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Measurement of the vibration of the middle ear ossicles with removed eardrum: A method for quantification of ossicular fixation

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ABSTRACT

Chronic inflammation of the middle ear is a common disease in which the mobility of the middle ear ossicles may be reduced; resulting in hearing impairment. Knowledge of the degree of ossicular mobility is useful in helping a surgeon determine how to proceed with treatment. In advanced cases, mobility can be assessed by manually pressing on the ossicles, but in less advanced cases manual assessment can provide limited useful information. Ossicular vibration can be measured with a laser vibrometer, but only the manubrium of the malleus is optically visible without removing the eardrum. Since the eardrum is the means by which acoustic energy is translated into the mechanical motion of the ossicles, removing it renders any subsequent measurements of ossicular motion meaningless. We therefore devised a technique in which the ossicles are vibrated magnetically. After measuring the response of the umbo to acoustic stimulation, we removed the eardrum and attached a small magnet to the manubrium. An electromagnetic excitation coil was then used to vibrate the magnet, and the signal to the coil was adjusted until the vibration of the ossicles matches that achieved acoustically. In this paper we explain the method and describe some test measurements on a vinyl membrane, and some preliminary results obtained on a fresh-frozen human temporal bone before and after artificial fixation of the ossicles.

1. Introduction

Sound entering the ear canal causes the eardrum to vibrate. These vibrations are then transferred to the middle ear ossicles (the malleus, incus and stapes) and from these to the inner ear. The purpose of the middle ear system lies in impedance matching between sound travelling in the air filled outer ear and sound travelling in the fluid filled inner ear.

The most lateral ossicle, the malleus, is closely connected to the eardrum at certain zones along the manubrium. The eardrum itself has a conical shape and its apex is referred to as the umbo, where the manubrium is closely attached to the eardrum. The malleus is connected to the incus, and the incus has a long process which is connected to the top of the stapes.

A number of medical conditions affect the middle ear system. Chronic inflammation of the middle ear (chronic otitis media) is a fairly common disease which leads to many structural changes in the ear, which may in turn lead to reduced ossicular mobility [1]. As well as inflammatory processes, ossicular motion can also be hampered by calcification of the joints. Reduced mobility in the ossicles is an important source of conductive hearing loss and, in many cases, surgical intervention is considered necessary to preserve or improve a patient's hearing.

During surgery, a surgeon must decide whether or not to remove partially fixed ossicles, and reconstruct the ossicular chain, or to leave them in place. Knowledge of the degree of ossicular mobility is useful in helping a surgeon determine the best course of action, and maximise the hearing outcome of the operation. This analysis is often performed manually, with the surgeon pressing on the ossicles and observing their response. This is a relatively crude method and, while it can be helpful in cases of full fixation, it offers little help in cases of partial fixation. In order to help a surgeon make the best decision, a more objective method of measuring ossicular motion is required.

Laser Doppler vibrometry is commonly used in fundamental studies of the mechanics of hearing, and its use as a diagnostic tool has been investigated previously [2,3]. With this technique, the vibration of the umbo and the short process of the malleus can be measured through the ear canal, as at these places the malleus is closely coupled to the eardrum. However, in such measurements the presence of the eardrum means that other points, on the incus and stapes, are optically inaccessible. In temporal bone studies the other ossicles can be exposed by opening the facial recess. This method has even been used to make measurements of stapes and

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incus velocity in live human subjects [4,5]. Temporarily removing the eardrum to expose the ossicles is much less invasive than drilling an opening in the middle ear wall, so this technique is commonly used to evaluate ossicular mobility.

However, since the eardrum is the essential component by which acoustic information is translated into the mechanical motion of the ossicles, its removal eliminates the means by which the ossicles are stimulated. This renders any subsequent measurements of their motion meaningless. Thus, if laser vibrometry is to help a surgeon, a different means of stimulation is required.

In this paper we present a new method that makes use of a small magnet and an excitation coil to vibrate the ossicles without the eardrum being present. We describe our set-up and method, and present results of tests on a vinyl membrane and of measurements on a fresh-frozen human temporal bone with artificially fixed ossicles. We discuss the viability of our method and its future potential.

2. Experimental set-up and method

2.1. Optical set-up and microscope

The vibration velocity of the eardrum and ossicles was measured with a laser Doppler velocimeter (Polytec model OFV-534). The laser has a spot size of 200 μm at a distance of 30 cm. The power of the laser beam is <1 mW and the wavelength is 628 nm. As the laser is Class 2 (<1 mW CW 620–700 nm, safety norm EN 60825-1 (2001)) it does not require the use of safety goggles or other protective measures, except for avoiding to stare directly into the beam. When the laser beam is directed onto a vibrating object the vibrometer delivers an electrical signal that is proportional to the object's velocity; hence, measurement sensitivity increases with the frequency of vibration, and the technique is nearly insensitive to slow movements. This is an important asset as the rather large but slow movements of a patient (caused by heart beat and breathing) will inevitably be superimposed on the very small vibration amplitudes of the eardrum and ossicles.

