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Hearing beyond the limit: Measurement, perception and impact of infrasound and ultrasonic noise

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ABSTRACT

In our daily lives, many sources emit infrasound due to their functions or as a side effect. At the other end of the hearing frequency range, airborne ultrasound is applied in many technical and medical processes and has also increasingly moved into everyday life. There are numerous indicators that sound at these frequencies can be perceived and can influence human beings. However, the precise mechanisms of this perception are unknown at present and this lack of understanding is reflected by the unsatisfactory status of the existing regulations and standards. In this paper, the current status of measurement capabilities, the knowledge about perception mechanisms, and the assessment of infrasound and airborne ultrasound are described. To contribute to the question of whether these sounds may be of any risk to the hearing system, the results of several studies using audiological methods and neuroimaging are presented. They were implemented within an EU-funded international project in order to improve the objective understanding of the auditory perception of infrasound and airborne ultrasound in humans.

INTRODUCTION

Although considerable improvements have been reached during the last few decades, noise remains an important and critical environmental factor and its effect continues to pose significant risks to human health and well-being. In Europe, road traffic is the most dominant source of environmental noise with an estimated 125 million people affected by noise levels greater than 55 decibels (day-evening-night level) [1]. Despite this unsatisfactory situation for the living conditions in Europe, the knowledge about noise perception and noise impact as well as the metrological infrastructure for the reliable determination of quantitative noise measurands is at an acceptable though improvable level today.

This is, however, not the case for the knowledge available at the limits of the conventional hearing frequency range. At the low-frequency border, infrasound is the topic of a growing debate because concepts and equipment for renewable energy production such as wind farms, biogas plants or local cogeneration devices emit low-frequency sound and infrasound affecting people living in the vicinity. The measurement of infrasound is, in general, feasible but standards and calibration strategies are permanently under revision, and the measurement infrastructure is not yet completely developed. The perception of infrasound by humans is well documented but the mechanisms of interaction in the inner ear or other potential targets are not widely understood. This is further exacerbated by the fact that the subjective impact on humans seems to be more complicated than in the audible frequency range. Studies showed, for example, that wind park noise is perceived as more annoying than traffic noise [2, 3].

At the high-frequency border of the conventional hearing frequency range, the situation is similarly unsatisfactory. There have been a growing number of complaints about the annoying or even harmful impact of airborne ultrasound in the public or at workplaces and insurance companies are facing an increasing number of compensation claims. Contrary to infrasound, the measurement techniques of airborne ultrasound still lack significant elements such as practical measurement devices like ultrasound-level meters or accepted measurement methods at emission sites. Under this prerequisite, it is not astonishing that the perception mechanisms are still widely unclear.

This paper will focus on metrology issues of managing infrasound and airborne ultrasound: How can an improved quantitative characterization be realized and objective methods be used for a description of quite subjective factors? The status of measurement techniques and aspects of perception are also discussed. They are results of the international “EARS” project which was funded by the European Union under the auspices of the European Metrology and Research Programme (EMRP) and which has a successor (“EARS 2”) within the European Metrology Programme for Innovation and Research (EMPIR).

INFRASOUND

Measurement

Microphones for measuring infrasound sound pressure level (SPL) have been available on the market for many years. Although common pressure microphones can be used, special devices with a particularly low cut-off frequency are offered. These microphones can be calibrated by the reciprocity method and a calibration service is offered by several national metrology institutes (NMIs). These services are of a sufficient quality and are internationally harmonized which was proven by two key comparisons [4] carried out under the auspices of the Consultative Committee for Acoustics, Ultrasound and Vibration at the Bureau International des Poids et Mesures (BIPM).

These calibration procedures are of high level and require sophisticated techniques and microphones. The calibration and measurement in many practical situations and at everyday sites is still a challenge. Requirements and type approvals for sound level meters, the workhorse of all practical measurements, are only available down to 20 Hz as given by an international standard [5]. Activities being performed to extend this frequency range down to lower frequencies to include the measurement issues of infrasound sources into a reliable and regulated metrology infrastructure.

