Investigation on Auditory Cortex Activation by Low-Frequency Sound and Infrasound Using Magnetic Resonance Imaging: Stimulus Generation and Control, and Noise Assessment

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Introduction

Several physiological mechanisms protect the peripheral hearing organ from receiving atmospheric pressure fluctuations. The common understanding is, that infrasound just cannot be sensed by the ear. But the notion that infrasound does not reach the cochlea has been contested by numerous researchers, e. g. by Møller [1], who even proposed a hearing threshold for infrasound.

Vibroacoustic disease (VAD) comprises both a somatic part caused by vibration stress of the human body [2], and a psychosomatic part, linked to the enhanced sensitivity for low-frequency sound (f < 100 Hz) and infrasound (f < 20 Hz) [3] which is not perceived by the vast majority of the population. Patients suffering from and complaining about low-frequency noise are often not taken seriously. Since subjective hearing tests are impossible in the clinical routine for both low-frequency sound and infrasound, an objective test is highly desirable.

After the finding that human otoacoustic emissions are strongly modulated by infrasound of 6 Hz [4], the question to be answered was, whether infrasound could even be observed in the activation of the auditory cortex. This is a report on a pilot study on this issue for subjects with normal hearing.

Methods and Material

A modern means for looking into the brain is Magnetic Resonance Imaging (MRI). MRI scanners, however, produce rather loud sounds themselves, which complicate the identification of brain activation by test sounds. Additional difficulties are:

- Normal head- or earphones cannot be used while the subject is inside the MRI device, due to huge magnetic fields that do not allow the usage of metallic equipment.
- For the same reasons standard microphones cannot be used.

In this study tone bursts were presented to subjects (12 right-handed women, age 20 to 60 years, all volunteers), lying in the MRI device (1.5 Tesla scanner with standard head coil), see Figure 1. Test signals were generated by a computer, then amplified or attenuated and fed to a modified loudspeaker driver system, attached to a silicone tube (length 12 m, inner diameter 6 mm), leading to the subjects' right ear, as shown in Figure 2. An optical, metal-free microphone (Sennheiser MO 2000) was coupled to the sound path near the ear canal by means of a T-fitting to monitor the sound pressure level.

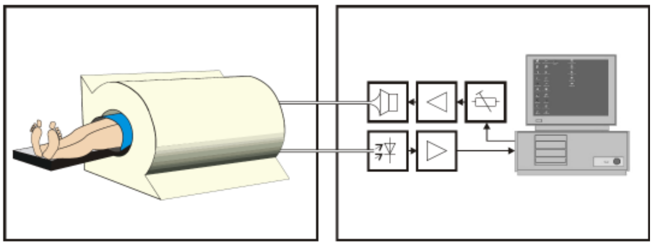

Figure 1: left: MRI operational room: 1.5 T scanner, standard head coil; right: Control room: PC, attenuator, amplifier, dynamic loudspeaker system, feeding into silicone tube (inner diameter 6 mm, length 12 m, top middle). Fibre-optical line (bottom middle) connects optical microphone (left, not shown) to control box (right) with light-to-voltage transducer.

Since only frequencies below 1 kHz were considered, neither standing waves nor resonances were observed. Calibration was done using an occluded ear simulator (IEC 60711 [5]) instead of the living ear. Between 2 Hz and 1 kHz the optical microphone, at its measuring position, exhibited a flat frequency response (±4 dB) referred to the

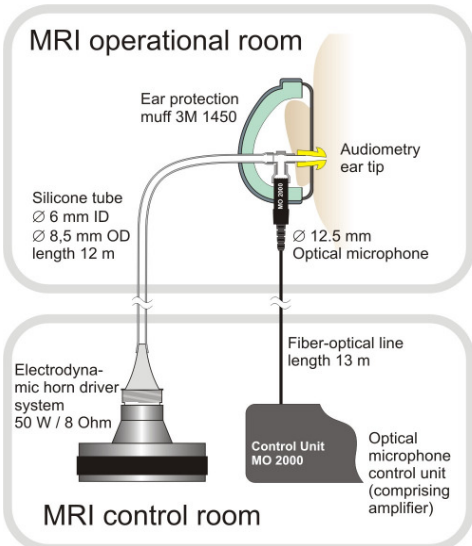

Figure 2: Sound coupling to the ear. Electrodynamic loudspeaker system (bottom left) feeding into silicone tube, through ear muff; into subject's ear (top right). Optical microphone (top right) is coupled via T-fitting to ear tip, its fibre-optic line is connected to control box (bottom right).

