Acta of Bioengineering and Biomechanics
Vol. 17, No. 4, 2015

Original paper
DOI: 10.5277/ABB-00289-2015-03

Numerical study of Hough technique in surgery of otosclerosis, using the finite element method

FERNANDA GENTIL[1, 2]*, MARCO PARENTE[1], PEDRO MARTINS[1], CARLA SANTOS[1],
EURICO ALMEIDA[2], ANTÓNIO FERREIRA[1], RENATO NATAL[1]

[1] FEUP – INEGI, Porto, Portugal.
[2] Clínica ORL – Dr. Eurico de Almeida, Portugal.

Purpose: Otosclerosis is a metabolic bone disease of the otic capsule that can cause the stapes fixation, resulting in conductive hearing loss or, in a profound sensorineural deafness threshold. Surgery is one of the possible treatments for the otosclerosis. To repair small focus of otosclerosis in the anterior crus of the stapes, in 1960, Hough suggested the implementation of a technique in which part of the anterior crus is fractured and the stapes turned. As a result, the posterior crus of the stapes is the only connection with the inner ear. In this work, the outcome of Hough's surgical technique was simulated. Methods: Based on computerized images, a finite element model of middle ear ossicles and tympanic membrane was created, as well as a model where the stapes has changed. The discretization of the tridimensional solid model was made using the ABAQUS software. The mechanical properties used were taken from the literature and adequate boundary conditions were applied. Results: The results obtained with the Hough technique simulation were compared with a representative model of the normal ear, taking into account the displacements obtained on the central part of the stapes footplate and the maximum principal stress in the stapes crus. Conclusions: The results obtained are closer to the normal ear model, therefore Hough technique stands out as a good option to correct small focus of otosclerosis.

Key words: *finite element method, otosclerosis, stapedectomy, stapedotomy, stapes*

1. Introduction

The ears are sensory organs of the auditory system, involved in the detection of sound. Three ossicles (malleus, incus, and stapes) are attached in a chain to the tympanic membrane and transform sound waves into mechanical vibrations that pass to the inner ear, where they are converted into electrical impulses which the auditory nerve sends to the brain. The stapes, the smallest bone in the human body, is the third component in the tympano-ossicular chain of the middle ear.

Otosclerosis is a disease that can cause stapes fixation, resulting in different kinds of hearing loss. It is a disorder that involves the growth of abnormal bone around stapes footplate. The most common clinical presentation of otosclerosis is a patient with 15–45 years (more in women) with progressive deafness, bilateral (80%), and tinnitus (75%) [19]. The tonal and vocal audiometry, tympanometry, and acoustic reflexes, are the most used diagnostic tests. Hearing aids are an acceptable option for patients with otosclerosis. However, surgery is the more effective solution.

When the surgical procedure, stapedectomy, with interposition of a stapes prosthesis was introduced by Shea (1956) [21], a new period in the surgical treatment of otosclerosis started [9], [22]. Since then, a great effort has been made to improve the properties of biomaterials used in surgery, as well as the surgical technique itself. Stapedectomy, involving the complete removal of the stapes, has been the initial surgical technique, but nowadays it has been largely replaced by stapedotomy [23]. The stapedotomy is thought by many otologic surgeons to be safer and reduce the chances of post-operative complications. Decision to perform total or partial stapedectomy ver-

---

* Corresponding author: Fernanda Gentil, FEUP – INEGI, R. Dr. Roberto Frias Nº 404, 4200-465 Porto, Portugal. Tel: +351914763107, e-mail: fernanda.fgnanda@gmail.com