Another open question is the application of weighting filters to the measurement data. A-weighting is widely used but its use is controversially discussed whether it is appropriate [6, 7]. The main argument against it is that it underestimates the effects of infrasound [8] and reflects mainly the activity of the inner hair cells which represent “normal” hearing activity (see explanation in the following section) whereas the perception of infrasound might mainly be accomplished by the outer hair cells. G-weighting is exclusively used for the assessment of infrasound and the relation to the adjacent low-frequency audible range is not very clear.

Perception

Although the frequency range of hearing is defined between 16 Hz and 16 kHz [9], humans are able to perceive acoustic signals with frequencies down to at least 2.5 Hz. The infrasound is detected with the ear but tonal sensation is lost when the frequency significantly decreases below 20 Hz. The sensation becomes discontinuous in character [10].

The mechanisms of perception are still the matter of a controversial debate, but it seems to be clear that infrasound enters the ear canal, travels via the middle ear, and reaches the inner ear and the cochlea. Pressure differences move the liquids in the scala vestibuli and the scala tympani via the helicotrema and, thus, the basilar membrane produces large-scale displacements [7, 11]. These displacements excite the hair cells and since the stereocilia of the outer hair cells are fixed in the tectorial membrane, they seem to be more strongly deflected than the inner hair cells by the slow but large-scale movement. This is supported by the decrease in steepness of the hearing threshold-versus-frequency function by 6 dB (see also Figure 1) [7].

Since one of the basic perception mechanisms of infrasound is a hearing sensation, hearing thresholds were determined, and data down to a frequency of 2 Hz could be obtained [12]. They document the hearing sensation but show that the hearing threshold rises strongly with frequency and only quite high SPLs induce a hearing sensation. In the EARS project, these data were completed with an investigation of hearing thresholds [13] using insert earphones and, for the same test person group, a determination of loudness. A categorical loudness scaling method was used defining 11 classes between “inaudible” and “too loud” which were assigned to a scale between 0 to 50 categorical units. A coupling to the loudness scaling in phon was made by a comparison with 1 kHz tones.

