World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:12, No:2, 2018

Design and Modeling of Human Middle Ear for Harmonic Response Analysis

Shende Suraj Balu, A. B. Deoghare, K. M. Pandey

Abstract**—**The human middle ear (ME) is a delicate and vital organ. It has a complex structure that performs various functions such as receiving sound pressure and producing vibrations of eardrum and propagating it to inner ear. It consists of Tympanic Membrane (TM), three auditory ossicles, various ligament structures and muscles. Incidents such as traumata, infections, ossification of ossicular structures and other pathologies may damage the ME organs. The conditions can be surgically treated by employing prosthesis. However, the suitability of the prosthesis needs to be examined in advance prior to the surgery. Few decades ago, this issue was addressed and analyzed by developing an equivalent representation either in the form of spring mass system, electrical system using R-L-C circuit or developing an approximated CAD model. But, nowadays a three-dimensional ME model can be constructed using micro X-Ray Computed Tomography (µCT) scan data. Moreover, the concern about patient specific integrity pertaining to the disease can be examined well in advance. The current research work emphasizes to develop the ME model from the stacks of µCT images which are used as input file to MIMICS Research 19.0 (Materialise Interactive Medical Image Control System) software. A stack of CT images is converted into geometrical surface model to build accurate morphology of ME. The work is further extended to understand the dynamic behaviour of Harmonic response of the stapes footplate and umbo for different sound pressure levels applied at lateral side of eardrum using finite element approach. The pathological condition Cholesteatoma of ME is investigated to obtain peak to peak displacement of stapes footplate and umbo. Apart from this condition, other pathologies, mainly, changes in the stiffness of stapedial ligament, TM thickness and ossicular chain separation and fixation are also explored. The developed model of ME for pathologies is validated by comparing the results available in the literatures and also with the results of a normal ME to calculate the percentage loss in hearing capability.

Keywords**—**Computed tomography, human middle ear, harmonic response, pathologies, tympanic membrane.

I. Introduction

THE human ME is a delicate and vital organ that performs various functions such as receiving sound pressure and producing vibrations of eardrum and propagating it to inner ear [1]. It consists of TM, three auditory ossicles named as malleus, incus and stapes. These elements are connected with ligaments and muscle tendons such as superior mallear ligament (SML), stapedial annular ligament (SAL), Tympanic annular ligament (TAL), lateral mallear ligament (LML), anterior mallear ligament (AML), superior incudal ligament (SIL), posterior incudal ligament (PIL), tensor tympani tendon (TTT) and posterior stapedial tendon (PST). Joints present in the ME are incudomalleolar joint (IMJ) and incudostapedial joint (ISJ) as shown in Fig. 1. Malleus is attached to TM by manubrium fold (MF) [2]. The malleus transfers the vibrations to the subsequent bones in the ossicular chain. The smallest bone in the ear is stapes and it is the last component in the ossicular chain. The stapes is connected to oval window of cochlea by SAL and is set in motion by incus.

Incidents such as traumata, infections, ossification of ossicular structures and other pathologies may damage the ME organs [3]. Cholesteatoma is a destructive infectious condition consisting growth of keratinizing squamous epithelium in ME or mastoid process. This can cause destruction of ME bones (ossicles), mainly incus, and further cause hearing loss. The conditions can be surgically treated by employing tympanoplasty. Tympanoplasty is a surgical operation performed to reconstruct the TM or the small bones of the ME [4]. In order to replace the damaged incus with artificial columella, tympanoplasty is performed. However, the suitability of the tympanoplasty needs to be examined in advance prior to the surgery. In this study, analysis is done on developed model for the dynamic response of stapes footplate and umbo by replacing the damaged incus with artificial columella. The model is analyzed to identify and determine the effects of sound vibrations on all ME elements. It is very difficult to perform in-vivo experimentations on ME as it is very small, delicate and vital organ. Thus, numerical simulation technique is adopted to determine the vibration effects by using the Finite element (FE) method [5]. It is performed by developing the intricate geometry of ME and assigning the properties and boundary conditions to the elements of ME to determine the frequency response. The material selected for artificial columella is silicon and titanium as these are highly biocompatible and corrosion resistant [6].