Received: January 19th, 2015
Accepted for publication: March 10th, 2015

sus stapedotomy depends on the extent of stapes fixation and other characteristics of the stapes footplate, and on the surgeon preference [11]. The most common area of stapedial fixation in otosclerosis is the anterior crus of stapes. To correct small focus of otosclerosis, Hough, in 1960, suggested the implementation of a technique in which part of the stapes anterior crus is breached and the posterior one is rotated, getting only the connection between the stapes footplate and the inner ear made through the posterior crus [8], [12]. The anterior crus of the stapes is cut using a microdrill. The anterior part of the stapes footplate, with the otosclerotic focus, is lifted out of the oval window using a 45° microhook, and is removed. The posterior part is transposed towards the middle of the oval window, using a hook, pushing the posterior crus of the stapes in an anterior direction. The oval window is covered with a gelfoam plate [18]. This procedure allows for removal of the pathologic portion of the stapes footplate and normal reconstruction of mucous membrane and endosteum at the oval window [13]. The technique can be developed without cutting the stapedius tendon. This has a potential advantage in patients who work around loud noises. In this procedure, the stapes footplate, the incudoestapedial joint and the stapes posterior crus are preserved. The posterior crus is placed on a graft of perichondrium, which covers the oval window, thus allowing the passage of sound. However, it is crucial to know the level of stress that the posterior crus is subjected and also if it has sufficient strength to support that level of efforts. In this work, the simulation of Hough's surgical technique was carried out and the results compared with the ones achieved using a model representative of the normal ear, taking into account the displacements that occur in the central part of the stapes footplate and the maximum principal stress in the stapes crus.

2. Material and methods

The first step of this work was the creation of the tympano-ossicular chain of the middle ear, tympanic membrane and ossicles (malleus, incus and stapes) including ligaments and muscles based on computerized tomography images. A finite element model was created [5] by using the ABAQUS software [10]. The ossicles are modelled by tetrahedral elements (C3D4), assumed to have isotropic behaviour, and with elastic properties obtained from literature [20]. The tympanic membrane is modelled by hexahedral (C3D8) elements and it was divided into *pars flaccida*, on its upper and *pars tensa* (membrane itself). Three layers of elements were created with different characteristics, simulating the behaviour of tympanic membrane. The *pars flaccida* was considered isotropic, with only one layer. Internal and external layers of *pars tensa* were considered isotropic and the fibrous intermediate layer was considered orthotropic with the tangential and radial Young's modulus as described in the literature [2], [6], [7].

The ligaments and muscles were modelled using linear elements of type T3D2. The hyperelastic nonlinear behaviour for the ligaments was modelled using Yeoh material model [6], [3], [17], [24]. Hill model was used for the muscles [7], [16]. Fluid elements, of type F3D3, were used to simulate the cochlear fluid. The incudomaleolar joint (connection between the