The vibrometer unit was attached to a surgical microscope (OPMI Sensera/S7, Carl Zeiss). In this set-up, fine positioning of the laser is achieved by adjusting the orientation of a small mirror placed in front of the vibrometer, an operation which is performed by means of piezo motors. Focussing of the laser is achieved in a similar way.

2.2. Acoustic and magnetic stimulation

The sound needed for acoustic stimulation was generated using an open field loud speaker system. The speaker was positioned some 40 cm from the ear, and the sound pressure level was measured using a probe microphone (Bruel & Kjær probe microphone, type 4182). Using a free field system positioned at some distance generates a relatively homogenous sound field, meaning calibration is rather insensitive to small positional changes.

Once the eardrum was removed, magnetic stimulation was used to drive the ossicles. For this purpose a small custom made neodymium magnet (0.5 mm thickness, 1 mm diameter and weighing 0.003 g) was attached to the malleus. The magnet is gold coated so that it is physiologically inert. A custom built pancake coil was used to drive the magnet. This was driven via a power amplifier (DAP P-900 Vintage Stereo Amplifier). The coil consists of 87 spiral coiled windings, with a central hole of 100 mm and an outer diameter of 200 mm.

The central hole was chosen to be large enough so that in future clinical applications the device can be placed over the ear leaving the surgeon ample space to perform the surgery. The construction of the coil was a trade-off between various demands: keeping resistance as low as possible (to prevent heating), having a large enough number of windings to obtain a strong magnetic field, and having an impedance which is matched to the amplifier. The inductance of the coil is 1.4 mH, giving an impedance of 8.8 Ω at a frequency of 1000 Hz, which is well matched to the amplifier's 8 Ω output impedance. The resistance of the coil is only 3 mΩ, so heat dissipation is kept minimal even at high stimulation currents. The pancake construction delivers a magnetic field which spreads out in space in front (and behind) the coil. This is necessary as in the realistic situation the magnet will be positioned 20–30 mm in front of the coil due to the length of the ear canal.

2.3. Measurements on an artificially fixed temporal bone

Measurements were performed on a preserved (fresh-frozen) human temporal bone (provided by Medcure Inc., USA). It has been shown that the freezing–thawing process does not introduce any significant changes to the biomechanics of temporal bones such that they are considered good models for fresh ones [6].

To start the procedure an initial measurement was made on the temporal bone with the eardrum intact. The eardrum was stimulated acoustically and the vibrometer positioned to measure at the umbo. Next, the eardrum was removed and the small magnet was attached to the manubrium, at a point close to the umbo, using Vaseline. The magnet was attached to the lateral side of the manubrium, just above the umbo so that the laser could remain focussed on the same point as before.

Next, the electromagnetic coil was used to vibrate the magnet, and hence also the malleus. The coil was positioned above the temporal bone, with the ear canal near its centre, as if the coil were resting on a patient's head. Malleus vibration was again measured near the umbo, as was done during the acoustic stimulation, and, using an iterative method, the input signal to the coil was adapted until the vibration response obtained at the umbo using magnetic stimulation was the same as the response obtained during acoustic stimulation, to within a margin of 1 dB.

To fixate the ossicles, glass ionomer luting cement was used (GC Corporation, Tokyo, Japan). This cement was originally developed for dental applications. In dentistry the cement needs to establish a close contact with dentine in order to avoid penetration of bacteria. We therefore expect that the material will also form a rigid contact to the ossicles. Nevertheless, the fixation model is a point of concern: to obtain a good fixation the tissue lining covering the ossicles needs to be removed. This is done by gently scratching the ossicle's surface, but as we cannot be certain that the bone is fully free of tissue there is some degree of uncertainty in the control of the fixation. This issue remains a point of concern if we want to establish the relationship between the degree of fixation and the vibration response of the ossicles.

To expose the ossicles, the attic of the middle ear cleft was opened by drilling a hole in the tegmen tympani from the middle cranial fossa side. The approximate size of the hole was 5 mm. The hole gave access to the most rostral (or superior) portions of the malleus and incus and to the short process of the incus. The cement was then applied in three stages. In the first fixation, a drop of cement was applied in the space between the lateral attic wall of the temporal bone at the buttress site and the short process of the incus. Next, a drop was applied beside the first to fixate the most superior portion of the incudis body to the lateral attic wall. In the third fixation another drop of cement was applied in the space between the lateral attic wall and the superior portion of the malleus head, aiming to fixate the malleus. A drawing of the middle ear ossicles, showing the location of the cement is shown in Fig. 1.

At each stage of fixation, a measurement was made on the umbo and at the tip of the long process of the incus. The measurement points are illustrated in Fig. 2. These images were taken from a 3D