FINITE ELEMENT MODELING OF TISSUE DEFORMATION AND OPENING PHENOMENA IN THE COLLAPSIBLE EUSTACHIAN TUBE

Samir N. Ghadiali (1,2) , J. Douglas Swarts (1), William J. Doyle (1)

(1) Department of Pediatric Otolaryngology, Children's Hospital of Pittsburgh

(2) Department of Chemical Engineering, University of Pittsburgh

INTRODUCTION

Otitis media (OM) is a common childhood disease that includes inflammation of the middle ear (ME) mucosa and accumulation of fluid within the ME space. Although bacterial/viral infections and nasal allergies contribute to the onset of OM, the persistence of OM has been related to ET dysfunction[1]. The ET is a collapsible tube which connects the ME space with the nasopharynx. The structure of the ET is similar to other respiratory airways in that the lumen contains a fluid layer, the mucosa, and is surrounded by osseous, cartilaginous, and muscular elements. Under normal conditions, the ET exists in a "closed" configuration which protects the ME from nasopharyngeal pathogens. However, the ET is also responsible for maintaining ambient ME pressures and clearing ME fluid into the nasopharynx. These functions are typically performed during swallowing where contraction of the surrounding musculature opens the ET, increases the cross-sectional lumen area and thus reduces the resistance to air flow. In the absence of these openings significant underpressures develop in the ME resulting in the transudation of fluid into the ME space and the ensuing disease complications.

Previous studies [2, 3] have demonstrated that insufficient ET opening during swallowing may be due to anatomical or mechanical abnormalities. However, the precise mechanisms by which various mechanical and/or anatomical properties alter ET opening phenomena have not been investigated. Therefore, the goal of this study is to develop sophisticated finite element models of ET opening phenomena that incorporate the essential anatomical and mechanical features, i.e. muscle force magnitude and elastic/viscoelastic tissue properties. These computational models will be used to understand how the mechanical/anatomical structure influences ET function and to predict the effectiveness of various treatment options. For example, several tissue engineering methods, including cartilage/muscle stem cell augmentation, have been proposed to treat ET dysfunction. The computational models will be used to evaluate the potential therapeutic value of these methods and to identify the optimal mechanical properties of these tissue constructs.

METHODS AND MATERIALS

During swallowing, contraction of the muscular elements, which are attached to the lateral portion of the ET, can "pull" open the ET lumen by deforming cartilage and other soft tissue elements. Tissue deformation in this system is governed by the equilibrium stress-balance and constitutive equations.

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0, \text{ where, } \sigma_{ij} = \frac{E}{(1+\upsilon)}\left(\frac{\upsilon}{1-2\upsilon}\varepsilon_{mm}\delta_{ij} + \varepsilon_{ij}\right) + \mu_w \frac{\partial \varepsilon_{ij}}{\partial t} \quad (1)$$

where *i* represents the x, y and z Cartesian directions, σ_{ij} is the Cauchy stress tensor, E is the stiffness modulus, υ is the Poisson's ratio, μ_w is the tissue viscosity, ε is the strain tensor ($\varepsilon_{mm}=\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}$), and δ_{ij} is the Kronecker delta function. Although we utilize a linear constitutive relationship, non-linear tissue properties can also be successfully implemented. The ADINA finite element package (Watertown, MA) was used to solve these equations in a 2D model of the ET (using plain-strain analysis) as well as a complete 3D model.

2D Modeling techniques

To accurately capture the *in vivo* anatomy, the 2D compuational domain was obtained from a cross-sectional histological image at the narrowest portion of the ET (Figure 1a). This image was used to obtain high quality contours of the ET cartilage and lateral membranous wall (LMW). In addition, the insertion location and angle of the tensor veli palitini (TVP) and levator veli palitini (LVP) were also recorded. As shown in Figure 1b, this information was used to create a 2D finite element model of the collapsed ET. Here, the medial-superior portion of the cartilage was fixed to approximate its attachment to the cranial base. The mechanical properties (E, υ, and μ_w) of the cartilage elements were based on measurements in ear cartilage while the LMW element properties were based on measurements in juvenile monkeys. Muscle contraction during swallowing was simulated by applying a distributed muscle force (F_{muscle}) on the cartilage/LMW surfaces in the appropriate direction.

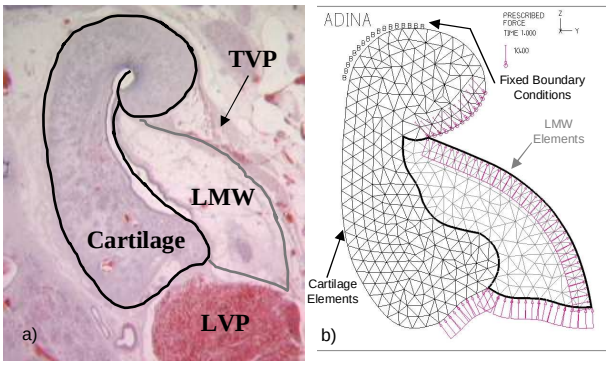

Figure 1 a) Histological image of the ET b) 2D FEM model

This simulated swallowing behavior resulted in tissue deformation and opening of the ET lumen (see Figure 3a). The resistance to airflow in the opened ET, R_v, was calculated using a simple fluid flow model [4].