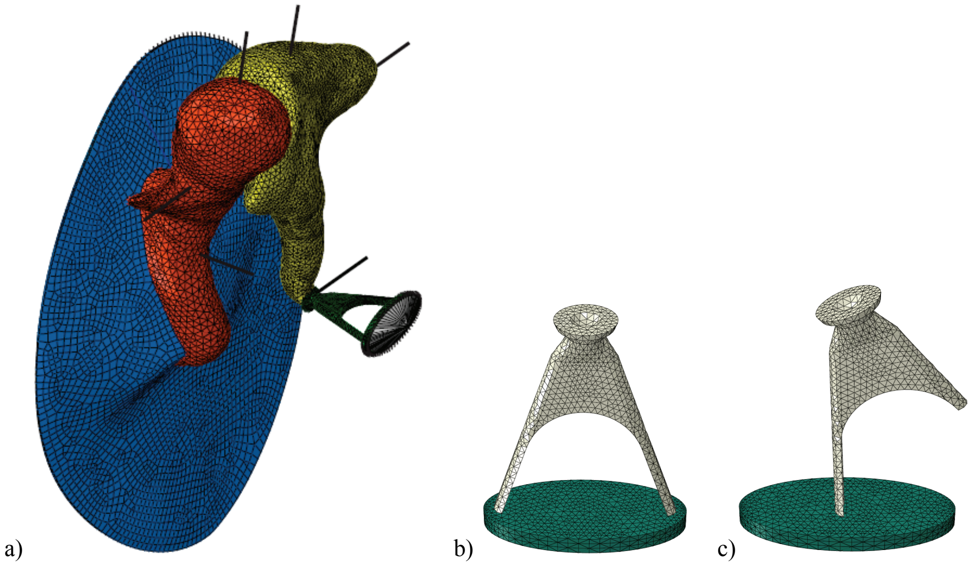

Fig. 1. Normal model (a); normal stapes (b); transformed stapes with Hough technique (c)

malleus and the incus) and incudostapedial joint (connection between the stapes and the incus) were simulated using contact formulation. The basic Coulomb friction model available in ABAQUS software [10] was used, with friction coefficient equal to 0.7 [4].

Boundary conditions include tympanic sulcus, ligaments (the superior, lateral and anterior ligaments of the malleus; posterior and superior ligaments of the incus and the stapes annular ligament) and muscles (the tensor tympanic muscle of the malleus and the stapedius muscle of the stapes) [6].

Based on Hough technique, the existing stapes was modified, and a new model was created (Fig. 1). The stapes footplate was kept unmodified and a "Abaqus *tie" boundary condition was applied between the base of the crus and the footplate.

3. Results

A dynamic study was made for a frequency range between 100 Hz and 10 kHz (human audible frequency range). A sound pressure level of 80 and 105 dB SPL (0.2 Pa and 3.557 Pa, respectively) was applied at the tympanic membrane. In Fig. 2, the stapes footplate displacements are shown, when the sound pressure level of 80 dB SPL is applied at the tympanic membrane.

The graphic shows the results for the model representative of the normal ear and for the model simulating Hough technique, no highlighting significative differences.

The experimental results obtained by Lee [15] and computational results of Prendergast [20] are shown in the same figure and we can see that are closed of other results.

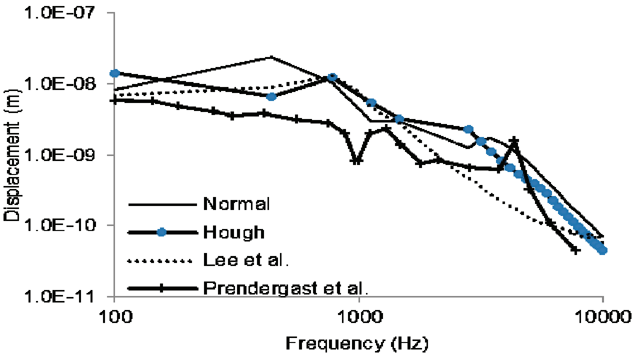

Fig. 2. Stapes footplate displacements for 80 dB SPL applied at the eardrum

For a sound pressure level of 105 dB SPL, the results for the normal ear were compared with the experimental study of Kurokawa [14] (Fig. 3). The simulation results of the stapes footplate displacements are in accordance with the results obtained by the other author, for both sound pressure levels, with the Hough technique providing the closest results to the normal model.