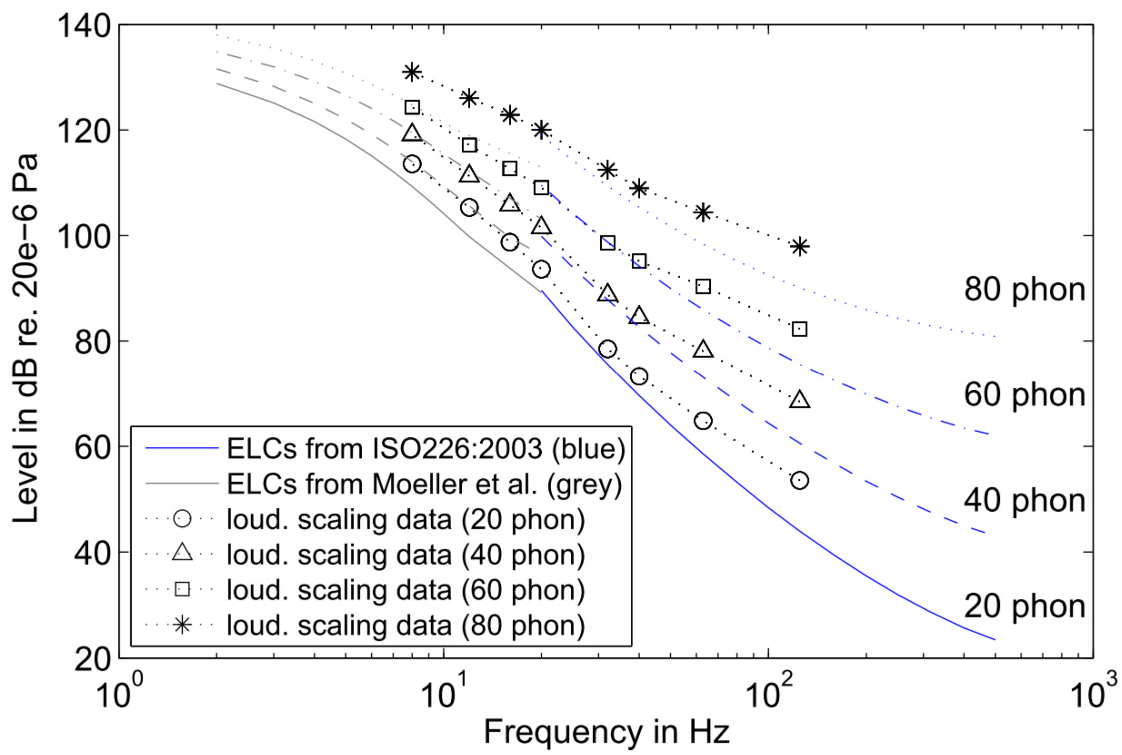

Figure 1: Equal loudness contours (ELC) for infrasound stimulation obtained with categorical loudness scaling; the blue lines are ELCs from international standard ISO226:2003 [15], the grey lines present data from [14] for comparison.

Figure 1 shows equal loudness contours as obtained within the project. Loudness values up to 80 phon could be determined and a link to data of the audible frequency range taken from standard ISO 226 is obvious.

The most striking feature of the data is the obviously decreasing sound pressure level difference between the contour lines. This is equivalent to a decreasing dynamic range of hearing in this frequency range, defined as the difference between the hearing threshold and the pain threshold. Such a decreasing acceptance range is accompanied by the effect that even signals with sound pressure levels only slightly above the hearing threshold will be registered as annoying. Regulations for infrasound exposure on humans should consider this effect with an appropriate reduction of the limit values.

It seems, however, also possible that the infrasound moves the otoliths and the gelatinous layers in a macula or a cupula inside the labyrinth of the inner ear. This could result in an activation of the hair cells of the vestibular system which are tuned to about 1 to 10 Hz and potentially match infrasound frequencies [16]. This could lead to a "sensory conflict" because movement or rotation is detected which is not confirmed by the other senses such as the sight. This might be a rationale for the hypothesis that infrasound produces symptoms known from motion sickness [16].

In general, the question of whether mechanisms other than hearing contribute to infrasound perception or annoyance is also important. Furthermore, hypotheses and speculations are discussed as to whether infrasound can also have an impact on humans at levels below the hearing threshold [17]. This is quite important for the process of defining limits, which has normally used hearing thresholds to take as reference to date.

A further complication of the discussion arises from the fact that temporary changes, such as the bounce effect [18], are known to influence cochlear sensitivity. In addition, infrasound could modulate audible sound which, in general, is also possible when the infrasound SPL is below the hearing threshold [17]. For example, because of the wind turbine blades periodically bypassing the tower, the modulation of audible sound is also an issue for the assessment of wind park noise [19, 20]. Although hypothesized, an increase in annoyance could not yet be clearly shown in laboratory model experiments [21].

Attempt to improve objective investigation of perception: brain imaging

There are serious arguments that hearing plays an important role in the perception of infrasound. To confirm this hypothesis and to analyse the processing of infrasound perception, the investigation of the representation of this hearing process in the brain is of high relevance. In animal experiments, cochlear microphonics, as the first element of electrical stimulation of nerve cells, were found from the third turn of the cochlea quite near to the apex [22]. Further processing of these signals is carried out along the hearing pathway, and finally the activation arrives at the cortical structures.

A consequent question was whether cortical areas, mainly the primary auditory cortex situated in Heschl's gyrus, respond to infrasound stimulation. In the EARS project an investigation of the brain was carried out to find areas of activation during infrasound stimulation using functional magnetic resonance imaging (fMRI) techniques. A blood oxygen level dependent (BOLD) technique was applied, and areas with high metabolic activity were detected.