Ossicular chain separation or dislocation is a pathological condition occurring due to fracture of temporal bone or traumatic TM perforations. The separation of the joint connecting the incus and stapes (ISJ) is the most common ossicular chain separation due to temporal bone trauma [5]. As the sound cannot be transmitted properly, it leads to conductive hearing loss. This condition can also be treated by tympanoplasty which requires replacing the damaged ossicle with prosthetic artificial ossicle. The condition is analyzed by reducing the properties of the ISJ to show the ossicular chain separation. The current modulus of elasticity assigned to the healthy ISJ is divided by 10, 100 and 1000 respectively to

Shende Suraj Balu (Research Scholar) is with the Department of Mechanical Engineering, National Institute of Technology Silchar, Assam, India (phone: +919209204151, e-mail: sssuraj0801@gmail.com).

A. B. Deoghare (Assistant Professor) and K. M. Pandey (Professor & Head) are with the Department of Mechanical Engineering, National Institute of Technology Silchar, Assam, India (e-mail: ashishdeoghare@gmail.com, kmpandey@mech.nits.ac.in).

examine the effects of the reduced stiffness due to trauma or infections. Thus, the results are plotted in the form of stapes footplate and umbo displacements to determine the percentage hearing losses. Therefore, the present study finds possible application in the treatment of ME tympanoplasty.

II. Materials and Methods

The human ME models in the form of high resolution 3-dimensional morphology are published and made available for non-commercial research purpose [2]. These are in the form of surface meshes which are used to obtain the idea of anatomical details. The SML and SIL are not made available in these resources. So, these ligaments are modeled and combined with other ME components with the use of 3-matic research software extension of MIMICS Research 19.0, as shown in Fig. 1. Parse tensa (PT) and Parse flacida (PF) are also combined in the current model in similar manner. These surface meshes need to be converted in volume meshes for the analysis of harmonic response. For this purpose, the ME components (.stl files) are meshed individually (.cdb files) using MIMICS Research 19.0. These meshed files are then assembled in ANSYS WORKBENCH 15.0 using Finite Element Modeler. The model consists of 17 solid components with 21 contacts. The bonded contacts are used to represent the connections in between the components. The material properties of the elements of ME used for analysis are depicted in Table I. Rayleigh damping coefficient, α and β, and Poisson's ratio are assumed to be 0 s^{-1}, 0.0001 s, and 0.3, respectively [5]. Edges of the PF are constrained in all degrees of freedom. The contacts between incus-stapes (ISJ) and malleus-incus (incudomalleolar joint) are represented by bonded contacts. Tympanic annular ring (TAR) is firmly connected to the PT. TAR is a structural ring clamped to bony ear canal at its periphery. The ligaments and tendons such as SML, PIL, SIL, LML, TTT, PST and AML act as connecting elements to the ossicular chain. The free ends of these ligaments and muscle tendons are fixed to tympanic cavity wall. The sound pressure is applied uniformly on the lateral side of TM. The load p to be applied on the lateral side of TM is calculated by (1),

$$spl = 10log\left(\frac{p}{p_{ref}}\right)^2 \tag{1}$$

where, spl - sound pressure level, p_{ref}-(20×10^{-6} Pa) reference sound pressure corresponding to audibility threshold [3].

Fig. 1 Components of ME

In the present study, the properties of the incus are replaced with the properties of silicon and titanium as an artificial columella, and also, the properties of ISJ are changed. The geometry of the incus and ISJ for which the properties are changed is shown in Fig. 2. The boundary conditions are applied to the model as discussed earlier. To validate the model, the frequency response is calculated at stapes footplate and umbo for the frequency range of 0 Hz to 10000 Hz at 100 dB (2 Pa). Percentage restoration of hearing capacity is calculated by comparing the amplitude of stapes footplate and umbo of tympanoplasty model with the healthy ME. The percentage restoration is calculated by (2):

$$Percentage\ restoration = \frac{amplitude\ of\ tympanoplasty\ ME}{amplitude\ of\ healthy\ ME} x100 \tag{2}$$

TABLE I
MATERIAL PROPERTIES OF ME COMPONENTS [5], [7], [8]