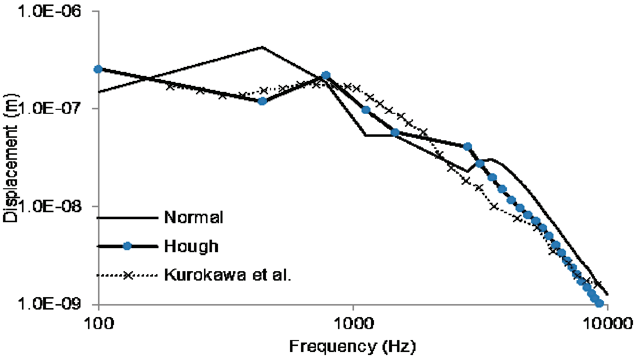

Fig. 3. Stapes footplate displacements for 105 dB SPL applied at the eardrum

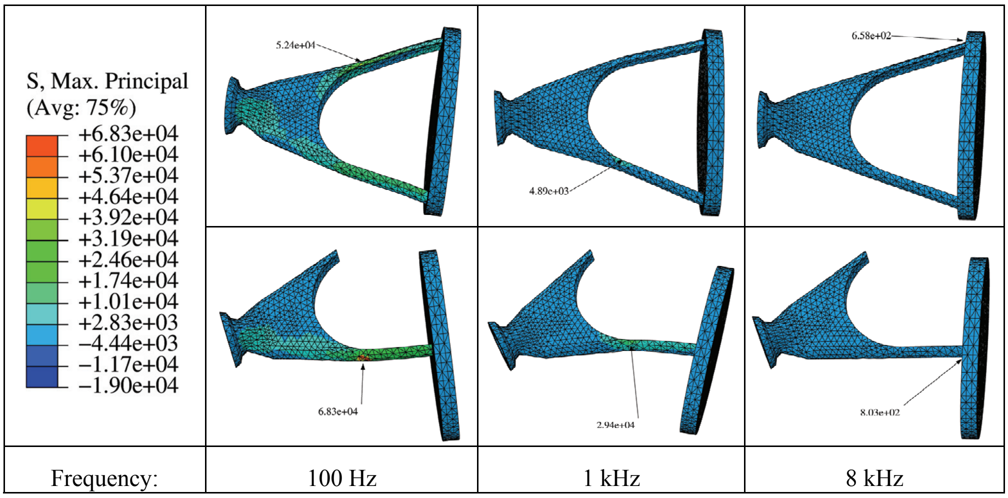

Fig. 4. Maximum principal stress (in Pa) in the stapes crus, for 100 Hz, 1 kHz and 8 kHz

In order to better understand the stress distribution in the stapes crus, between the two models, an analysis of the maximum principal stress was made, (Fig. 4), applying a pressure of 80 dB SPL at the eardrum and getting results for 100 Hz (low frequency), 1 kHz (middle frequency) and 8 kHz (high frequency). The greater stress was found for low frequencies and is created in the beginning of the crus near the stapes body; in the normal model this stress is distributed between two crus (5.24E+04 Pa) and in the model with only one crus this stress is greater (6.83E+04 Pa), although of the same order of magnitude. For middle frequencies the maximum principal stress appears in the posterior crus of the stapes, near its body; in the normal stapes 4.89E+03 Pa and the other 2.94E+04 Pa. For higher frequencies the maximum principal stress occurs near the stapes footplate, in the anterior crus for the normal model and in the posterior crus for other model.

4. Discussion

Although otosclerosis is considered one of the best known and manageable causes of hearing loss, there is a need for further scientific research that can provide surgical improvements. Decision to perform stapedectomy versus stapedotomy depends on the extent of stapes fixation and other characteristics of the footplate. Hough in 1960 suggested performing a partial anterior stapedectomy for small anterior foci of otosclerosis. He performed this technique by fracturing the middle of the footplate and anterior crus and extracting the anterior half of the stapes. He did this without cutting the stapedius tendon. This has a potential advantage in patients who work around loud noises [19].

Despite the efforts of introducing several other therapeutic options, the treatment of otosclerosis is, undoubtedly, surgical, being the stapedotomy the most accepted scientifically. The introduction of new methods that raise the opportunity of decreasing the duration and technical difficulties of surgery, allowing best audiological results and fewer postoperative complications constitute clinically significant contributions. In cases of small focus of otosclerosis, the outcome of the current work indicates that whenever the Hough technique can be applied, it is a good surgical option, since in addition to the audiological results being of good prognosis, this technique carries fewer post-surgical complications for the patient. This technique has given excellent long-term results in a large number of patients. In over 90% of the cases reported the air-bone gap has closed to within 10 decibels, and in 65% of the cases, the air-bone gap was over closed. Although some patients have been followed as long as seven years, there has been threshold regression of 10 decibels or more from the point of highest postoperative gain in only 1.5% of cases. Reported results recommend this technique as a step toward a more physiologic solution to the problem of stapedial ankyloses [13].

