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Research Paper

Tympanic membrane pressure buffering function at quasi-static and low-frequency pressure variations

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ABSTRACT

Deformation of the tympanic membrane is known to contribute to the pressure regulation processes in the middle ear cleft. In this paper we investigated pressure variations in the rabbit middle ear in response to sinusoidal varying pressures applied to the ear canal, with frequencies ranging from 0.5 Hz to 50 Hz and pressure amplitudes ranging between 0.25 kPa and 1 kPa. The transtympanic pressure difference was found to be smallest in the quasi-static range, and quickly increased as a function of frequency. The response curves showed asymmetry, with larger transtympanic pressures when positive pressures were applied in the ear canal. Normalized transtympanic pressure amplitudes remained fairly constant as a function of input pressure, with values in the range of 60%–70% relative to the applied pressure. The total harmonic distortion of the middle ear pressure signal was calculated and was found to be very small (≤2%) for low-pressure amplitudes and low frequencies. For pressure amplitudes in the order of 0.25 kPa –0.5 kPa, it increased to about 10% at 50 Hz. When a 1 kPa pressure amplitude was applied, variation between animals became large and distortion values up to 30% at 50 Hz were observed. The results showed that pressure buffering due to tympanic membrane displacement was most effective for compensating small transtympanic pressure loads at low frequencies.

1. Introduction

The ear is subject to pressure variations over a large frequency range. In the auditory range (20 Hz–20 kHz), the pain threshold of 120 dB SPL corresponds to a pressure amplitude of 20 Pa. In the very low frequency range (<20 Hz), however, pressure variations occur with amplitudes which can be several orders of magnitude larger: during an airplane liftoff or descent, or a dive under water, pressure variations of several kPa are commonly encountered, and even a simple elevator trip of a few floors leads to a pressure variation of several hundreds of Pascals. The gas exchange processes between the blood perfusion in the middle ear (ME) mucosa and the gases in the ME cleft also lead to a slow buildup of pressure differences between the ME and the environment (Loring and Butler, 1987).

Middle ear pressure (MEP) is regulated by a combination of Eustachian tube (ET) action, gas exchange processes, and deformation of the tympanic membrane (TM). As the TM is flexible, it is deformed by pressure gradients between the ME and the environment, thus changing the volume of the gases enclosed in the ME, and buffering part of the pressure change. The TM is therefore an important factor in ME pressure regulation, but at the same time a deficient regulation of pressure loads can lead to TM pathologies. Sustained ME under-pressure is a common clinical condition which can result in remodeling of the TM with atrophy, retraction pockets, atelectasis, and cholesteatoma including ossicular destruction (Tos et al., 1984; Ars et al., 1989; Sadé and Ar, 1997).

Quasi-static pressure changes in the ME can be measured indirectly with tympanometry in clinical circumstances (Thomsen, 1960) or directly using various other methods. Direct measurements can be done through a perforation in the mastoid (Flisberg et al., 1963; Hergils et al., 1990) or the TM (Buckingham and

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Abbreviations: EC, Ear canal; ECP, Ear canal pressure; ET, Eustachian tube; ME, Middle ear; MEP, Middle ear pressure; THD, Total harmonic distortion; TM, Tympanic membrane

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Ferrer, 1973; Sadé et al., 1976), as well as insertion of a pressure transducer through the ET (Takahashi et al., 1987). Numerous studies have investigated the influence of such pressures on the deformation of the TM (e.g. Dirckx and Decraemer, 1991; von Unge et al., 1993; Vorwerk et al., 1999; Lee and Rosowski, 2001) and the displacement of the ME structures (e.g. Hüttenbrink, 1988; Rosowski et al., 1999; Salih et al., 2016) using various techniques. Recently, the buffering function of the TM in humans was investigated with measurements of MEP change on test persons that were subjected to external pressure variations due to elevator trips (Padurariu et al., 2016). In such experiments it is, however, not possible to systematically investigate the dependence of the pressure buffering as a function of frequency and amplitude.

In the current work we used an animal model to measure pressure variation in the ME caused by pressure variation in the ear canal (EC). Measurements were taken over a wide range of amplitudes and frequencies, so the gap is bridged between the quasi-static pressure regime and the (very) low auditory frequencies. As the study focuses on the purely mechanical effect of the TM, measurements are done ex-vivo, so that the ET action or gas exchange effects are avoided.