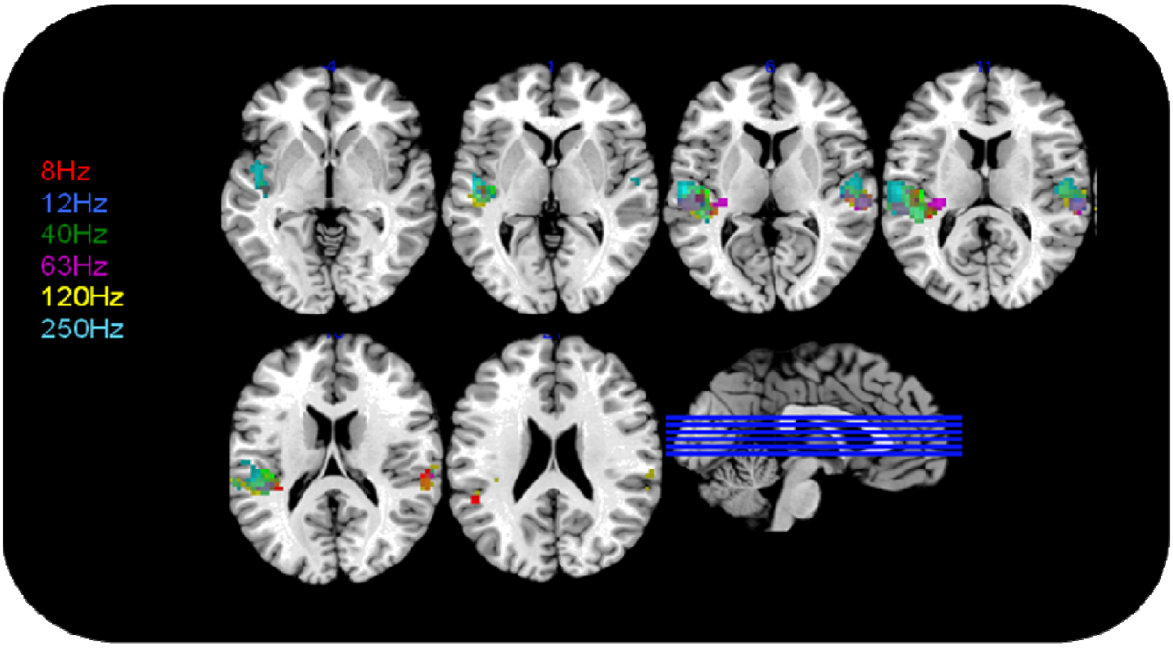

Figure 2: Slice images of brain obtained from fMRI, 16 test persons; stimuli: pure tones with a loudness of 20 phon, frequencies are colour coded, right ear, $p<0.001$, cluster size > 22.

Sixteen test persons listened to pure tones with frequencies between 8 and 250 Hz produced by a MRI-compatible sound source with very low distortion constructed in-house. Brain activity was found down to 8 Hz exclusively in the auditory cortex, see Figure 2. No other brain region was activated within the chosen significance level of $p = 0.001$ and the cluster size $N > 22$. As expected, the activity, described by the strength of the BOLD signal (beta values), decreased with decreasing frequency starting in the audible range at 250 Hz. Reaching a minimum activity level at about 20 Hz, the BOLD signal seemed to increase again at even lower frequencies. These data and further measurements suggest that the perception mechanisms may change at around 20 Hz. In addition, they clearly show that infrasound induces a hearing process.

Additional measurements with a magnetoencephalography (MEG) technique were carried out with the same test person group, and activation was measured at frequencies down to 12 Hz. The measured magnetic field structures changed significantly with decreasing frequencies and strongly depended on the individual person [23]. This could be a sign that the statistical dispersion between individuals in accepting or denying infrasound is quite large.

All measurements used short tones with durations in a range between a half and several single seconds. Longer stimulation was difficult to realize because of the necessary sparse sampling technique to avoid the influence of scanner noise in fMRI and the averaging requirements in MEG. A change in methodology allowed, however, the increase of the stimulation duration to at least several minutes. The idea was to measure the change of a long-term equilibrium state instead of activation following a short stimulation event. Thus, the regional homogeneity, representing local connectivity in the brain, was determined when the test persons were in a resting state compared to the situation when the resting state was influenced by infrasound [24].

