Multi-Frequency Technology for acoustic Reflexes

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Introduction

Tympanometry is a widely used objective method to assess the middle ear status. The basic idea is to measure the movability of the tympanic membrane as a function of static air pressure. Traditionally, a 226 Hz tone is used as a “probe tone” which is presented to the ear and recorded back with a microphone. Both speaker and microphone are located in a probe that needs to be sealed to the external ear canal and is connected to a pump that provides the static pressure. The movability is typically plotted as an equivalent air volume that changes with applied static pressure. It is a known fact that in certain middle ears, probe tone frequencies other than 226 Hz provide better information. Multi-frequency Tympanometry [1] and wide band tympanometry [2] have therefore been proposed to record tympanograms at more than one probe tone frequency simultaneously.

The acoustic reflex is the activity of the stapedius muscle and/or tensor tympani muscle of the middle ear, triggered by an auditory stimulus. The muscles apply force to the ossicle chain which stiffens middle ear mechanics, much like the static pressure in tympanometry does. It can therefore be measured with a similar setup as tympanometry, which is why both are often combined in one instrument.

An acoustic stimulus is presented to the ear in addition to the probe tone either ipsilateral or contralateral which triggers the stapedius muscle of the middle ear, while a compliance trace is recorded. The stimulus can also be provided electrically by a cochlea implant. Similar to tympanometry, the use of other probe tone frequencies than 226 Hz can help detecting the reflex in certain middle ears.

Since the sound level / phase change due to the reflex, as recorded by the probe microphone, is small, detecting the acoustic reflex is somewhat sensitive to artifacts. This includes both acoustic noise and test setup related effects, such as probe movement during recording. The use of more than one frequency to detect the reflex simultaneously should help making detection of the acoustic reflex more robust against artifacts. This paper therefore proposes a multi-frequency approach to the acoustic reflex.

Theory of operation

The main function of the middle ear is to transform the sound field from air conduction in the ear canal to fluid conduction in the inner ear. To deal with the different acoustic impedances of ear canal and cochlea, the area of the ear drum is much bigger than that of the stapes foot-plate. Additionally, the middle ear provides some protective mechanisms for the inner ear, including friction of ossicle joints and the acoustic reflex.

Like almost any mechanical system, the middle ear moving part has mass, compliance, and resistance. This means it can only work perfectly at one frequency, usually referred to as the middle ear resonance. Its resonance frequency typically is at about 1 kHz. The aucoustic reflex stiffens the middle ear mechanics, which also means it reduces its compliance and therefore moves its resonance frequency up. Figure 1 (left) illustrates the effect schematically.

The traditional probe tone frequency of 226 Hz will almost always be lower than the middle ear resonance frequency. Below resonance, the middle ear impedance acts as a spring, which means an added stiffness would reduce its compliance. This is what acoustic reflex testing observes. If plotted as an equivalent air volume, it will decrease during the reflex. Often, recording traces are inverted to produce a positive effect in the displayed trace.

However, if the probe tone frequency is higher than the middle ear resonance, the effect can be reversed, which means the recorded compliance (or equivalent air volume) can increase during the reflex period. At frequencies above resonance, the middle ear impedance acts as a moving mass, and added stiffness can increase movability. The blue trace in Figure 1 illustrates the effect. The simplified model data above is supported by measured data of real ears [3].

