies from about 20 kHz to 100 kHz and above. Recently, it was also reported that railway noises sometimes contain high-level components around 20 kHz[4]. Figure 1 shows an example of very high-frequency sound that was recorded on a street near the entrance of a parking lot in Tokyo. A prominent component can be observed at 19.3 kHz, which seemed to be radiated from rat repellents.

A problem is that it is not clear whether those very high-frequency and ultrasonic sounds over 20 kHz are inaudible and have no subjective effects at all on humans even when their level becomes extremely high. Lawton[1] reviewed the literature on auditory effects of very high-frequency and ultrasonic sounds. According to his report, 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. 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].

Some of those subjective influences depend on whether the sounds are audible or not. Therefore, it would be valuable to evaluate the influences in terms of the absolute threshold of hearing. Absolute thresholds for pure tones have been studied by many research groups[5–13]. These studies show that the absolute threshold starts to increase sharply when the signal frequency exceeds about 15 kHz; it reaches 80 dB SPL at the frequency of 20 kHz[5,8,10,13]. Above 20 kHz, however, only a few studies have been reported. Recently, Ashihara[14,15] made attempts to measure thresholds for tones at 22 kHz and 24 kHz, but no thresholds values below 85 dB SPL were obtained. Henry and Fast[6] 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 kHz to 20 kHz. Above
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Fig. 1 A power-spectrum of environmental sounds recorded on a street in Tokyo is shown. The sounds were recorded at the place near the entrance of a parking lot. A prominent peak can be found at about 19.3 kHz. This may be due to the ultrasonic rat repellents.

20 kHz, however, thresholds increased less rapidly. Sakamoto et al. [12] who measured hearing thresholds up to 20 kHz also reported that the threshold reached a plateau above 18 kHz. Although the mechanisms responsible for detection of ultrasounds are not specified, it can be said that the threshold above 22 kHz is higher than 85 dB SPL and the threshold increases less rapidly between about 18 kHz and 24 kHz.

There seem to be at least three hypotheses as follows that may explain why most of the listeners could detect tones at 24 kHz in Henry and Fast’s study [6].

Hypotheses:

1) When the level of the ultrasound is sufficiently high, a part of its energy reaches the inner ear. It can activate the auditory channels of the cochlea.

2) As von Gierke [16] suggested, high-level ultrasounds may generate subharmonics because of the non-linear characteristics of the eardrum or the middle ear. If some of them appeared in the audible area, the listener would detect them.

3) Subharmonics are generated in the audible area due to limited linearity of equipment although they are not observed in an acoustic analysis for some unknown reason.

In the case of hypotheses 1 and 2, it is practically appropriate to say that ultrasounds are audible. In the case of hypothesis 3, however, audibility of ultrasounds is not confirmed. It is necessary, therefore, to make sure whether detection of ultrasounds is due to subharmonic distortions of equipment or not.

One of the possible solutions would be to prepare equipment with sufficient linearity for the measurement. When very high-level sounds are used, sufficient linearity of equipment is definitely required [17,18]. While the threshold of hearing above 20 kHz seems to be higher than 85 dB SPL, it is sometimes lower than −10 dB SPL at around 4 kHz. It means that subharmonic distortions have to be smaller than −10 dB SPL when an ultrasonic tone is presented at the level above 90 dB SPL. This is not an easy condition to realize. Sakamoto et al. acknowledged that the signal to noise ratio was not large enough in their measurement system. As noted in their report, the listeners might have been responding to some low-frequency noise. In Henry and Fast’s study, 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.

Another and the more realistic solution may be to eliminate the influences of distortions by means of masking. If the level of acoustic distortions is higher than that of background noise, it can be observed in the acoustical analysis of the stimuli. Distortions as small as −10 dB SPL are not easy to observe but easy to mask by addition of noise. From the acoustical analysis of the stimuli and comparison between the absolute thresholds and thresholds under a masking condition, it can be confirmed whether detection of ultrasounds are merely due to acoustic distortions in the lower-frequency regions.

In order to make sure whether the tones above 20 kHz are detectable when there are not any detectable subharmonic distortions in the low-frequency regions, two experiments were conducted in the present study. Fifteen listeners’ absolute thresholds for tones between 2 and 28 kHz were measured in the first experiment. In the second experiment, thresholds were measured in the condition where the low-frequency area was masked by a broadband noise. Only listeners who had detected tones at 24 kHz or above in the first experiment participated in this experiment. If thresholds at frequencies above 20 kHz substantially increased when the area below 20 kHz was masked by the noise, it would indicate that the absolute thresholds obtained in the first experiment were due to subharmonic distortions in lower frequency regions.