A stimulation of 200 s of continuous infrasound was applied to test persons whose loudness scaling had been measured before. Three different modes (no tone, at individual threshold, and medium loud) were realized and BOLD sequences during a resting state were determined. When computing a whole-brain analysis comparing regional homogeneity, the only significant difference between all possible paired contrasts of regional homogeneity maps was observed when comparing the near-threshold condition with the supra-threshold condition. Here, we found significantly higher regional homogeneity in the anterior cingulate cortex (ACC) during the near-threshold condition. When using a more lenient cluster extent threshold, we also found higher regional homogeneity in the right amygdala (rAmyg). Taken together, it could be demonstrated that prolonged supra-threshold infrasound stimulation clearly perceived by all participants did not result in statistically significant activations anywhere in the brain. In contrast, near-threshold stimulation led to higher local connectivity in multiple brain areas, compared to both the no-tone as well as the supra-threshold condition.

These results show that prolonged infrasound exposure near the participants' individual hearing threshold led to higher local connectivity in three distinct brain areas, in rSTG, ACC and rAmyg, while no such effect was observed for stimulation above the hearing threshold. They also show that near-threshold infrasound was associated with connectivity changes at the network level, emphasizing the role of the rAmyg in infrasound processing. Infrasound induces changes in the neural activity of branches of the brain which are involved in emotional and autonomic control and response [24].

The fact that infrasound influences humans in a “less-conscious” resting state leads to the question of whether it also affects cognitive abilities. Not many studies on this exist [8] but from descriptions of the impact of infrasound on health [25, 26], the natural hypothesis is that infrasound disturbs, for example, memory skills and that cognitive abilities depend on personality factors such as depression, anxiety or neuroticism.

In experiments during the EARS project, an n-back working memory task was carried out with test persons under fMRI observation and the score was determined and compared with the brain activity [27]. Standardized questionnaires were used to investigate the influence of psychological factors by looking for the correlation of memory task scores with quantitative personality factor representations.

The results are not spectacular: No significant influence of infrasound was detected [27]. The scores of the memory test even increased slightly when infrasound was applied, but the result was not significant. The fMRI results showed typical activation structures for n-back memory tests but the only difference between the situation with and without infrasound stimulation was the expected auditory cortex activation which could be confirmed. In addition, no correlation with personality factors could be found. At least for this short duration, stimulation results show no influence of infrasound on cognitive abilities.

AIRBORNE ULTRASOUND

Measurement

A variety of microphones are available for measuring airborne ultrasound. Devices with a diameter of 12.6 mm (half inch) are well suited up to a sound frequency of 30 kHz, but for higher frequencies, smaller diameters like a quarter of an inch or an eighth of an inch have to be used. Measurement microphones at laboratory or working standard level have been manufactured for many years but both the quantitative characterization and the reliable traceability have not been possible at a level acceptable for contemporary quality management.

In the EARS project the first primary standard for the free-field calibration of working standard microphones (WS 3) up to 150 kHz was established [28]. It became the world's first reliable calibration facility providing traceability for airborne sound in this frequency range. This was a first step for the solid metrological underpinning of airborne ultrasound measurement and is the basis for building up secondary calibration services at various national metrology institutes [29]. These secondary services are also suitable for calibrating microphones which are not reciprocal but are often used in practice, including MEMS microphones. The higher uncertainty of this calibration is no real problem in applications.

The measurement infrastructure for everyday measurements is, however, not yet well developed. There is still no versatile sound level meter on the market that would be able to reliably measure airborne ultrasound in all relevant situations. No standards for requirements on devices or filter parameters exist, and a type approval is not offered yet although it is generally required for measurements and formal decisions in administrative or business matters.