ME component	Young's Modulus (N/m^2)	Density (kg/m^3)
AML	$2.1x10^6$	$1.2x10^3$
Incudo-malleolar joint	$1.4x10^{10}$	$3.2x10^3$
Incudo-stapedial joint	$6x10^5$	$1.2x10^3$
Incus	$1.4x10^{10}$	Body: $2.36x10^3$ Short process: $2.26x10^3$ Long process: $5.08x10^3$ Average: $3.23x10^3$
LML	$6.7x10^4$	$1.0 x10^3$
Malleus	$1.4x10^{10}$	Head: $2.55x10^3$ Neck: $3.7x10^3$ Handle: $4.53x10^3$ Average: $3.59x10^3$
Manubrium fold	$4.7x10^9$	$1.0x10^3$
TM		
Pars flacida	$1.1x10^7$	$1.2x10^3$
Pars tensa	$3.2x10^7$	$1.2x10^3$
PST	$5.2x10^5$	$1.0x10^3$
PIL	$6.5x10^5$	$1.0x10^3$
SAL	$4.9x10^5$	$1.2x10^3$
Stapes	$1.41x10^{10}$	$2.2x10^3$
SIL	$4.9x10^6$	$1.0x10^3$
SML	$4.9x10^4$	$1.0x10^3$
TTT	$7x10^7$	$1.0x10^3$
TAL	$6x10^5$	$1.0x10^3$
Columella titanium	$1.05x10^{11}$	$4.51x10^3$
Columella silicon	$1.124x10^{11}$	$2.33x10^3$

The relative percentage loss in hearing capability after changing the Young's modulus of ISJ for the condition of ossicular chain separation is calculated by using (3) given below.

$$Relative\ percentage\ loss = \frac{amplitude\ of\ normal\ ISJ - amplitude\ of\ changed\ ISJ}{amplitude\ of\ normal\ ISJ} \times 100 \quad (3)$$

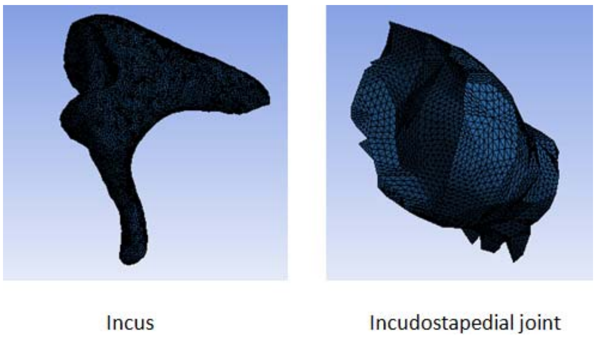

Fig. 2 Geometry of incus and ISJ

III. RESULTS AND DISCUSSION

The results obtained from the analysis are plotted in the form of graph as shown in figures below. The results derived at stapes footplate and umbo show similar trend of displacement and phase angle as observed in experimentation conducted by Gan et al. [9]. The results show close resemblance with each other which reveals that the model presented in this study is well applicable to analyze the behavior of ME. As the obtained values of the displacement of stapes footplate and umbo are very small (micro to nano range), the graphs are plotted using the logarithmic scale in order to observe the accurate behavior and trend of the displacement. This validated model is used to address the issues of cholesteatoma and ossicular chain separation that are clinically treated using tympanoplasty. The model enables modification in material properties of ME elements as per the required pathological condition.

A. Condition of Cholesteatoma

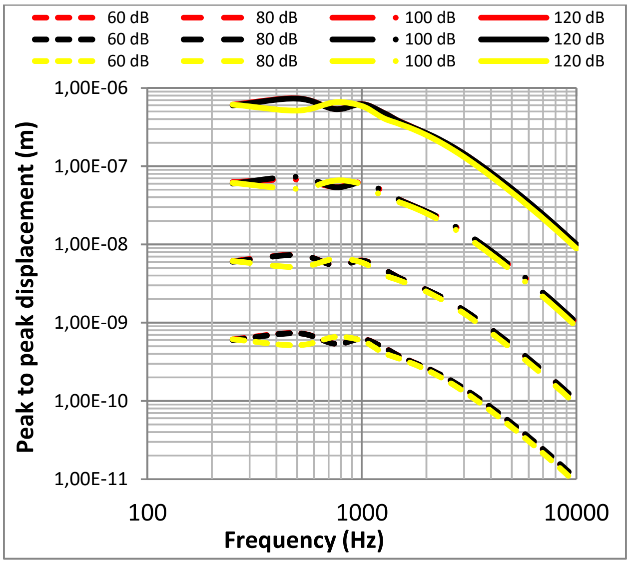

Fig. 3 Peak to peak displacement of stapes footplate, Healthy ME, Silicon, Titanium