In Henry and Fast’s study [6], thresholds values were determined by a method of adjustment. Listeners adjusted an attenuator until the tone was clearly heard. Although listeners could not know the absolute values of attenuation, they might have underestimated thresholds in this method. In the conventional method of limit, however, results can be biased by the listener’s criterion of judgment. Because of the simple paradigm of the method, the listener may respond by anticipation. It is sometimes difficult to distinguish true detection responses from guess responses or responses by anticipation.

In stead of the method of limit or the method of adjustment, a transformed up-down method combined with a two-alternative forced choice (2AFC) procedure [19] was employed in the present study.
2. EXPERIMENT I. ABSOLUTE THRESHOLD

2.1. Method

2.1.1. Listeners

Four male and 11 female listeners participated in the experiment. None of them had a history of otological disease. Their ages ranged between 18 and 33 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 AIST.

2.1.2. Stimuli

Absolute threshold values were measured at every 2 kHz from 2 kHz to 28 kHz. Pure tones with a 2-Hz amplitude modulation were used as signals so that they would be heard as intermittent tones. Duration of the signal was 2,000 ms. Figure 2 shows the characteristics of the synthesized sinusoids. The quantization noise was about 20 dB lower than the signal even when the signal was digitally attenuated by 96 dB. The signal was digitally synthesized and generated by a D/A converter (RME ADI-8 DS) at a sampling rate of 96 kHz and 16-bit resolution. The characteristics of the signal generated by the D/A converter can be seen in Fig. 3. It was confirmed that the distortions from the D/A converter were smaller than the signal at least by 80 dB.

The signal was amplified and fed to a loudspeaker or a super-tweeter. Tones below 12 kHz were presented by a loudspeaker (SONY SS-AL5mkII) whereas those above 14 kHz were presented by a super-tweeter (PIONEER PT-R100). In the present study, the midpoint between the two ears of the listener was defined as a reference point. The power-spectra of the tones at the reference point are shown on a logarithmic frequency scale in Fig. 4. In order to make distortions visible against the system noise, the signals were averaged by 16 times with the phase synchronized. Although harmonic distortions were eminent at frequencies higher than the signals, no prominent distortions can be observed in the lower frequency side of the signals.

As can be seen in Figs. 2 and 3, a digital attenuator could cover the range of 90 dB and wider. In the measurement at 16 kHz and below, an additional analogue attenuation of 10 dB was occasionally used to reduce the quantization noise level. The maximum level of presentation was between 88 and 99 dB SPL, depending on the frequency of the signal. At frequencies above 14 kHz, the maximum presentation level was always higher than 97 dB SPL. A high-pass filter (PIONEER DN-100) was used at 14 kHz and above to reduce the noise level in the lower frequency regions.

2.1.3. Procedure

A listener sat on a chair with a headrest, directly facing to the sound source in a soundproof room. The distance between the reference point and the sound source was 200 cm. The sound pressure level of the stimuli was calibrated at the reference point. A liquid crystal display was placed in front of the listener for instructions and visual feedback. The absolute threshold was measured with a 2AFC procedure. Two test intervals of 2,000 ms were presented to listeners. Only one of them contained a signal and the other was empty. A silent interval between the two test intervals was 300 ms. Listeners were asked to judge within 8 s after the interval presentation which test interval

Fig. 2  Characteristics of digitally synthesized signals are shown. The signals were sinusoids whose frequency were 4 kHz (left) and 20 kHz (right). They were synthesized with a resolution of 16 bit and a sampling rate of 96 kHz. The signals were digitally attenuated by 0 dB (top) and 96 dB (bottom).
had contained an intermittent tone. Visual feedback was given immediately after every response. The level of the stimulus varied adaptively according to the 3-down 1-up transformed up-down procedure so that the level would be converged to a threshold estimate.

A single run consisted of 10 reversals. The level of the tone was digitally controlled by experimental software and the minimum step size was 1 dB. The absolute threshold value was defined as the mean level of the last six reversal points. If the level exceeded the maximum level of presentation before 10 reversals were completed, the run automatically terminated and no threshold estimation was made. Head movement might cause deviation in sound pressure level at the eardrum especially at high frequencies. Measurements, therefore, were conducted at least twice for each listener. When the difference of threshold values between the first and the second measurements exceeded 5 dB, measurements were repeated until the difference of two successive measurements became less than 5 dB.

2.2. Results

After a few reversals during the measurement, the level almost always stayed within a few decibels around the threshold, otherwise it diverged. If the listener was responding by guessing or anticipation, the level was not supposed to be stable and the threshold could not be estimated.

