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Dynamic properties of human incudostapedial joint—Experimental measurement and finite element modeling

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ABSTRACT

The incudostapedial joint (ISJ) is a synovial joint connecting the incus and stapes in the middle ear. Mechanical properties of the ISJ directly affect sound transmission from the tympanic membrane to the cochlea. However, how ISJ properties change with frequency has not been investigated. In this paper, we report the dynamic properties of the human ISJ measured in eight samples using a dynamic mechanical analyzer (DMA) for frequencies from 1 to 80 Hz at three temperatures of 5, 25 and 37 °C. The frequency–temperature superposition (FTS) principle was used to extrapolate the results to 8 kHz. The complex modulus of ISJ was measured with a mean storage modulus of 1.14 MPa at 1 Hz that increased to 3.01 MPa at 8 kHz, and a loss modulus that increased from 0.07 to 0.47 MPa. A 3-dimensional finite element (FE) model consisting of the articular cartilage, joint capsule and synovial fluid was then constructed to derive mechanical properties of ISJ components by matching the model results to experimental data. Modeling results showed that mechanical properties of the joint capsule and synovial fluid affected the dynamic behavior of the joint. This study contributes to a better understanding of the structure–function relationship of the ISJ for sound transmission.

1. Introduction

The incudostapedial joint (ISJ) is a synovial joint connecting the incus and stapes in the middle ear. ISJ consists of the articular cartilage, meniscus, capsule, and synovial fluid [1–3]. The function of the ISJ is to transmit mechanical vibration of the tympanic membrane (TM) to the stapes and cochlea, and provide flexibility to the middle ear ossicular chain [4]. The sound transmission function of the middle ear is closely related to the mechanical properties of the ISJ [4,5]. Abnormalities of the joint have been shown to impose severe conductive hearing loss, which usually requires surgical reconstruction of the ossicular chain to restore the hearing [6–10]. Recent experimental studies suggested that the increased ISJ stiffness (ankyloses) reduced the mobility of the TM and stapes footplate at 0.5–1 kHz [11], while the reduced ISJ stiffness (separation) was related to the stapes mobility loss at high frequencies [12]. These experiments, however, were not specific enough to characterize the relationship between the ISJ stiffness and middle ear transfer function without providing the material properties of the joint quantitatively.

In addition to experimental studies, the lack of knowledge on dynamic properties of the ISJ affects the accuracy of finite element (FE) modeling of the human middle ear. The ISJ has been modeled as an isotropic elastic solid body [1,13–16], an isotropic viscoelastic solid body [17,18], and a synovial joint with viscoelastic capsule [4] in published FE models of the human middle ear. The material properties of the ISJ used in these models were determined through the cross-calibration process and had significant variation across the models [4,5,16].

Experimentally measured data on the mechanical properties of the ISJ is very limited. Zhang and Gan [19] conducted quasi-static uniaxial loading tests on human ISJ samples and this is the only published biomechanical measurement based on our knowledge. Their results demonstrated that the ISJ shows viscoelastic behavior with nonlinear stress–strain relationship under quasi-static loading. They used a FE model of ISJ to show that the behavior of the joint was closely related to the mechanical properties of the joint capsule, cartilage and synovial fluid. However, the human auditory frequency ranges from 20 Hz to 20 kHz which is the normal working frequency range of the ISJ. Thus, the dynamic properties of ISJ over the frequency range may provide a better understanding of the joint's transmission function and should be modeled more accurately to describe the joint behavior.

In this paper, we report the dynamic properties of human ISJ using a dynamic mechanical analyzer (DMA) with frequency–temperature superposition (FTS). DMA is a widely used system to measure dynamic properties of materials in the frequency domain.

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However, the frequency range of current DMA has limited high frequency access and a method to expand the testing frequency to high frequency, the FTS principle, has been reported [20,21]. The FTS principle is an empirical method which relates the effect of temperature change on dynamic properties of some materials (e.g. polymers) to that of frequency change [22,23]. In the past two decades, researchers have applied FTS principle in dynamic tests of biological tissues such as the bovine brain and vocal-fold [24–26]. Recently, our lab has reported the mechanical properties of the human TM and stapedial annular ligament (SAL) and the chinchilla SAL measured using DMA with FTS to extend measured complex modulus data of tissues to higher frequencies [27–29].

In the present study, the DMA with FTS was used for measuring dynamic properties of the human ISJ. ISJ samples were measured in the frequency range of 1–80 Hz at three different temperatures (5, 25 and 37 °C). The average complex modulus of the joints was obtained directly from the experiments. A 3D FE model of the ISJ consisting of the articular cartilage, joint capsule and synovial fluid was then constructed to identify the mechanical properties of ISJ components by matching the modeling results to the experimental data. The model was used to investigate the effect of the mechanical properties of the ISJ (the capsule and synovial fluid) on the dynamic behavior of the joint.

