Technical reports

The measurement of Eustachian tube function in a hyperbaric chamber using an ear canal microphone

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Abstract

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Objective: The purpose of this study was to further the understanding of the opening of the Eustachian tube in relation to changes in barometric pressure.

Design: An ear canal microphone was used to measure the specific sounds related to tube opening and possible eardrum movements. Five subjects with normal tube function were examined in a hyperbaric chamber (up to 304 kPa). All active and passive equalization events were recorded and correlated with the subjectively perceived pressure regulation in the measured ear.

Results: The signals recorded were clear and reproducible. The acoustic analysis distinguished between the different kinds of equalization. Subjective impressions were confirmed by the recorded frequency of acoustic phenomena (clicks). During compression, the sequence of active equalization manoeuvres was in a more regular and steady pattern than during decompression, when the click sounds varied.

Conclusion: The study established a simple technical method for analyzing the function of the Eustachian tube and provided new information about barometric pressure regulation of the middle ear.

Key words

ENT; ear; barotrauma; Valsalva manoeuvre; middle ear; physiology

Introduction

The Eustachian tube (ET) plays an important role in the functioning of the middle ear. It is essential for pressure regulation and for the drainage of middle ear secretions by means of the ciliated epithelium and the ET muscles.[1] Previous direct or indirect measuring methods (tympanometry, tubomanometry, sonotubometry) have proven inadequate to assess tube function, either because they are unphysiological, causing obstruction of the ear canal, or because they allow no other conclusion than to confirm tube opening during testing.[2,3] Moreover, these methods only provide a snapshot of tube ventilation. Existing methods cannot be used to examine tube function over longer periods of time and during exposure to changing pressure conditions as encountered when diving or during flight.

Knowledge about long-term tubal function would help to better understand inflammatory diseases of the middle ear, as many of these diseases are a direct or indirect consequence of chronically impaired ventilation. In addition, ET dysfunction may negatively affect the postoperative outcome of tympanoplasty or balloon Eustachian tuboplasty.[4–6] Reliable information about ventilation dysfunction could allow for more targeted planning of ear surgery. However, even examinations for professional groups exposed to pressure, such as pilots or divers, currently lack a method that provides long-term measurements in support of tube function diagnostics. In the German Armed Forces, assessment of Eustachian tube function in hyperbaric chamber tests is based entirely on clinical aspects, i.e., occurrence of ear pain during compression.

A practical, physiological, long-term measuring method would help to obtain much needed data and potentially improve diagnostics. The new assessment method presented here works by recording and analyzing acoustic signals in the ear canal. The method is based on the phenomenon that specific sounds (‘clicks’) can be registered along with openings of the ET. There are different explanations in terms of the origin of such sounds. On the one hand, these sounds were considered as related to movements of the tympanic membrane (TM) during pressure equalization. On the other hand, there are strong indications that the clicks correlate with the action of the tube-opening muscles (*m. tensor* and *m. levator veli palatini*).

This phenomenon served as the starting point for our study, which aimed to record the movements of the TM with an ear canal microphone (ECM) and establish this method as a practical way of obtaining long-term measurements.

Methods

SUBJECTS

Informed consent of the subjects was obtained in accordance with the Helsinki declaration. Before the tests inside the pressure chamber were conducted, the reproducibility of the method was validated in 14 subjects with normal ET function (three women, 11 men; median age 38, range 30 years) at standard atmospheric pressure while these subjects performed two methods of active equalization. Active equalization by means of the Valsalva manoeuvre was performed by closing the mouth and pinching the nose closed while trying to exhale. The subjects stopped exhalation when they perceived a popping sound of the TM. Active equalization by moving their soft palates was performed using a movement similar to yawning. Seven subjects who were unable to clear their ears acted as a control group.

For the pressure studies, five healthy volunteers (all male, median age 26, range 22 years) with normal ET function were compressed in the Hydra 2000 hyperbaric chamber (Haux-Life-Support, Karlsbad, Germany) These five subjects were experienced pressure chamber personnel and met the previously described prerequisites. Experienced pressure chamber personnel were chosen because they are familiar with the increasing feeling of pressure in the middle ear and know how to perform various techniques of pressure equalization. They were familiar with the test situation and the test environment.