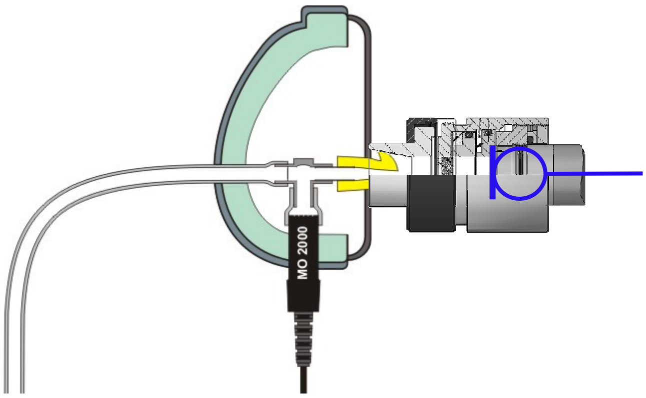

Figure 3: Calibration of optical microphone at the interface of sound tube and ear canal, using occluded-ear simulator B&K 4157 with built-in microphone B&K 4134

simulator's internal microphone (see Figures 3 and 4). The measurement paradigm is shown in Figure 5. Only two

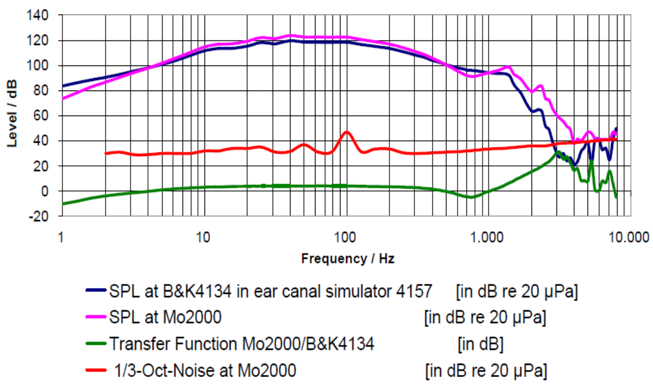

Figure 4: Steady-state frequency responses of microphones in-situ, as shown in Figures 2 and 3, with U_{RMS} = 1 V at the loudspeaker

frequencies were tested: 500 Hz, which is known to surely activate the auditory cortex, was applied with 102 dB SPL.

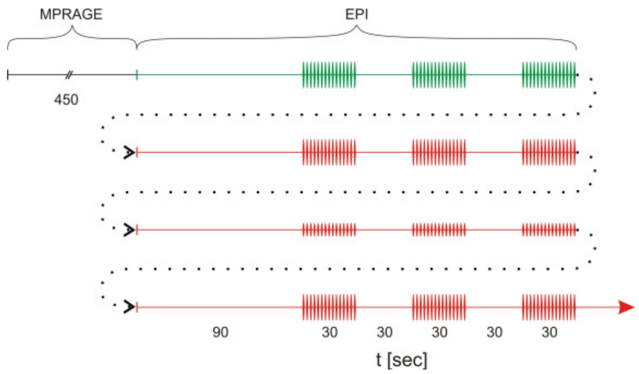

Figure 5: Stimulation paradigm: Bursts (amplitudes not to scale) are raised-cosine shaped sinusoids of 1 s duration, followed by 1 s pause, repeated 15 times within 1 block. Quiet intervals after blocks are 30 s long. Quiet intervals before 3 blocks are 90 s long. First row, green: 500 Hz, 102 dB SPL. Second row, red: 12 Hz, 120 dB SPL. Third row red: 12 Hz, 90 dB SPL. Fourth row, red: 12 Hz, 110 dB SPL. MRI scanning routine during acoustic stimulation: Echo Planar Imaging (EPI). Acquisition of anatomic image: Magnetization Prepared Rapid Gradient Echo (MPRAGE).

The second stimulus frequency was 12 Hz, which was applied with 3 different sound pressure levels (90 dB, 110 dB, 120 dB SPL). The tones were given in bursts with raised-cosine envelopes of 1 s length, followed by 1 s pauses. 15 contiguous bursts were followed by 30 s pause. During 240 s the scanner shot images of slices of the subject's head in order to get "functional" 3D images.

The acoustic stimuli and the scanner noise were recorded by means of the optical microphone near the ear canal entrance, and the data were analysed off-line.

Results

In Figure 6, the black curve shows the operational room noise spectrum when the MRI scanner itself was in idle mode.