Fig. 3 shows the peak-to-peak displacement of stapes footplate. For a healthy ME, the resonance occurs at around 1 kHz. In the obtained results, this value occurs in the range of 0.8 to 0.9 kHz. As the frequency is increased over 2 kHz, a gradual decrease in the displacement is found. The peak of resonance is approximately at 0.7 kHz as observed by Gan et al. [10]. From Fig. 3, the displacements of the stapes footplate using the proposed materials are in close proximity with both the healthy ME and results observed by Gan et al. [9]. The average displacement of the stapes footplate for a healthy ME at sound pressure level of 100 dB is 3.07 nm. The displacements of stapes footplate from the obtained results for artificial columella are 2.87 nm and 2.79 nm for silicon and titanium, respectively. The percentage restoration of hearing capacity in terms of amplitude of displacement is 93.48 % and 90.87% for silicon and titanium, respectively.

Fig. 4 shows the phase angle of stapes footplate for a healthy as well as modified ME models derived using silicon and titanium. The results of the derived model show similar trend in correspondence to the healthy ME as well as those observed by Gan et al. [9].

Fig. 5 shows the peak-to-peak displacement of umbo having similar trend as observed by Gan et al. [10]. The average displacement of umbo for a healthy ME at sound pressure level of 100 dB is 7.88 nm. The average displacement of umbo from obtained results for artificial columella is 7.25

nm and 7.21 nm for silicon and titanium respectively. The percentage restoration of hearing capacity in terms of amplitude of displacement is 92.00% and 91.49% for silicon and titanium respectively. From the above results, it becomes possible to determine the restoration effect using the derived tympanoplasty model.

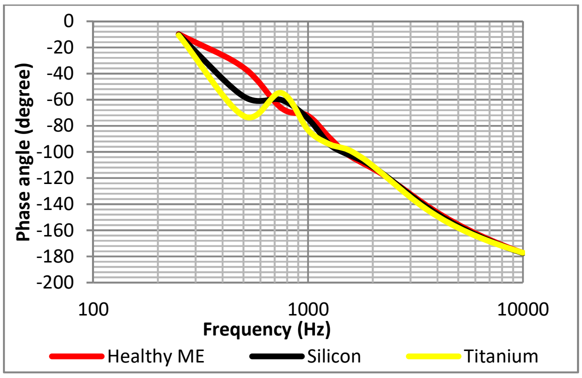

Fig. 4 Phase angle of stapes

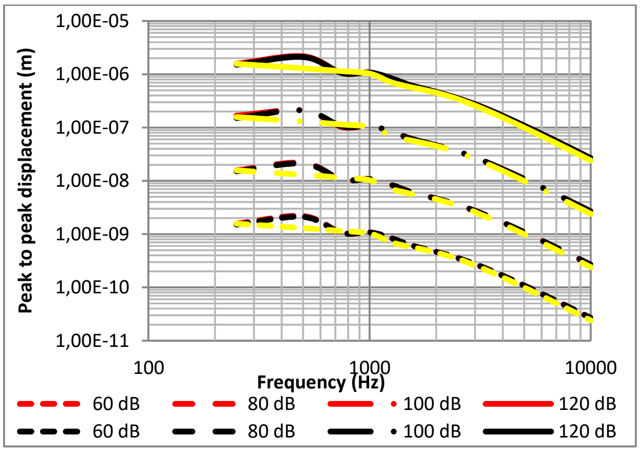

Fig. 5 Peak to peak displacement of umbo ■ Healthy ME, ■ Silicon, ■ Titanium

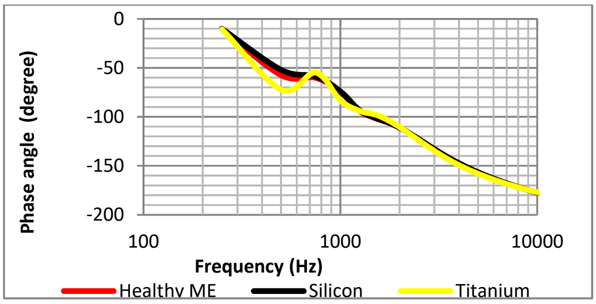

Fig. 6 Phase angle of umbo

Fig. 6 shows the phase angle of stapes footplate for a healthy as well as modified ME models derived using silicon and titanium. The derived model shows similar trend in correspondence to the healthy ME as well as the results observed by Gan et al. [9].