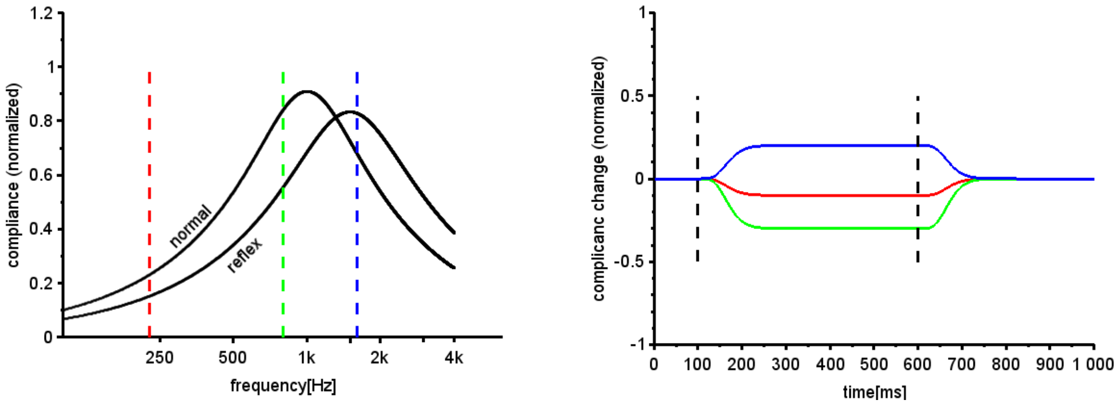

Figure 1: Left panel: General effect of the acoustic reflex on the middle ear's acoustic compliance. During the reflex, the resonance frequency moves up. This results in a compliance drop at lower frequencies and a compliance rise at high frequencies. Right panel: Expected reflex response at the 3 frequency marked in the left panel. The red trace represents the traditional, 226 Hz recording.

Methods

An existing acoustic reflex setup was modified in firmware to allow recording four different frequencies simultaneously. Since the original framing was optimized for a 226 Hz probe tone frequency, the additional frequencies were selected to be multiples of 226 Hz. This also avoids any beating issues, since the resulting waveform is periodic at 226 Hz. A sample probe signal is shown in Figure 2 (left).

Narrow band filters for each of the four frequencies were implemented digitally via a quadrature detection scheme. All filters use the same absolute bandwidth, which results in equal settling times for all filters. This is desirable to be able to compare response-traces of all frequencies later. Higher frequencies can be expected to be less impacted by environmental noise, since acoustic noise typically has a $\frac{1}{f}$ or $\frac{1}{\sqrt{f}}$ (aka "pink") spectrum.

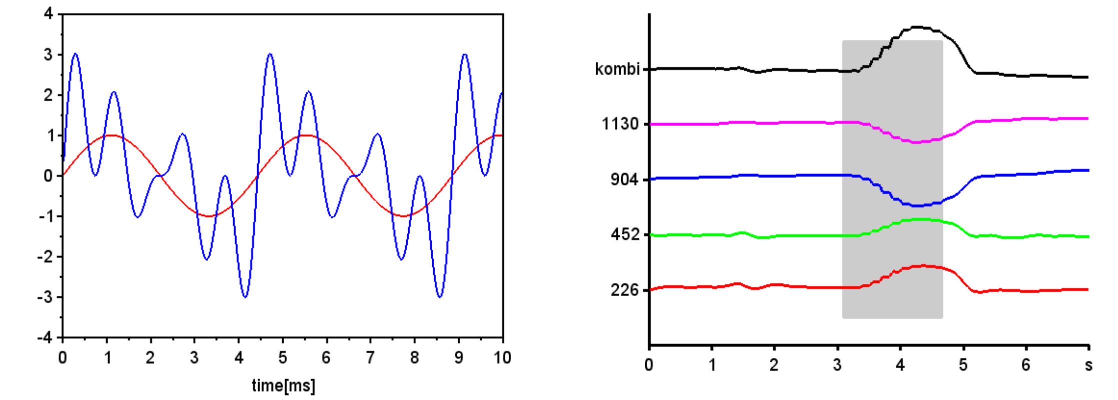

Figure 2: Left panel: Probe signal with four frequency components (226, 452, 904, 1130 Hz). Since components are selected to be multiples (1, 2, 4, 5) of 226 Hz, the resulting signal's period is still 1/226 Hz or 4.42 ms. The red trace illustrates the 226 Hz tone alone.Right panel: Multi-Frequency reflex recording at 1 kHz, 95 dBHL ipsilateral. gray area indicates the stimulus period. A sign inversion from 904 Hz on indicates the middle ear resonance to be between 452 and 904 Hz.