To point out the advantages obtained by this technique in relation to stapedectomy, only a limited part of the vestibule is exposed to possible trauma, and the risk of elevation of the endosteum of the vestibule during removal of the entire footplate is eliminated. The simplicity of using a portion of the native stapes itself, instead of a prosthesis, has both an aesthetic appeal and practical advantages. All the tissues needed for reconstruction are readily available in the same surgical field. Exposure of the stapes footplate is significantly enhanced while the long process of the incus is distracted laterally and there is no need to measure, manipulate, or crimp a prosthesis. These factors can simplify the stapedectomy operation, minimize the number of variables facing the surgeon, and perhaps even reduce the operating time and costs incurred [1].

With the numerical study presented in this work, one can observe that the movement of the stapes footplate obtained with the model representing a normal ear are similar to the one obtained with the model that simulates the Hough technique. In respect to the maximum principal stress, obtained in the stapes crus, it presents greater values for low frequencies and near the stapes body. For higher frequencies the maximum value is obtained near to the stapes footplate. Once that with the Hough technique, the stapedius tendon is not cut, it is expected that for the high frequencies, the stapes footplate stress decreases, protecting the inner ear from harmful sounds. Additionally, it may be concluded that the Hough technique can be a good option to treat small focus of otosclerosis.

Acknowledgements

We are gratefully indebted to the Ministério da Ciência, Tecnologia e Ensino Superior – Fundação para a Ciência e a Tecnologia in Portugal and FEDER for the funding provided under the research project "Estudo bio-computacional do zumbido", reference PTDC/SAU-BEB/104992/2008, and the project "Biomechanics: contributions to the healthcare", reference NORTE-07-0124-FEDER-000035 co-financed by Programa Operacional Regional do Norte (ON.2 – O Novo Norte), through the Fundo Europeu de Desenvolvimento Regional (FEDER), and research grant SFRH/BPD/1080/2010, and SFRH/BD/74731/2010.

References

[1] BAKER R.S., HOUGH J.V.D., *Stapedectomy with preservation of the posterior crus*, Operative Techniques in Otolaryngology – Head and Neck Surgery, 1998, Vol. 9(1), 8–12.

[2] GARBE C., GENTIL F., PARENTE M., MARTINS P., JORGE R.N., *Aplicação do método dos elementos finitos no estudo da membrana timpânica*, Audiologia em Revista, 2009, Vol. 3, 99–106.

[3] GENTIL F., JORGE R.M.N., FERREIRA A.J.M., PARENTE M.P.L., MARTINS P.A.L.S., ALMEIDA E., *Biomechanical simulation of middle ear using hyperelastic models*, J. Biomech., 2006, Vol. 39 (Suppl. 1), 388–389.

[4] GENTIL F., JORGE R.M.N., FERREIRA A.J.M., PARENTE M.P.L., MOREIRA M., ALMEIDA E., *Estudo do efeito do atrito no contacto entre os ossículos do ouvido médio*, Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería, 2007, Vol. 23(2), 177–187.

[5] GENTIL F., JORGE R.N., PARENTE M.P.L., MARTINS P.A.L.S., FERREIRA A.J.M., *Estudo biomecânico do ouvido médio*, Clínica e Investigação em Otorrinolaringologia, 2009, Vol. 3(1), 24–30.

[6] GENTIL F., PARENTE M., MARTINS P., GARBE C., JORGE R.N., FERREIRA A., TAVARES J., *The influence of mechanical behaviour of the middle ear ligaments: A finite element analysis*, J. Eng. Med., 2011, Vol. 225(1), 68–76.