At frequencies of 18 kHz and below, absolute threshold values were obtained from all listeners. The average threshold values of the all listeners are shown in Fig. 5. Thresh-
old values specified in ISO/DIS 389-7 [20] are also shown in the same figure. A rapid increase of the thresholds was observed between 14 kHz and 18 kHz. At 20 kHz, four listeners’ threshold values exceeded the limit of the measurement system. Thresholds at 22 kHz were obtained from six listeners.

Even at 24 kHz, thresholds were measurable for four out of 15 listeners. Their absolute thresholds are shown in Fig. 6. The absolute threshold values at 24 kHz were always higher than 88 dB SPL. These four listeners participated in Experiment II. They were identified as Listeners 1, 4, 5, and 15.

3. EXPERIMENT II. MASKED THRESHOLD

In order to make sure if the absolute thresholds at 24 kHz and 24 kHz obtained in Experiment I were due to subharmonics in the audible area, masked thresholds were measured.

3.1. Method

Thresholds were measured for tones at 14, 20, 22, and 24 kHz using a 2AFC procedure. Only for Listener 15, thresholds were also measured for tones below 12 kHz.

The method was almost the same as that in Experiment I except that both intervals contained a masker. The masker was a 20-kHz low-pass filtered noise whose duration was 2,000 ms including linear onset and offset ramps of 100 ms each. The signal always started and ended simultaneously with the masker. The signal was an intermittent tone as was in Experiment I. The tones above 14 kHz were presented by a super-tweeter (PIioneer PT-R100) and those below 12 kHz in the case of Listener 15 were presented by a loudspeaker (SONY SSAL5MkII). The masker was presented by a loudspeaker (DENON SC-A33-M) that was placed close to PT-R100 or SS-AL5MkII. The level of the masker at the reference point was fixed at 57 dB SPL. The level of the signal varied adaptively according to the 3-down 1-up transformed up-down method.

The power-spectrum of the masker at the reference point is shown in Fig. 7. The power-spectrum of a 24-kHz tone averaged by 16 times is also shown in the same figure. It is evident that the level of the noise was sufficiently high to mask all distortions below 20 kHz. If the absolute thresholds for tones above 20 kHz were merely due to subharmonics in the audible area, they would be affected by the addition of masker.

3.2. Results

Filled diamonds in Fig. 6 represent the thresholds obtained under the existence of masking noise. The difference between the absolute and masked thresholds at 14 kHz was about 10 dB in Listener 4 and more than 20 dB in Listeners 1, 5, and 15. The masked threshold values for tones below 12 kHz in the case of Listener 15 were between 29 and 39 dB SPL and were obviously higher than the absolute thresholds. Thresholds for tones above 20 kHz were not affected markedly by the addition of noise. Increment of the thresholds was only a few decibels in Listeners 1, 5, and 15 and almost negligible in Listener 4.

4. DISCUSSION

In the present study, threshold values for tones at 24 kHz were obtained from four listeners. As can be seen in Fig. 6, their absolute thresholds (open squares) rose sharply as the frequency of the tone increased from 14 kHz to 20 kHz. It agrees well with the previous studies [5,8,10,13]. Between 20 kHz and 24 kHz, the increment of threshold was rather small especially in Listener 1. This is similar to what Henry and Fast [6] observed. As the 2AFC procedure was employed, results in the present study were not supposed to be affected by listeners’ criterion of judgment. It is certain, therefore, that these listeners repeatedly detected the ultrasonic tones in the present study.

In order to make sure whether detection of ultrasounds was merely due to subharmonic distortions of the equipment, effects of the masking were investigated in Experiment II. The masked threshold values for tones at 14 kHz and below were always above 29 dB SPL indicating that an audible tone, if any, with a level lower than about 30 dB SPL was masked by the noise. The addition of noise slightly increased the thresholds above 20 kHz. The increments were rather small, however, especially in Listeners 4 and 5. If the listeners had been listening to subharmonic distortions in Experiment I, thresholds in Experiment II should have been affected by the addition of masker or the
The level of distortions should have been higher than about 30 dB SPL. If there had been distortions with the level of 30 dB SPL or higher, they should have been easily observed by an acoustic analysis. These results of Experiment II and the acoustical analysis of the stimuli suggest that the thresholds at 22 kHz and 24 kHz are not due to acoustic subharmonics in the audible area. Hypothesis 3 proposed in INTRODUCTION was rejected.

The acoustical analysis could prove that the acoustic subharmonics were sufficiently small. It is not sure whether there were subharmonics in the auditory system as were suggested in Hypothesis 2. A slight increase of the thresholds implies that the subharmonics in the auditory system might contribute to the thresholds to some minor extent. In the case of Listener 4, however, detection of the tone cannot be attributed to any subharmonics because the effect of masking was almost negligible. Although Hy-

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**Fig. 6** Absolute and masked threshold values obtained from Listener 1 (top left), Listener 4 (top right), Listener 5 (bottom left) and Listener 15 (bottom right) are shown.