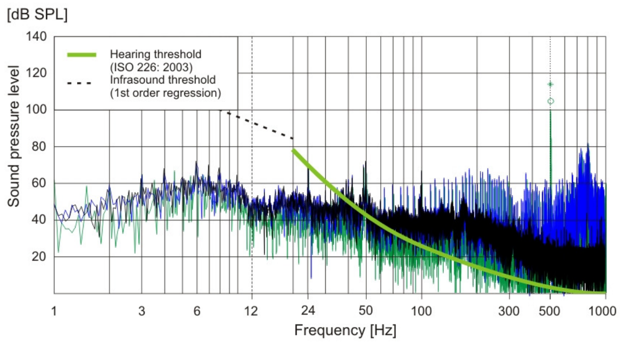

Figure 6: Spectra of ambient noise in operational room (black) and EPI mode scanner noise (blue) with 87 dB (unweighted), 86 dB (A) SPL. The emerald green line (-cluster) is the 500-Hz burst signal. The small green circle denotes its SPL value; the green asterisk denotes its peak equivalent SPL value. The light green line depicts the normal hearing threshold as given in ISO 226. The dashed line means the first order approximation of the infrasound threshold estimate by Møller and Pedersen [1]

The blue curve shows the room noise plus scanner noise spectrum in the EPI mode. The total sound pressure level of that noise was 87 dB (unweighted), or 86 dB (A).

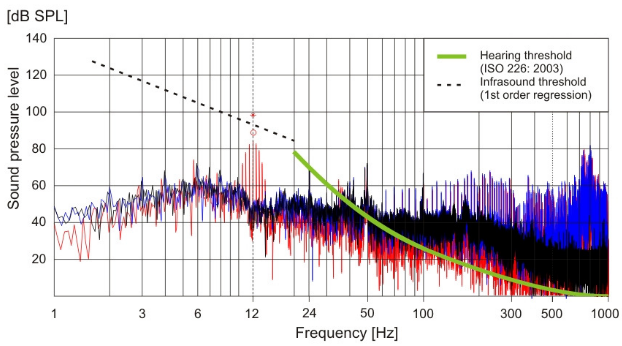

Figure 7: 12 Hz, 90 dB SPL test signal spectrum (red) together with noise spectra and thresholds as in Fig. 4. The red small circle at 12 Hz denotes the SPL value of the modulation line cluster around 12 Hz, the red asterisk denotes its peak equivalent SPL.

Figure 7 shows the 12 Hz, 90 dB SPL burst signal spectrum (red) together with the EPI mode scanner noise (blue) already given in Figure 6. The 12 Hz signal (red) lies below Møller's threshold estimate (dashed line).

Figure 8 shows the 12 Hz, 110 dB SPL burst signal spectrum along with the noise spectra as in Figures 6 and 7. Unfortunately, this test signal spectrum exhibits heavy odd-order harmonic distortions, which question the signal's characteristic as "Infrasound", since they lie up to 20 dB above the normal threshold. This will be discussed below.

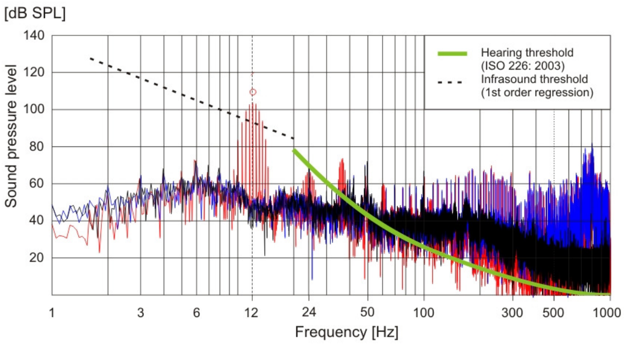

Figure 8: 12 Hz, 110 dB SPL test signal spectrum (red) together with noise spectra and thresholds as in Figure 4. The red small circle at 12 Hz denotes the SPL of the modulation line cluster around 12 Hz, the red asterisk denotes its peak equivalent SPL. Modulation line clusters around 36 Hz, 60 Hz, and 84 Hz represent harmonic distortion above normal threshold.

The brain activation is shown in Figures 9 to 11, depicting the mean activation over all 12 subjects. Figure 9 illustrates the activation caused by the 500 Hz, 102 dB bursts.

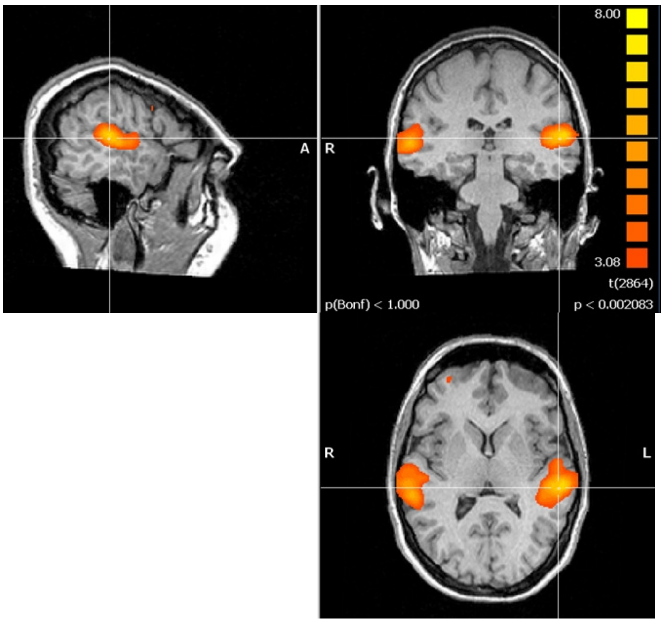

Figure 9: Images of mean activation over all 12 subjects in response to the 500 Hz, 102 dB SPL burst signal, right ear (R) stimulation: The activation is just noticeably enhanced in the left hemisphere (L, contralateral). (Activation scale rising from red to yellow.)

