

## Understanding extended high-frequency hearing thresholds

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### ABSTRACT

The standard clinical test of hearing is pure-tone audiometry, which measures the lowest detectable level of pure tones, typically between 0.25 and 8 kHz. There is increasing interest in extended high-frequency (EHF) audiometry, above 8 kHz. Basal (high-frequency) cochlear regions are especially sensitive to the effects of ageing, with a rapid increase in EHF thresholds with age. However, even across young adults, the variability in EHF sensitivity is remarkable: EHF thresholds can vary by over 50 dB between individuals with normal hearing in the standard clinical range. The cause of this variability is not fully understood. While there are calibration difficulties due to resonances in the ear canal, this cannot explain the extent of the variability. Some studies suggest that the EHF region is especially sensitive to noise damage, and that EHF loss might be an “early warning” of the potential for losses at lower frequencies, but the evidence is inconsistent. There is better evidence that EHF thresholds are particularly sensitive to the effects of ototoxic drugs. There is also evidence that EHF loss is associated with speech perception difficulties, although this may not be causal: EHF loss may instead be a marker for sub-clinical damage at lower frequencies. Understanding the causes and consequences of EHF hearing loss remains an important challenge.

Keywords: Audiometry, Hearing Loss, Extended High Frequencies

### 1. INTRODUCTION

Clinical hearing testing is based on pure-tone audiometry (PTA), which involves measurements of hearing thresholds over a range of test frequencies. Testing rarely extends to frequencies above 8 kHz. For example, the British Society of Audiology recommends testing between 250 Hz and 8 kHz (1). These standard measures have a wide range of practical uses, including clinical diagnosis, and occupational hearing health monitoring. Standard PTA is also used extensively in hearing research, for assessment of hearing loss and as a screening tool for participants. However, there is increasing interest in measuring hearing thresholds at frequencies above 8 kHz, up to as high as 20 kHz: the “extended high-frequency” (EHF) range. Even if losses in the EHF region do not have a substantial effect on perception directly, they may act as an “early warning” of the potential for hearing loss at lower frequencies, and they may also act as a marker for deficits that do not affect the audiogram in the standard range (“sub-clinical” deficits).

The variability in EHF thresholds is remarkable, even among listeners with clinically normal hearing. Some of this variability may result from problems of calibration in the EHF range, due in part to individual differences in ear canal anatomy which affect standing wave interference patterns. This is particularly an issue for insert earphones, although even in this case calibration issues probably don’t account for more than about 20 dB of the variance in thresholds (2, 3). Figure 1 shows mean hearing thresholds for a group of young listeners from a recent study in our laboratory, using circumaural headphones designed for EHF testing. The error bars show clearly how much more between-subject variability there is at EHF than at lower frequencies. Also shown are thresholds for two listeners with similar thresholds in the standard clinical range, but wildly different hearing thresholds in the EHF range. Both these listeners would be categorized as having “normal hearing” if they visited an audiologist, but it is obvious that their hearing abilities differ greatly in the EHF region. What does this

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tell us about the hearing of these individuals?