**Fig. 7** The signal and the masker at the reference point were shown. The signal was a 24 kHz tone averaged by 16 times and the masker was a 20 kHz low-pass noise. They were recorded at the sampling rate of 96 kHz and the FFT size was 8,192 points.
Another possible explanation is the one introduced in Hypothesis 1 that high-level ultrasounds could directly activate the auditory channels. In this case, the effect of masking would depend on the signal to noise ratio in these auditory channels. The reason why the thresholds slightly increased in Experiment II will be discussed in the following paragraphs. What the sharp increase of the thresholds above 14 kHz represents and why the threshold curve changes its slope at around 20 kHz will be also discussed.

Although it has been repeatedly observed that the thresholds of hearing start to increase sharply at about 14 kHz, what is responsible for this sharp increase is not fully understood. Frequency characteristics of the middle ear have been studied and the amplitude at the stapes is known to fall off by 12 to 15 dB/octave above 1 kHz [21–24]. 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. The increase of the threshold above 14 kHz seems to be much steeper than low-pass filter characteristics at the middle ear. Buus et al. [25] tried to explain what would be responsible for this steep increase of thresholds. They proposed three explanations: inefficient transmission of acoustic energy to the inner ear, decreasing sensitivity of auditory channel tuned to high frequencies, and running out of channels or the end of cochlea. Their tentative conclusion was that the sharp increase of thresholds seemed to reflect the characteristics of the last (highest) auditory channel. The reason why the thresholds slightly increased in Experiment II will be discussed in the following paragraphs. What the sharp increase of the thresholds above 14 kHz represents and why the threshold curve changes its slope at around 20 kHz will be also discussed.

The characteristic frequency (CF) of the last auditory channel of the cochlea is between 14 kHz and 18 kHz as suggested by Buus et al. [25]. The threshold curve above this frequency may represent the upper side slope of the last auditory channel’s tuning curve. 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 reaches a plateau at about 20 kHz.

Figure 6 indicates that the tones at the level below about 30 dB SPL were masked by the low-pass filtered noise. If the threshold of the last auditory channel was lower than 30 dB SPL, a part of the masker energy would fall in this channel and thresholds for ultrasounds would be affected by the masker in Experiment II. If the CF of the last auditory channel was about 14 kHz and ultrasounds were perceived via this channel, the masking effect should be larger than 20 dB for the ultrasounds in the cases of Listeners 1, 5, and 15. The masking effects observed in Experiment II were rather small, indicating that the CF of the channel was above 14 kHz. If the CF of the last auditory channel was higher than 18 kHz, the masker would have little effect on the thresholds for ultrasounds because the absolute thresholds at 18 kHz were always higher than 30 dB SPL. Thresholds for ultrasounds were slightly affected by the masker in the cases of Listeners 1, 5, and 15. The CF of the auditory channel that determined the threshold, therefore, seems to be lower than 18 kHz. In the case of Listener 4, not enough energy of the masker might fall in the last auditory channel because her threshold at 16 kHz already exceeded 40 dB SPL.

5. CONCLUSIONS

Hearing thresholds for pure tones from 2 kHz to 28 kHz were measured for 15 listeners. The maximum measurable level was more than 90 dB SPL. Although no threshold was obtained for tones above 26 kHz, thresholds were obtained from six listeners at 22 kHz and four listeners at 24 kHz. In such cases, a pronounced decrease in the growth rate of threshold was observed at around 20 kHz. The absolute threshold values at 24 kHz were higher than 88 dB SPL in every case.

Thresholds for tones were also measured under the existence of a 20-kHz low-pass filtered noise to make sure whether the listeners had been listening to subharmonic distortions in the lower-frequency regions. The addition of masker evidently affected the threshold when its value was less than about 30 dB SPL. Above 20 kHz, threshold values were always higher than 75 dB SPL and they were not markedly affected by the masker. These results confirm that the thresholds obtained for tones above 20 kHz were not due to acoustic subharmonic distortions. These data also suggest that some listeners could perceive pure tones up to at least 24 kHz when their levels exceed about 90 dB SPL. The present results proved the audibility of high-level ultrasounds and would be useful for providing criteria for industrial and commercial use of ultrasounds.

Some implications about the topics why the threshold starts to increase abruptly at around 14 kHz and how tones above 20 kHz are perceived were discussed based on the assumptions by Buus et al. [25].

REFERENCES