The 12 Hz, 110 dB activation image, shown in Figure 10, is very similar to that in Figure 9, though the tendency to the left, contralateral, hemisphere is greater.

The 12 Hz, 90 dB stimulus yields almost no activation, as is shown in Figure 11.

Figure 10: Images of mean activation over all 12 subjects in response to the 12 Hz, 110 dB SPL burst signal, right ear (R) stimulation: The activation is significantly enhanced in the left hemisphere (L, contralateral). (Activation scale rising from red to yellow.)

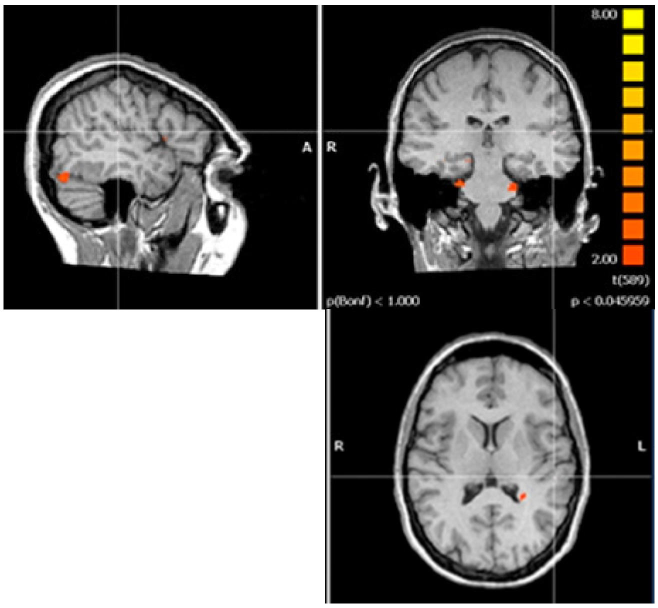

Figure 11: Images of mean activation over all 12 subjects in response to the 12 Hz, 90 dB SPL burst signal, right ear (R) stimulation. There is no significant stimulus-related activation. (Activation scale rising from red to yellow)

Discussion

To successfully achieve a very clear activation image from the reference test signal at 500 Hz, the stimulus level was set to 102 dB (unweighted) SPL.

It was assumed, that this level, applied for only 90 seconds, did not pose a hazard for the ear's health, since it can be converted to an energy equivalent long-term rating level of 75 dB (A) (8 h noise exposure) [7, 8, 9].

Furthermore, the stimulus envelopes were very slow (1 s raised-cosine), so that the stapedius muscle reflex had enough time to act as a protection. None of the subjects showed a temporal threshold shift after the session.

In regard to the distorted 12 Hz, 110 dB tone burst, it has to be considered, whether the harmonics could be able to stimulate such high activation as seen in Figure 9.

- If the plain brain activation was not caused by the 12 Hz infrasound, then it would have been caused by low-level, low frequency sound below 100 Hz.
- Comparing the activation images of the 12 Hz, 110 dB burst with the images of the 500 Hz, 102 dB burst, it seems improbable, that only the harmonics at 36, 60, and 84 Hz could cause such high activation. It is more probable, that the 12 Hz fundamental infrasound frequency was involved in this activation.

Summary

It was found that low-frequency sound ($f < 100$ Hz) can activate the auditory cortex in females with normal hearing. Activation by infrasound ($f < 20$ Hz) could not be proven without doubt in this study, due to harmonic distortion of the 12 Hz stimulus.

The activation depended on stimulus level, and the left hemisphere (contralateral) dominated. The MRI scanner noise in EPI mode did not mask low-frequency stimuli.

Conclusions

The use of an optical microphone (MO 2000) was found to be very helpful for calibration, and this microphone should be used in the future for in-situ monitoring at the subject's ear during MRI measurement.

A significant improvement in the performance of the high-level stimulus generation devices used in this study will be necessary to reduce harmonic distortion. Technically, this is supposed to be a minor problem.

In future measurements, stimulation with 6 Hz should be feasible with good prospects, and a test group of patients suffering from VAD should be compared to the present control group.

References

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