EAR CANAL MICROPHONE (ECM)

A lavalier microphone (Sennheiser, Wennebostel, Germany) was used as the ECM. The lavalier was connected to a tubular earpiece that was tightly plugged into the ear canal in a fixed position to ensure consistent placement (Figure 1). The tube system of the earpiece had an additional perforation to allow for changes in ambient pressure. The microphone was brought as close as possible to the eardrum. The distance between microphone and TM was less than 2 cm. The ECM recorded the sounds that were created in the ear canal by pressure equalization as acoustic signals and transformed them into electrical signals using the built-in audio amplifier of the computer and audio-processing software (Ableton Suite 8.2.1).

To examine the effect of different distances between the microphone and the TM, we compared two acoustic tubes with lengths of 1.5 and 3.0 cm respectively. To analyze the potential effect of patient movements or movement of the ECM inside the ear canal on acoustic signals, we asked the subjects to move their heads from left to right and back ten times.

Perforated, commercially available ear defenders were placed over the ears and the ECM to block out background noise caused by the pressurization of the chamber. The electrical signals of the ECM were transmitted through the hull of the chamber via a flange connection and then amplified outside by a computer-integrated amplifier. The measurements were limited to the examination of one ear only (signal 1). By means of a hand-held switch, the subject transmitted a second signal to provide information on subjectively perceived pressure regulation in the measured ear (signal 2). At the same time, a piezoresistive, absolute pressure sensor (type 4005B) inside the pressure chamber transmitted the actual chamber pressure to an external amplifier (type 4618A0, Kistler, Winterthur, Switzerland) (signal 3) (Figure 1). All three recorded signals were converted into digital information by a digital oscilloscope using an analogue-to-digital converter (PowerLab 8/35, ADInstruments, Castle Hill, Australia). They were simultaneously analyzed using a suitable data processing programme (LabChart version 7.0.2). The oscilloscope displayed the voltage change (in mV or V) over time (in ms). During the pressurization cycle, the subject and their equalization behaviour were monitored by an inside observer and recorded by a video camera.

Voltage and time data are reported as mean ± SD, rounded to the nearest whole numbers.

HYPERBARIC PROTOCOL

The pressure chamber protocol started with the compression of the subject to 304 kPa with a duration of descent of 3 minutes. The participant then spent 3 min at this pressure level, before ascending to a normobaric environment during the subsequent decompression phase (duration of ascent: 6 min). To compensate for the volume changes during compression, pressure was actively (voluntarily) equalized only by moving the soft palate whenever the subject felt the need to equalize the pressure. In the decompression phase, the necessary equalization of the middle ear occurred passively (involuntarily) via the tube.

Results

Both the ECM and the pressurization cycle were well tolerated by all subjects. The subjects were able to insert the earpiece themselves and it remained in the desired position for the duration of the measurement in all cases. The signals recorded by the ECM during the pre-tests were clear and reproducible. The recorded sounds always coincided with the performed manoeuvre.

Differences in tube length caused only minor changes in the recorded voltage peaks but no changes in duration of the acoustic signal recordings. Head movements were found to cause no errant signals, although the subjects did not move their heads during measurements in the hyperbaric chamber.

During acoustic analysis in the control group at normobaria, no acoustic signals could be registered during the attempted

Figure 1
Schematic drawing of the test assembly; image of seated subject inside the hyperbaric chamber of the Naval Institute of Maritime Medicine

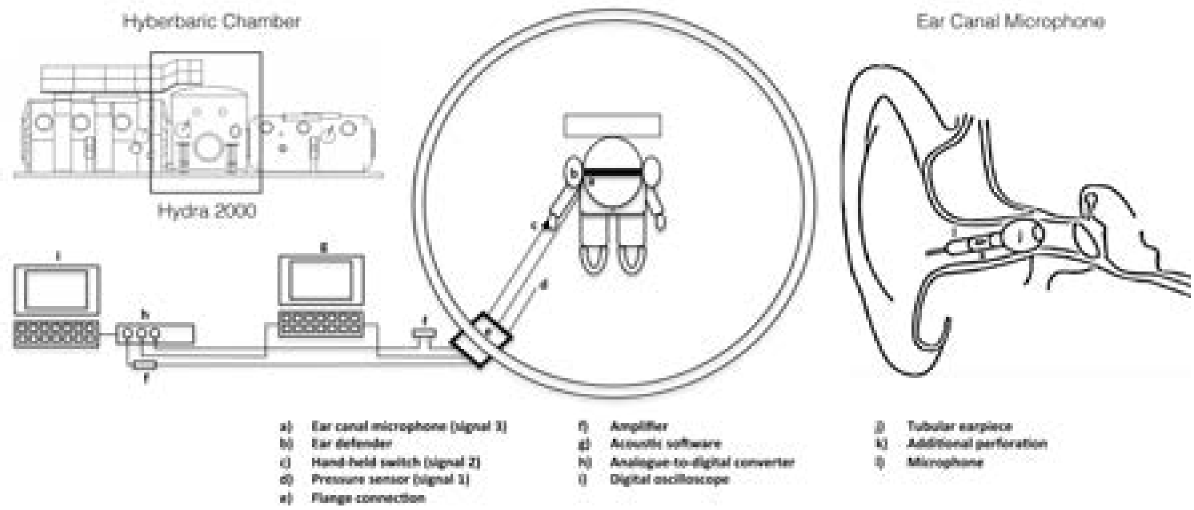


Figure 2
Voltage change caused by eardrum movements as a result of soft palate movement