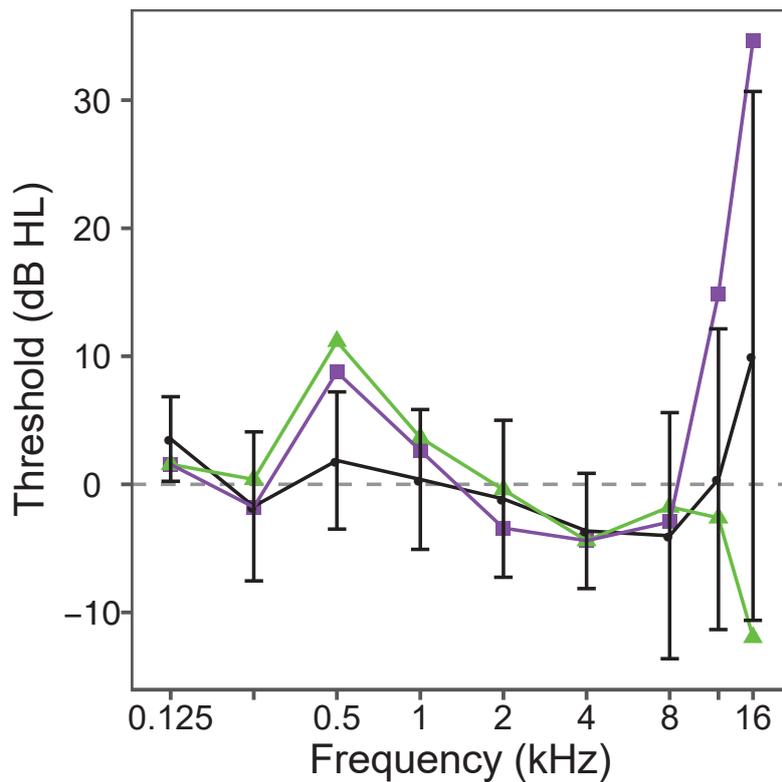


Figure 1 – Mean hearing threshold as a function of frequency for a group of normal-hearing listeners, 19-39 yrs (black circles). Error bars show +/- 1 standard deviation. The purple squares and green triangles show the results for two listeners with very similar thresholds up to 8 kHz, but markedly different thresholds above 8 kHz (in the EHF range).

## 2. EHF THRESHOLDS AS AN EARLY WARNING OF HEARING DAMAGE

### 2.1 Effects of Age

Hearing deteriorates as we age, from early adulthood onwards. A “ski-slope” loss in the audiogram is characteristic of the effects of ageing, with high frequencies affected much more than low frequencies. The EHF region is particularly sensitive to ageing. In one study, mean hearing losses at 16 kHz were greater than 20 dB for listeners aged 30-39 years compared to listeners aged 15-19 years, even though thresholds up to 8 kHz were almost unchanged in this age range compared to the younger listeners (4). Figure 2 shows a typical pattern of hearing thresholds as a function of age, using data from our laboratory. Age-related hearing loss is due in part to a reduction in the endocochlear potential, which degrades hair cell function. However, lifetime noise exposure and the effects of ototoxic drugs compound the effects of age *per se* (5). These two causes tend to affect the cochlear base, and hence increase the loss at high frequencies, leading to a steeper increase in hearing loss with frequency.

The utility of EHF monitoring for the effects of age *per se* are questionable at present, since we have no clear means yet of halting or reversing the decline. However, EHF testing may be useful for assessing, and preventing, damage due to noise exposure or ototoxicity, as described in the following sections.

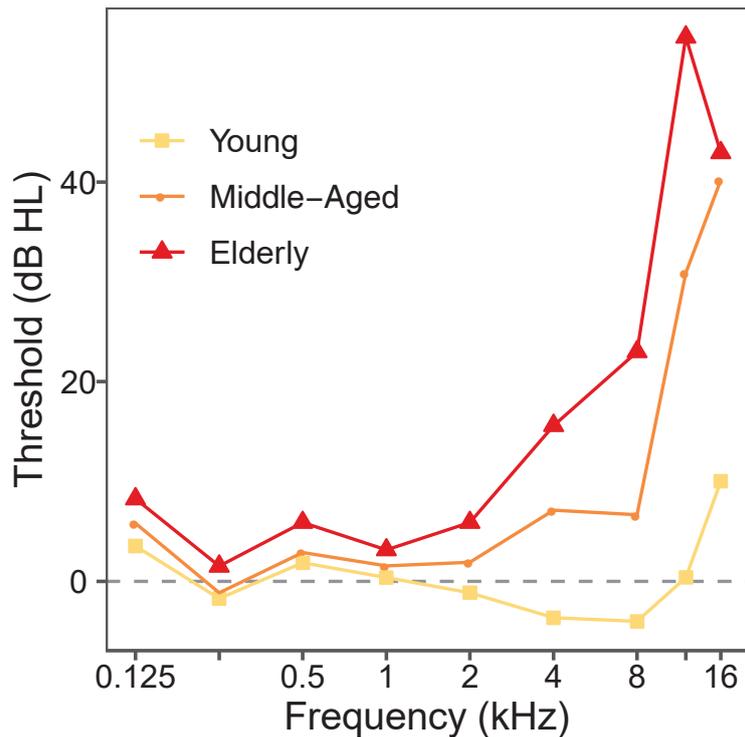


Figure 2 – Mean hearing threshold as a function of frequency for groups of young (19-39 yrs), middle-aged (40-59 yrs), and elderly (60-74 yrs), participants.