2. Methods

2.1. Specimen preparation and experimental setup

Eight (four left and four right) fresh human temporal bones (TBs) with an average donor's age of 69 years were involved in this study. All TBs were provided by Life Legacy Foundation, a certified human tissue supply source for medical and military research. The experiments were conducted within one week after the TB samples were received. The TB samples were covered by wet paper soaked in a prepared solution made of 0.9% saline and 15% povidone at 5 °C to maintain the physiological condition before the experiment. Each TB was examined using a light microscope to ensure that the middle ear appeared normal. The middle ear ossicles were then accessed by opening the tegmen tympani and removing the TM together with the malleus. The scala vestibule of the cochlea was opened and the stapes footplate was exposed through the medial side. The TB was then trimmed to a cube with a size of 1.5 cm × 1.5 cm × 1.5 cm to expose the ISJ with incus and stapes. A #11 scalpel was used to cut along the SAL to separate the footplate from the oval window. Note that special care was applied to keep the ISJ unstretched during the separation of the footplate from the bony wall. Finally, the stapedial tendon was removed to assure the ISJ was the only stress-bearing soft tissue in the test.

The schematic diagram of the experimental setup is shown in Fig. 1A. The ISJ specimen was fixed onto a sample holder using copper wire and melted paraffin. The load cell (5 lb, WMC-5-455 Bose, Eden Prairie, MN) of the DMA (ElectroForce 3200, Bose, Eden Prairie, MN) was placed between the sample holder and the *X*–*Y* translational stage. The translational stage was used for aligning the ISJ with the load cell in the *Z* axis under a surgical microscope (Zeiss, OPMI 1-FC), viewing from the front and lateral directions. The long process of the incus was fixed to the middle ear bony wall using cyanoacrylate gel glue. This type of glue had been validated by previous studies to provide stable fixation on the surface of biological tissues [19,27]. After the glue dried, a sharp-tip tweezer was used to assure the incus was completely immovable. The specimen was then raised up to a position where the stapes footplate was directly in contact with the lower end of the adapter. Cyanoacrylate gel glue was applied between the stapes footplate and the wooden adapter connected to the upper grip of the DMA (Fig. 1B). During this process, the ISJ stayed straight as shown in Fig. 1B indicating the structure was intact before the experiment. After the glue dried, a preload of 0.02 N compression was applied on the ISJ specimen before the experiment was started to assure all samples were tested under the same initial conditions. The preload was zeroed out before the start of the dynamic tests. The specimen was placed in a temperature-controlled chamber with a size of 25 cm × 25 cm × 10 cm (Fig. 1A). The fluctuation of the temperature inside the chamber during the test was controlled within ±1 °C by a system consisting of a thermal couple, a negative feedback circuit and a fan delivering hot or cold air.

For the dynamic measurements, sinusoidal displacements with an amplitude of 0.1 mm at the frequencies of 1, 2, 5, 10, 20, 40, 60 and 80 Hz were applied on the stapes footplate, and the force was measured by the load cell. Each measurement was performed at three temperatures: 5, 25 and 37 °C. The moisture of the specimen was maintained by adding 0.9% saline solution every five minutes onto the specimen using a syringe. At each frequency and temperature, results recorded in the first five seconds of the test were abandoned to serve as the preconditioning process. Therefore, each dynamic test itself included the preconditioning process with exactly the same testing conditions.

2.2. Dimensions and viscoelastic material model of ISJ specimen

The ISJ was separated after the completion of the dynamic test. The lenticular process of the incus and the head of the stapes were examined under a microscope. Images of the lenticular process of the incus were captured by a digital camera through the microscope (Fig. 2). The stapes head was assumed to share the same geometry with the lenticular process of the incus based on the histological images provided by Zhang and Gan [19]. Under the assumption that the cross section of the ISJ was elliptical [19], the lengths of the long axis *a* and short axis *b* were measured by image analysis software (ImageJ). The measurement was based on calculation of the pixels with a scale calibrated by a standard 1 mm scale bar next to the specimen as shown in Fig. 2. The largest values of *a* and *b* in perpendicular directions were accepted and the cross-sectional area of the ISJ was calculated by $A = \pi ab/4$. Table 1 lists the geometry data from eight ISJ specimens with the mean and standard deviation. The length of the ISJ could not be measured by direct observation. Therefore, we used the value of 0.28 mm, which was the length of the ISJ capsule measured from a histology section reported by Zhang and Gan [19].

Based on the dimensions of each specimen, the ISJ was initially assumed as an isotropic viscoelastic body to derive its complex modulus. Even though the quasi-static test of the ISJ reported the nonlinear behavior of the ISJ, the material model of the joint can still be considered as linear viscoelastic in this study because the deformation is small. Both the displacement *d* applied on the stapes footplate and the force *F* measured with the load cell were sinusoid signals for each frequency *f*, defined as

$$d = d_0 e^{i2\pi ft} \tag{1}$$

$$F = F_0 e^{i(2\pi ft+\delta)} \tag{2}$$

where d_0 and F_0 are the amplitude of the displacement and force, respectively, and δ is the phase delay between the displacement and force. The complex modulus at frequency *f* is calculated by

$$|E^*| = \frac{\sigma_0}{E_0} = \frac{F_0/A}{d_0/L} \tag{3}$$

$$E' = |E^*|\cos\delta \tag{4}$$

$$E'' = |E^*|\sin\delta \tag{5}$$

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