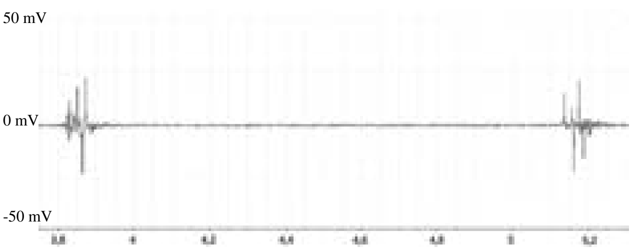


Figure 3
Voltage change caused by eardrum movements as a result of a Valsalva manoeuvre

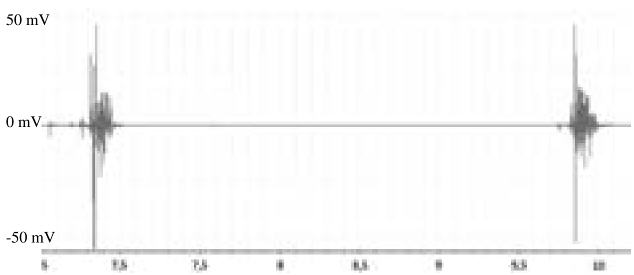
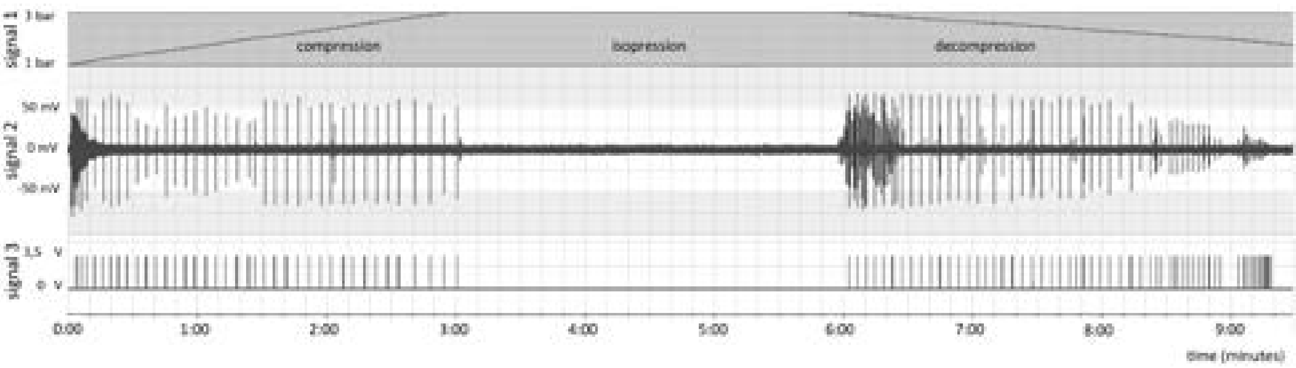


Figure 4
The captured signals during the pressurization cycle of a single individual; the voltage amplitude of passive equalization is similar to the voltage amplitude of active equalization; however, the amplitude and interval length decreases towards the end of the decompression phase; the diagram also shows the distorting effect of background noise during the early compression and decompression phase as well as a constant residual noise level



Valsalva or moving their soft palates. In subjects with normal ET function, we were able to differentiate between pressure equalization achieved by performing a Valsalva or by movements of the lower jaw. This difference could also be seen in the typical voltage configuration. The oscilloscopic representation of the characteristic popping sound caused by movements of the soft palate consistently showed a cluster with a mean value for amplitudes of 85 ± 45 mV and a duration of 71 ± 32 ms (Figure 2). In comparison, the signals produced when the Valsalva manoeuvre was performed had a voltage amplitude that was about twice as high (180 ± 62 mV) and lasted twice as long (192 ± 60 ms) (Figure 3). The sound pattern showed a multi-peak configuration, with maximum displacements at the beginning of the cluster and subsequent peaks only one third of the magnitude of the first displacements.