In this study, stimuli were ipsilateral tone bursts of 1.5 s duration. Total recording frames were 7 seconds long. To avoid interference with the detection, stimuli were pulsed at a rate of 226 / 36 = 6.3 Hz and detection performed in pulse pauses. Contralateral stimulation does not need this provision.

Results

The simulations above suggest that for certain middle ears, other probe tone frequencies than the standard 226 Hz may be more effective to use. The multi-frequency approach allows doing so within one measurement, and responses can be compared directly under exactly equal conditions. A result is shown in Fig. 2, right. The response for the 452 Hz is lower, and from 904 Hz on a sign change can be observed, indicating the middle ear resonance in the relaxed state is between 452 and 904 Hz.

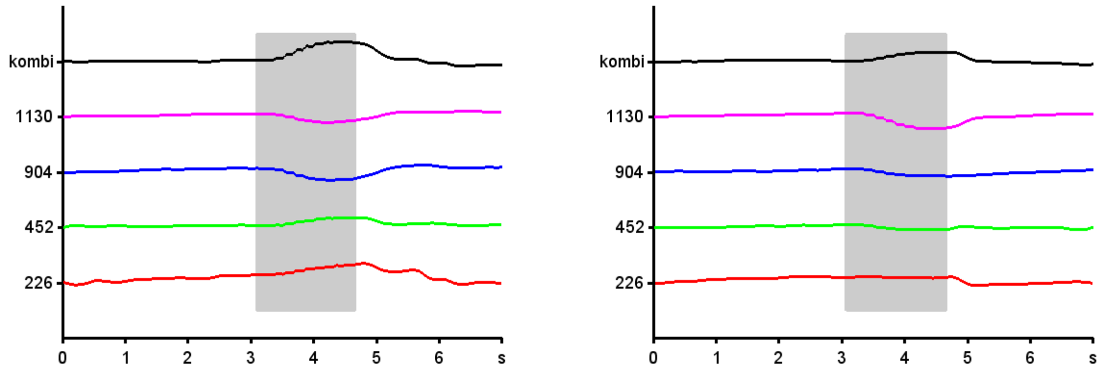

Figure 3: Multi frequency reflex recordings at 1 kHz, 95 dBHL ipsilateral. The Left panel: Middle ear pressurized with a static pressure of -100 daPa. The 226 Hz trace is almost flat in the preloaded state, while higher frequencies still show a reflex response. Right panel: Middle ear pressurized with a static pressure of 200 daPa.

If the eardrum is pressurized at 100 daPa, the 226 Hz trace tends to provide a much smaller reflex response, while the other frequencies still perform well (Figure 3, left). A sign-corrected sum (top trace) trace provides a stable response for both relaxed and pressurized situations. The effect of pressure expectedly is stronger at 200 daPa (Figure 3, right). In this state, only higher frequencies provide significant responses.

Figure 4 illustrates the behavior of the proposed method if artifacts occur. Since all traces are recorded simultaneously, artifacts are also synchronous on all traces, which allows for a multi-channel analysis.