[7] GENTIL F., PARENTE M., MARTINS P., GARBE C., PAÇO J., FERREIRA A., TAVARES J., JORGE R.N., *The influence of muscles activation on the dynamical behaviour of the tympano-ossicular system of the middle ear*, Comput. Methods Biomech. Biomed. Engin., 2013, Vol. 16, 392–402.

[8] GLASSCOCK M.E., STORPER I.S., HAYNES D.S., BOHRER P.S., *Twenty-Five Years of Experience with Stapedectomy*, Laryngoscope, 1995, Vol. 105, 899–904.

[9] HÄUSLER R., *General history of stapedectomy*, Adv. Otorhinolaryngol., 2007, Vol. 65, 1–5.

[10] HIBBIT D., KARLSSON B., SORENSON P., *ABAQUS Analysis User's Manual*, version 6.5. Hibbit, Karlsson & Sorenson Inc., USA, 2004.

[11] HOUGH J.V.D., DYER Jr. R.K., *Stapedectomy: causes of failure and revision surgery in otosclerosis*, Otolaryngol. Clin. North. Am., Medline, 1993, Vol. 26, 453–470.

[12] HOUGH J.V.D., *Partial Stapedectomy*, Ann. Otol. Rhinol. Laryngol., 1960, Vol. 69, 15–22.

[13] HOUGH J.V.D., *Partial Stapedectomy: A Physiological Approach to Stapedial Ankylosis*, JAMA, 1964, Vol. 187(10), 697–702.

[14] KUROKAWA H., GOODE R.L., *Sound pressure gain produced by the human middle ear*, Otolaryngology – Head and Neck Surgery, 1995, Vol. 113(4), 349–355.

[15] LEE C.F., CHEN P.R., LEE W.J., CHEN J.H., LIU T.C., *Computer aided three-dimensional reconstruction and modeling of middle ear biomechanics by high-resolution computed tomography and finite element analysis*, Biomedical Engineering-applications, Basis & Communications, 2006, Vol. 18(5), 214–221.

[16] MARTINS J.A.C., PIRES E.B., SALVADO R., DINIS P.B., *A numerical model of passive and active behavior of skeletal muscles*, Comput. Methods Appl. Mech. Eng., 1998, Vol. 151, 419–433.

[17] MARTINS P.A.L.S., JORGE R.M.N., FERREIRA A.J.M., *A Comparative Study of Several Material Models for Prediction of Hyperelastic Properties: Application to Silicone-Rubber and Soft Tissues*, Strain, 2006, Vol. 42, 135–147.

[18] MIRKO T., *Surgical Solutions for conductive Hearing Loss*, Vol. 4 of the Manual of Middle Ear Surgery, Cap. 7 – Otosclerosis, Thieme, 2000, 88–92.

[19] MULLER C., *Otosclerosis, Grand Rounds Presentation*, UTMB, Dept. of Otolaryngology, Francis B. Quinn, Jr. and Matthew W. Ryan (eds.), 2003.

[20] PRENDERGAST P.J., FERRIS P., RICE H.J., BLAYNEY A.W., *Vibro-acoustic modelling of the outer and middle ear using the finite element method*, Audiol. Neurootol., 1999, Vol. 4, 185–191.

[21] SHEA J.J., Jr., *Fenestration of the oval window*, Ann. Otol. Rhinol., 1958, Vol. 67, 932–951.

[22] SLATTERY W.H., HOUSE J.W., *Prostheses for stapes surgery*, Otolaryngol. Clin. North Am., 1995, Vol. 28(2), 253–264.

[23] VELEGRAKIS G.A., *Otosclerosis: state of the art*, Otorhinolaryngologia – Head and Neck Surgery Issue, 2011, Vol. 43, 6–16.

[24] YEOH O.H., *Characterization of elastic properties of carbon-black-filled rubber vulcanizates*, Rubber Chemistry and Technology, 1990, Vol. 63, 792–805.