B. Condition of Ossicular Chain Separation

The cases of ossicular chain separation are identified on the basis of conductive hearing impairment due to trauma and other symptoms. The model is analyzed for incudostapedial separation by dividing the Young's modulus of ISJ by 10, 100 and 1000, respectively [5]. The obtained results show that the ME harmonic response is highly influenced by decrease in Young's modulus of ISJ at both lower as well as higher frequency. Effect of the changes in Young's modulus of ISJ on the displacement of stapes footplate and umbo is calculated and plotted in the graphs.

Fig. 7 shows the peak to peak displacement of stapes footplate. The graph shows that the decrease in Young's modulus of ISJ significantly reduces the mobility of stapes footplate. The relative hearing loss calculated in percentage is 58.96%, 76.52% and 99.13% for the 10th, 100th and 1000th fraction of Young's modulus of healthy ISJ, respectively. Decrease in Young's modulus also reduces the amplitude of displacement which leads to decrease in hearing loss.

Fig. 8 shows the peak to peak displacement of umbo. From the graph it can be said that not much variation is seen in the results. As the ISJ is situated after the umbo, it has less effect on the vibration of umbo, and very less variation is seen due to change in Young's modulus of ISJ. The relative hearing loss calculated is 12.87%, 17.16% and 24.20% for the 10th, 100th and 1000th fraction of Young's modulus of healthy ISJ, respectively.

IV. Conclusion

The developed model is based on a consideration that incus is replaced by an artificial columella made of silicon and titanium and the Young's model of ISJ is taken in 10th, 100th and 1000th fraction of healthy subject, respectively. The model is proposed to estimate the restoration effect of hearing capability by comparison of umbo & stapes footplate displacements in case of cholesteatoma condition and to estimate the hearing loss in case of ossicular chain separation condition. Thus, the results are appropriate and may be referred for clinical practice. Further, it can be stated that the proposed model enables to diagnose the effect of material properties for investigating the cholesteatoma and ossicular chain separation condition and endorsing the restoration of hearing ability. An approach of this kind can be useful in developing a new treatment for recovery of conductive hearing losses.

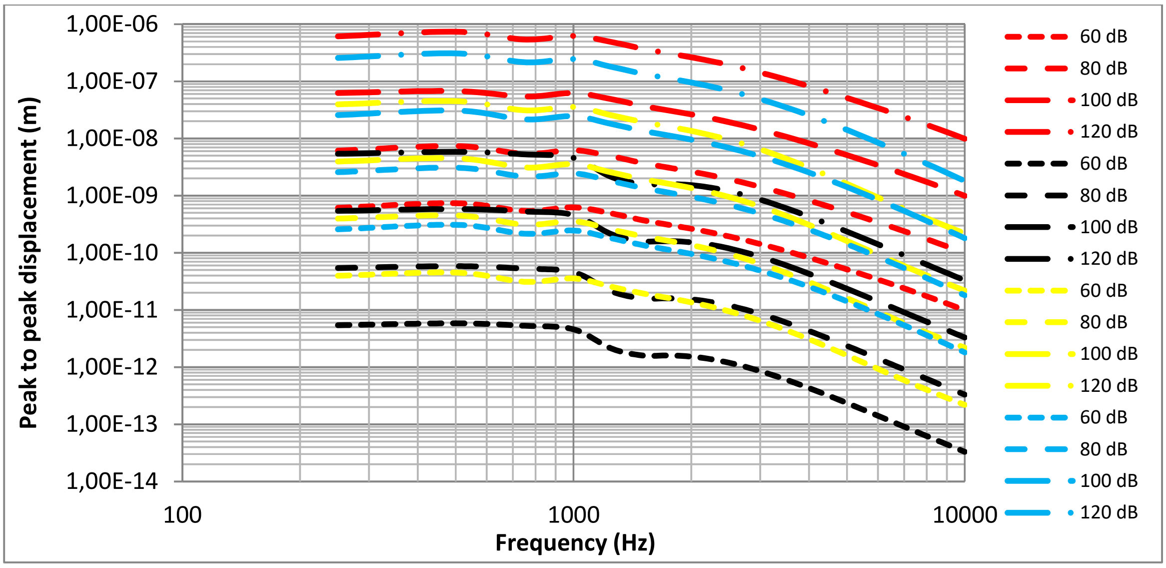

Fig. 7 Peak to peak displacement of stapes, Normal ISJ, ISJ by 10, ISJ by 100, ISJ by 1000