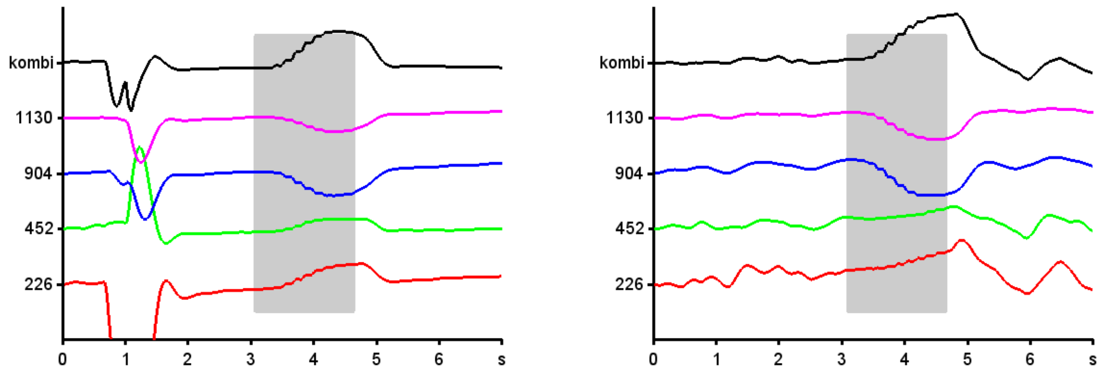

Figure 4: Multi frequency reflex recordings at 1 kHz, 95 dBHL ipsilateral. Left panel: Patient induced artifact (clearing throat) in the pre-stim period. The artifact is clearly reduced in the combination trace. Right panel: movement artifact (touching the probe cable) throughout the recording. The 226 Hz trace does not provide a clear response, while higher frequencies and the sum trace still do.

A very strong artifact was generated by the subject clearing his throat prior to the stimulus onset. The artifact is clearly strongest in the 226 Hz trace, which is an expected effect since the artifact mainly generates low frequencies. The other traces are still impacted, but much less intense. The combined trace shows a clear reduction of the artifact amplitude with a very stable reflex response.

An ongoing mechanical artifact was applied in the right panel by continuously touching the probe cable. Traditional recording alone would not have shown a clear response, while the combined one does. It is important to note that this type of artifact detection / suppression is only possible if all traces were recorded simultaneously.

Finally, combining data from multiple frequencies can also help performing reflex tests closer to threshold. Figure 5 shows an example. While the single traces do not show significant reflex responses, the summed trace still does. This indicates that multi-frequency detection of the acoustic reflex can provide more stable responses closer to threshold, compared to traditional recording.

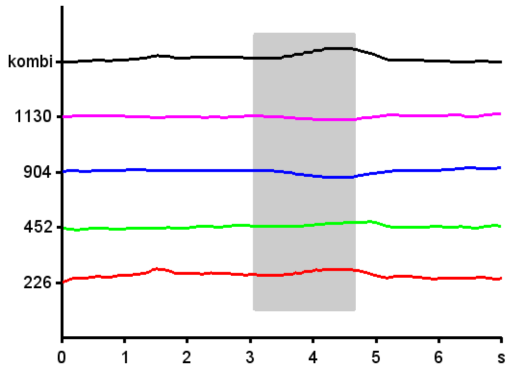

Figure 5: Recording close to threshold (1 kHz, 90 dBHL). The 226 Hz trace does not show a clear response, while the sum trace still does.

Conclusion

First experience with multi-frequency acoustic reflex recording indicates that it improves traditional acoustic reflex testing in several aspects:

- It allows reliable testing atypical middle ears without the need to search for an alternative probe tone frequency manually; it may make external pressure compensation obsolete.
- It provides more robustness against artifacts, such as external noise or subject related artifacts by aligning responses of the different probe frequencies.
- Reliable responses can be recorded closer to threshold by combining traces.

Since no additional test time is needed, the additional information comes at no “cost”. Therefore, even if only the standard 226 Hz response is finally used for any reason, no extra test time has been spent.

Note: Patents are pending on the described method.

Literature

[1] Kandzia, F. An optimized protocol for acoustic impedance measurements: „Simultaneous multi component multi frequency tympanometry“ DGA Tagungs-CD 2015

[2] Margolis, R. H.; Saly, G. L. & Keefe, D. H. Wideband reflectance tympanometry in normal adults The Journal of the Acoustical Society of America, ASA, 1999, 106, 265-280

[3] Peake WT, Rosowski JJ. (1997). Acoustic properties of the middle ear. In: MJ Crocker (Eds.) Encyclopedia of Acoustics. (pp. 1337-1346) New York: Wiley.