This situation is also reflected by the status of knowledge and experience in measuring and characterizing ultrasound fields at workplaces and in public areas. For many ultrasound sources, no traceable quantitative "footprint" exists, and measurements are hindered by the lack of widely accepted standardized measurement procedures. Due to the small wavelengths, strategies from the audible frequency range cannot simply be transferred to ultrasound. In the EARS project the first measurement cycles for a variety of common ultrasound sources were carried out and the focus was on small transportable devices such as cleaning baths or animal repellent systems [30]. As an example, in Figure 3 the directivity of the sound pressure level, generated by a commercial cleaning vessel at the maximum power setting, is shown. Different measurands were determined and unexpected high values were found. At a distance of 0.5 m in front of the opening of the vessel, a peak value of 146 dB was measured. It is reduced at the side of the device but the natural mitigation action, i.e. closing the vessel, would increase the values in this direction. Another experience from these measurements was that the choice of measurands is critical and a methodology for a serious assessment of airborne ultrasound is indispensable and needs to be developed.

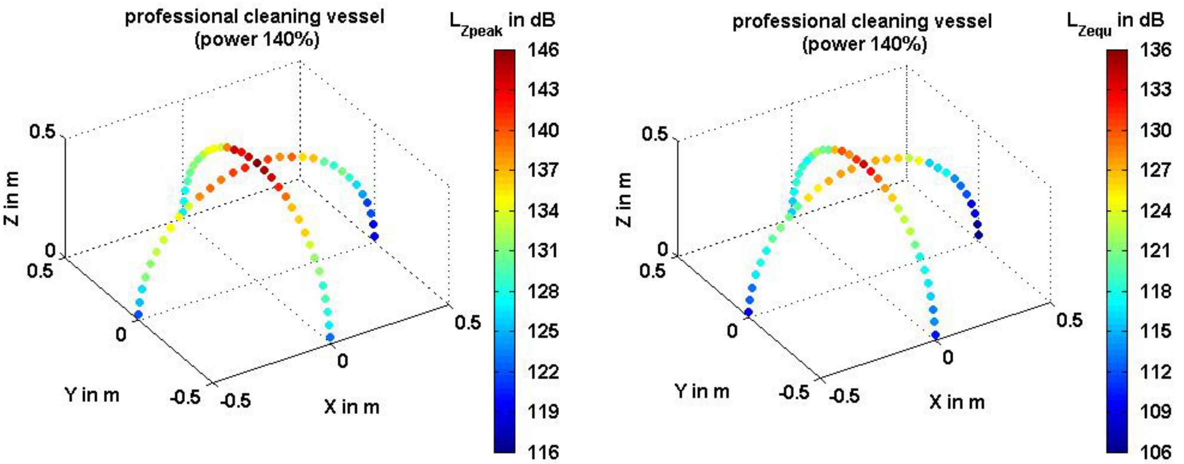

Figure 3: Directivity measurement of sound emission from a commercial 10 L cleaning vessel, left: peak value of sound pressure level, right: equivalent sound pressure level, the top of the upper bath rim lies in the (*X*, *Y*) plane.

Perception

Although it is still under discussion, it seems to be most probable that a hearing sensation is also possible at ultrasound frequencies [31]. Hearing thresholds were measured by various groups but not much data are available [31]. The results depend strongly on the kind of sound conduction and excitation. To the authors' knowledge, hearing thresholds and sensation during stimulation via air conduction could only be detected up to 40 kHz [32] and required quite high SPL. Stimulation by bone conduction worked much more effectively and signals with frequencies up to 95 kHz were found to induce a hearing sensation. This sensation had a pitch comparable to tones between 12 kHz and 14 kHz and was quite independent of the stimulus frequency. Hearing thresholds were determined [33] and the increase in hearing level depended strongly on frequency. In the EARS project, hearing thresholds were also determined as a prerequisite for brain activation measurements confirming results of previous studies [34]. The statistical dispersion of the data obtained was much wider than in the audible frequency range and this fact should be incorporated into limit consideration.