## 2.2 Effects of Noise Exposure

Noise exposure damages the sensitive hair cells in the cochlea, particularly the outer hair cells which are responsible for amplifying the motion of the basilar membrane; a process that is essential for normal hearing sensitivity. Noise-induced hearing loss (NIHL) is traditionally associated with an audiometric “notch” between 3 and 6 kHz (the feature is a notch, since audiograms are usually plotted with lower thresholds at the top). This corresponds to the region of the cochlea that is maximally stimulated by broadband stimuli after filtering by the middle ear. However, several studies suggest that EHF thresholds may also be especially sensitive to noise exposure and that EHF threshold elevation may occur before any effects in the standard clinical range, although the findings are mixed and other studies show little relation (6). A possible reason for the negative findings is the difficulty of estimating lifetime noise exposure reliably (6), since the estimates are largely based on self-report and depend on what events are included and how noise levels are calculated (7). It is particularly important to determine if EHF threshold elevation is a useful predictor of future hearing loss in the standard clinical range. If so, this would make EHF thresholds a valuable tool for monitoring hearing health, for example, in occupational settings, and EHF testing could be used to screen for individuals at risk of losing hearing ability due to recreational activities.

Recently, there has been considerable interest in “cochlear synaptopathy;” a loss of synapses between inner hair cells and auditory nerve fibres that is caused by noise exposure or ageing in animal models (8), and that can occur in the absence of any elevation in hearing threshold (i.e., the loss would be sub-clinical in humans). The main measure of cochlear synaptopathy in humans is wave I of the electrophysiological auditory brainstem response (ABR), which reflects auditory nerve function. However, attempts to find associations between noise exposure and ABR wave I in humans have been mixed, with the majority of studies showing no relation (9). Some of the positive studies have not controlled for EHF thresholds. ABR wave I is strongly affected by basal cochlear generators, and hence an NIHL in the EHF region could cause a reduction in wave I that is misinterpreted as synaptopathy. Another possibility, however, is that an EHF loss is a marker for synaptopathy in a lower frequency region (10). If so, then EHF testing might have utility for the diagnosis of synaptopathy.

## 2.3 Effects of Ototoxic Drugs

As described above, ototoxic drugs such as the chemotherapy medication cisplatin, tend to cause

more damage to the base of the cochlea than to the apex. There is good evidence that ototoxic drugs particularly affect EHF thresholds, and that EHF threshold monitoring is a valuable tool for early identification of hearing loss due to these drugs, at least for patients with measurable thresholds in this range (11).

### 3. EHF THRESHOLDS AND SPEECH PERCEPTION

Speech identification is the main purpose of hearing for most humans, and hence serves as the key exemplar of a “real-world” hearing task for comparison with other measures of auditory ability. In particular, speech identification in the presence of an interfering background noise is a good test of general hearing ability, and arguably the most significant difficulty experienced by listeners with a hearing impairment. Despite the ubiquity of PTA for hearing testing, it is well established that standard PTA is a poor predictor of speech identification in noise across listeners (12). PTA clearly does not capture well the essential auditory and cognitive deficits that are associated with poor performance on one of the most important real-world listening tasks. Hence other measures are required to understand the mechanisms that underlie the differences between individuals.

There is some evidence for an association between deficits in speech identification in noise and elevated EHF hearing thresholds, independent of loss in the standard audiometric range (13, 14). Note that this does not imply that there is a direct *causal* relation between the two. There is some evidence that frequency components between 8 and 10 kHz improve the quality of speech and provide useful information for consonant recognition, especially if the low frequency components are degraded (15). EHF components also contribute to the localization of speech stimuli, in particular for determination of sound elevation (16). However, there is little evidence that frequencies above 10 kHz contribute to speech perception directly. Hence, it is possible that the relation between EHF thresholds and speech-in-noise performance observed in some studies may be because EHF loss is a marker for sub-clinical deficits at lower frequencies (14). These deficits might include sub-clinical hair cell damage and cochlear synaptopathy (see Section 2.2).

### 4. SUMMARY

EHF testing shows considerable promise for monitoring hearing health, particularly for patients on ototoxic medication, and possibly also for listeners exposed to occupational or recreational noise. EHF thresholds may be important in localizing sounds. However, there may be little direct impact of EHF losses on real-world tasks such as speech perception. Instead, EHF loss may be a marker for sub-clinical deficits at lower frequencies.

### ACKNOWLEDGEMENTS

The work was supported by the Biotechnology and Biological Sciences Research Council (BB/M007243/1), and by the NIHR Manchester Biomedical Research Centre.

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