The signals collected during the pressurization cycle showed the same characteristics. The recorded sounds coincided with the subjective signals the participant transmitted with the hand-held switch (more than 95%) as well as with the pressure equalization behaviour as recorded on video. During the three-minute descent, the tube opened 39 ± 6 times on average. The intervals between tube openings were regular and lasted 3–5 seconds.

The patterns obtained from the captured signals during decompression varied between subjects. The average number of passive equalization events was 76 ± 18. Amplitude size and interval length decreased continuously after the first third of the ascent phase (Figure 4). In one subject, one ear exhibited a considerably higher frequency of passive pressure equalization with time intervals as short as 100 ms. Owing to the high frequency of events (>> 150), the subject was unable to give clear push-button signals. The subject perceived the events as an intermittent, soft bubbling sound. The differences in passive equalization between different subjects as described above were also found when comparing the left and right ear of individual subjects. As background noise was considerable, especially during initial compression and decompression, we were unable to completely avoid distortions of the captured acoustic signals despite using ear defenders.

Discussion

The idea of utilizing the sounds related to openings of the Eustachian tube during middle ear ventilation, e.g., as induced by a Valsalva manoeuvre, is not new. The Toynbee tube is widely known in ENT medicine and allows the medical professional to hear the characteristic sounds when the tube opens. These acoustic phenomena may be partially related to inward/outward movements of the TM. However, studies on the acoustic phenomena occurring during myoclonic contractions of the soft-palate muscles give a different explanation. This is explained as a sudden breakdown of the surface tension of the ET during its opening.[7,8] From personal experience and our measurements we strongly support this theory. The ECM presented in this study builds on this idea and makes use of modern technological possibilities for acoustic detection and recording.

Similar approaches have used other methods such as sonotubometry. However, even recent improvements in sonotubometry using perfect sequences only provide an average concordance with ET opening of 74%.[4] In contrast, the described technique offers considerably more reliable information on successfully performed pressure equalization.

The method represents an indirect approach to measuring ET tube function but meets two important prerequisites to qualify for experimental testing as a dynamic, long-term measuring method. Firstly, pressure equalization was physiologically provoked by using a hyperbaric chamber. Secondly, using the ECM leaves the ear canal unobstructed and thus allows for continuous pressure equalization and therefore natural movement of the TM. In another study, similar conditions were met using a differential manometer in the external ear canal that registered rapid pressure changes caused by movements of the TM.[9] In contrast to our study, a hypobaric chamber was used, with smaller volume changes (decompression to 88 kPa, volume expansion of 15%). Other methods have been based on mechanical and optical measurements of TM movement.[10–12] These, however, encountered problems owing to difficulties in placing the sensors. Our study allowed the ECM to be positioned by the subjects themselves and we encountered no sensor displacements.

Another method using TM displacement measured with a loudspeaker and microphone has also been described.[13] During two one-minute measurements, only comparatively small pressure changes were simulated and passive pressure equalization was shown in a schematic representation (± 2 kPa, ± 25% volume difference). In our study, we were able to show active and passive equalization under greater ambient pressure changes. It was also possible to differentiate consistently and clearly between two types of ear clearing. The passive equalization variant with very short and frequent ET opening seen in our study may indicate that the ET in divers functions exceptionally well.

Furthermore, the decreases in amplitude and interval of the recordings of ET opening after the first third of decompression might be explained by more frequent movements of the TM due to the increase in volume changes near the surface, according to Boyle's law. Our findings also support the statement that opening of the ET is similar to a reflex mechanism with relatively constant duration.[14] That study concluded that, in order to equalize higher pressure gradients, a series of ET openings is needed, rather than the tube opening for an extended period of time.

Conclusion

An ear canal microphone provided objective, quantitative and reproducible recordings related to ear clearing manoeuvres at ambient pressure and during chamber compressions to 304 kPa.pressure. Although there is room for some technical improvements, the results achieved so far have demonstrated the feasibility of the method. This new method allows for new ways of evaluating ET function, e.g., in long-term measurements, during pressure equalization tests or during compression chamber examinations. The method is suitable not only for aviation and diving medicine but could conceivably be applicable in otology in general. For this purpose, the method requires further development. Similar to long-term ECG or blood pressure measurement, this method could eventually be used for actual long-term measurement to record if and how often a patient's Eustachian tube opens under normal and changing pressure conditions.

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Conflicts of interest: nil

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Footnote: Supplementary audio material can be provided by the authors on request.