Perception mechanisms are still a matter of controversial debate. It seems that the hearing pathway is involved as in the audible frequency range and no special organ for perception [35] exists. The determination of brain activities has turned out to be just as complicated (see below), although for bone-conduction excitation significant proof was detected [36, 37]. Different hypotheses are drafted which could briefly be summarized as:

- Ultrasound hearing is a "normal" hearing process. It comprises an excitation of an area of the basilar membrane close to the oval window [38, 39].
- Ultrasound hearing stems from an excitation of inner hair cells in the (last) high frequency critical band. The spectral side lobe of the stimulus at the fundamental frequency excites the inner hair cells [40] at this position in the organ of Corti.
- Subharmonics are the basic mechanism transforming part of the ultrasound energy into the hearing frequency range [41].
- Ultrasound directly excites the nerve cells [42 - 44].
- A movement of the basilar membrane is generated by radiation force from the ultrasound coupled into the organ of Corti because of an impedance mismatch between the scala tympani and the scala vestibule. Here analogies to the action of modulated medical ultrasound were proposed [45].

There are rationale for and also arguments against every hypothesis. With the knowledge available at the moment, a clear decision cannot be made.

Attempt to improve objective investigation of perception: brain imaging

Fujioka et al. [46] used MEG for investigating brain activity in response to airborne ultrasound up to 40 kHz. They could not find any response between 20 kHz and 40 kHz. Contrary to these findings, Hosoi et al. [37] measured N1m brain activity components for tone bursts up to 40 kHz using MEG, but their stimuli were presented via bone conduction. Oohashi et al. [47] could show the influence of ultrasonic frequencies on hearing by using music with extraordinarily high-frequency spectral components as a stimulus by applying electroencephalography (EEG) and positron emission tomography (PET).

In the EARS projects, an alternative experiment was carried out using two different brain imaging modalities, MEG and fMRI. Measurements were carried out with a couple of test persons all engaged in three experiments: 1) a determination of the hearing threshold and the definition of individual SPL stimulation data, 2) MEG investigation looking for nerve cell activation via induced magnetic fields and 3) an fMRI investigation using the BOLD technique looking for metabolic activation of the brain by ultrasound. Several stimuli with frequencies between 14 kHz and 24.2 kHz were used and the stimuli were presented at three different levels (-10 dB, -2 dB, and 5 dB) with respect to the sensation level of the respective test person. All stimuli were presented via an ear plug directly to the ear canal and, naturally, used air conduction to reach the ear drum.

The results were quite unexpected: At 14 kHz both imaging modalities showed a clear signal but at no other frequency could any brain activation be detected. This is, in particular, surprising since all test persons reported a sensation of the sound. Several issues need, however, to be included in a discussion which can be found in [34].

CONCLUSIONS

The knowledge about noise perception at the borders of our hearing is still rather poor. This is in contrast to the situation in the audible frequency range where quite profound understanding about the mechanisms of perception and of impairment of hearing exists and strategies of conservation have been introduced well into occupational and everyday life. This is reflected by the status of standards and moreover safety limits are not well represented. The limited knowledge hinders progress and every discussion about safety is accompanied by some vagueness.

Furthermore, technical problems make the definition of safety limits difficult. The spreading of the determined hearing thresholds and other thresholds is much wider than in the audible range, restricting the quality and reliability of any limit value. The dynamic range, here defined as the difference between the hearing and the pain thresholds, decreases at the limits of hearing. Sounds of moderate loudness which would be accepted in the audible frequency range are already perceived as annoying. In the ultrasound region, the margin seems to be so small that the hearing threshold could act as the ultimate limit for any exposure in this frequency range.

A controversial debate is being held about the definition of percentiles from statistical data on thresholds of hearing and annoyance or even about health problems induced by noise or other environmental factors. One serious question is: Which proportion of the public will be included into the safety margin? This question is often posed to the scientific community but it should be accepted that such a question cannot be answered completely by scientific studies or investigations. To a significant extent, this issue will remain a political question and discussions need to be held in institutions and bodies which have been appointed and are able to manage such debates.

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