2. Materials and methods

2.1. Sample preparation

Rabbits used in this study were sacrificed using intravenous injection of sodium pentobarbital 60 mg/kg (Dolethal, Ethical Agents Ltd, Auckland, New Zealand). The injection was performed in the vein of the pinna after local surface anesthesia with lidocaine spray (Xylocaine, AstraZeneca, Ukkel, Belgium). All preparations were conducted according to the rules set by the Belgian legislation and the local ethical committee of the University of Antwerp, and were in accordance with the Guiding Principles for Research Involving Animals and Human Beings as adopted by the American Physiological Society. The temporal bone was dissected from the skull. The EC was connected with instant glue (Loctite 401, Loctite, Düsseldorf, Germany) to a 2 cm long plastic tube, through which pressure was applied. At the medial side of the bullae, a hole of 2 mm was drilled using a dental bur. Through the hole, a 2 cm long metal tube was glued with dental glue (OptiBond Solo Plus, Kerr, Orange, CA, USA) to measure the MEP as a function of ear canal pressure (ECP). A miniature pressure sensor (Endevco 8507C-1, Meggit Sensing Systems, Basingstoke, UK) for measuring MEP was connected to the metal tube using a 3-way valve so that the ME could be vented before starting measurements. Specimens were kept humid during the preparation and measurement by using an ultrasonic humidifier (BU-1300, Bonaire, Salisbury, Australia).

2.2. Pressure generation

A custom-built pressure generator was used to apply sinusoidal pressure changes to the EC. As shown in Fig. 1, the pressure setup consists of an electromagnetic actuator (Vibration Generator (2185.00), Frederiksen, Endeavour Hills, Australia) that is attached to an adaptable volume connected to a tube. When the actuator moves, the volume and hence the pressure of the enclosed gas change, since the amount of gas remains constant. With a pressure sensor (PDCR 10/L, Druck, Inc., New Fairfield, CT, USA) coupled to the tube, the pressure values were measured and used in a custom-built feedback system (Aernouts and Dirckx, 2011). This way the actual pressure follows the desired values with an accuracy of better than 2% over the entire frequency and pressure range. The feedback control unit (FU) was connected to a function generator (TDS 210, Tektronix, Beaverton, OR, USA), and was used to generate sinusoidal pressure changes with frequencies varying from 0.1 to 100 Hz within the range of −2 to +2 kPa. The calibration of the pressure generation system and the MEP pressure sensor were checked extensively, and proved to be perfectly stable within the measuring resolution over long periods of time (months).

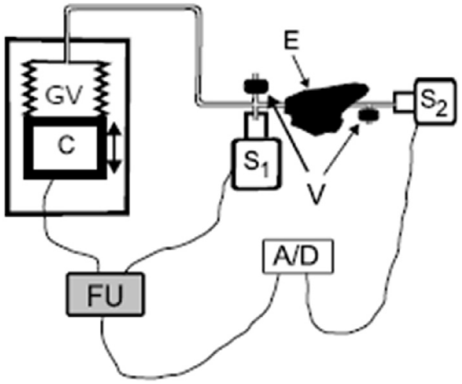

Fig. 1. Schematic drawing of the experimental setup; (GV): compressible gas volume, (C): electromagnetic actuator, (S1): pressure sensor to measure the actual pressure generated by the system which is applied to the EC, (FU): feedback control unit, (S2): pressure sensor to measure the MEP, (V): two valves used to ventilate between measurements, (E): specimen, which is glued via two tubes to the pressure sensors and (A/D): A/D port that sends/receives the signals to/from a PC.

2.3. Measurement protocol

With an A/D port (NI DAQPad-6015, National Instruments, Austin, TX, USA) connected to a PC, pressure generation and measurement was controlled from custom written software in Matlab (Mathworks, Natick, MA, USA). The setup allowed to apply pressures with a precision of 10 Pa. Measurements were conducted in fresh specimens, within less than 20 min after sacrificing the animal. Four periods were recorded after completing two initial pressure cycles, so that the specimen was preconditioned to reduce viscoelastic effects. Pressures at both the EC and ME were measured simultaneously, so that the time-dependent response of the TM could be obtained. ECPs with amplitudes of 0.25, 0.5 and 1 kPa and frequencies of 0.5, 1, 2, 5, 10, 20, 30, 40 and 50 Hz were applied. The specimens were ventilated before each cycle of pressure measurements. In this way the measurement always started at zero pressure. This measurement protocol allowed us to minimize static pressure gradient build-up, which can occur due to changes in environmental conditions (e.g. changing barometric pressure due to weather conditions, draft due to room ventilation systems etc.). Results using low-pressure amplitudes were recorded first to avoid possible effects of inelastic deformation caused by the higher pressure values. After the measurements, a static under-pressure and over-pressure of 2 kPa was applied to the ear to check for ET opening action, but no leakage was observed.

When the actuator (C) moves, the pressure in the gas volume (GV) changes as the total gas content remains fixed. With the feedback control unit (FU) a desired pressure value is obtained.

2.4. Total harmonic distortion

It is well known that the TM and ME show nonlinear behavior in the quasi-static regime at large pressure amplitudes (Hüttenbrink, 1988; Dirckx and Decraemer, 1991, 1992; Aerts and Dirckx, 2010). Consequently, a nonlinear pressure response as a function of ECP is to be expected. To quantify the level of such a nonlinearity, the total harmonic distortion (THD) was calculated, which is a popular