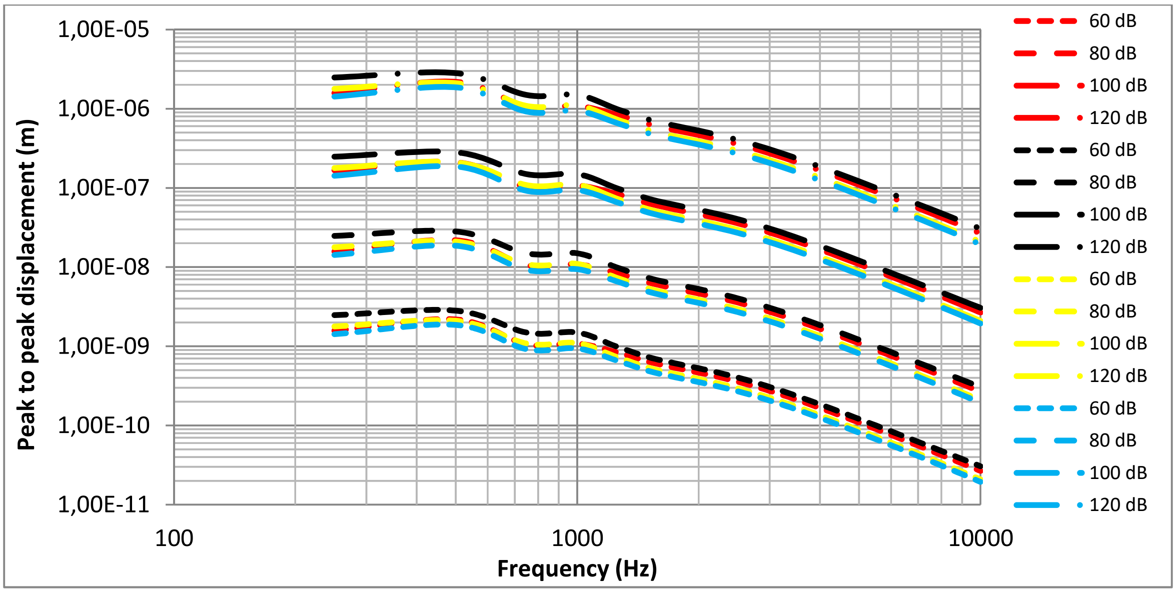

Fig. 8 Peak to peak displacement of umbo Normal ISJ, ISJ by 10, ISJ by 100, ISJ by 1000

ACKNOWLEDGMENT

The author would like to thank Mr. Dhiraj S. Bombarde for sharing his views in current study and for his kind help and support.

REFERENCES

[1] P. W. Alberti, *Occup. Expo. to Noise Eval. Prev. Control*, 53–62 (2001).
[2] D. De Greef, J. A. N. Buytaert, J. R. M. Aerts, L. Van Hoorebeke, M. Dierick, and J. Dirckx, *J. Morphol.*, 276, 1025–1046 (2015).
[3] T. Higashimachi, T. Maeda, T. Oshikata, and R. Toriya, *3rd Int. Conf. Des. Eng. Sci.*, 117–122 (2014).
[4] S. N. Merchant, M. J. McKenna, and J. J. Rosowski, *Eur. Arch. Otorhinolaryngol.*, 255, 221–8 (1998).
[5] F. Zhao, T. Koike, J. Wang, H. Sienz, and R. Meredith, *Med. Eng. Phys.*, 31, 907–916 (2009).
[6] S. Z. Khalajabadi, N. Ahmad, A. Yahya, M.A.M. Yajid, A. Samavati, S. Asadi, A. Arafat, and M.R. Abdul Kadir, *Ceram. Int.*, 42, 18223–18237 (2016).
[7] Q. Sun, R. Z. Gan, K.-H. Chang, and K. J. Dormer, *Biomech. Model. Mechanobiol.*, 1, 109–122 (2002).
[8] S. Naderi, A. Dabbagh, M. A. Hassan, B. A. Razak, H. Abdullah, and N. H. Abu Kasim, *Ceram. Int.*, 42, 7543–7550 (2016).
[9] R. Z. Gan, M. W. Wood, and K. J. Dormer, *Otol. Neurotol.*, 25, 423–435 (2004).
[10] R. Z. Gan and M.W. Wood, 478–485 (2001).