$$R_v = \Delta P/Q = \mu L \Gamma_S / A^2 \qquad (2)$$

This model assumes fully developed, low Reynolds number flow in an arbitrary geometry where L is the assumed length of the ET, μ is the viscosity of air and A is the cross-sectional area. Γ_S is a generalized hydraulic-geometric shape factor related to the wetted perimeter and can be calculated for any arbitrary shape [4]. Therefore, this technique is particularly suited to biological systems where the cross-section lumen shape is complex. This 2D model was used to investigate the sensitivity of R_v as a function of various tissue mechanical properties which can be treated with tissue engineering therapies.

3D Modeling techniques

The model presented above assumes that the 2D cross-sectional geometry observed at the narrowest portion of the ET adequately describes tissue deformation along the length of the ET. However, the ET is a highly complex 3D structure in which spatial variations in tissue deformation along the axis of the ET may be significant. Therefore, we have also developed 3D reconstructed models that accurately simulate the *in vivo* geometrical variations. These 3D models were constructed using serial histological images obtained in 0.75 mm increments along the length of the ET (z-axis). High quality contours of the cartilage and LMW at each z-location were lofted to create a 3D solid model using ProEngineer (Needham, MA). These solid models were then meshed with the finite element package using a free-form technique (Figure 2). Once the appropriate boundary conditions were applied, these 3D models were used to simulate tissue deformation and lumen opening during swallowing. As a result, a 3D flow resistance parameter was calculated and compared to the 2D R_v to determine if these 3D modeling techniques are required to accurately assess *in vivo* ET opening phenomena.

RESULTS

Examples of the results obtained from the 2D deformation analysis are shown in Figure 3. Figure 3a shows the strain magnitudes and open lumen area that would develop during swallowing. Prediction of strain magnitudes may be important in understanding tissue remodeling while the lumen area can be used to calculate the flow resistance parameter, R_v. Figure 3b and 3c demonstrate how tissue mechanical properties, LMW elasticity (E_{LMW}) and muscle force magnitude, influence the flow resistance generated during swallowing. These results indicate that changes in R_v are significantly more sensitive to changes in F_{muscle} as compared to changes in E_{LMW}.

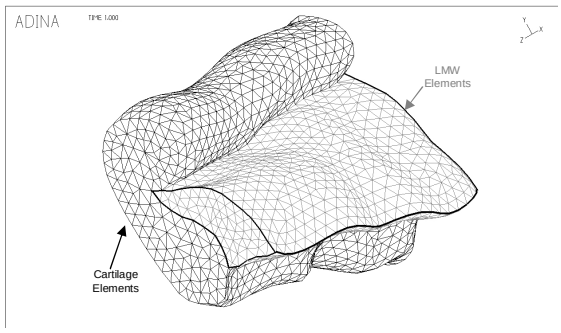

Figure 2 3D FEM model of the ET

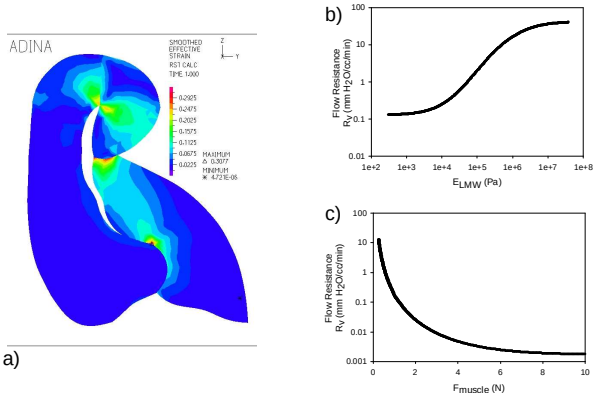

Figure 3 a) Deformed ET and strain contours, b) Influence of E_{LMW} and c) F_{muscle} on flow resistance

CONCLUSIONS

We have developed sophisticated 2D and 3D finite element models of the tissue deformation process that results in ET opening during swallowing. These models are based on the *in vivo* anatomy and can be used to understand how alterations in various tissue mechanical properties affect the opening phenomena. Specifically, 2D simulations indicate that ET opening is more sensitive to muscle forces than LMW elastic properties. Therefore, these studies will be useful in identifying which tissue elements should be targeted for treatment. These studies may also be useful in identifying design parameters (i.e. change in tissue mechanical properties) of these novel tissue engineering constructs.

REFERENCES

1. Bluestone C. D., Stool S. E., and Kenna M. A., 1996, *Otitis Media, Atelectasis, and Eustachian Tube Dysfunction*, W.B. Saunders Company, Philadelphia.
2. Swarts J. D. and Rood S. R., 1990, "The morphometry and three-dimensional structure of the adult eustachian tube: implications for function," Cleft Palate J, vol. 27, pp. 374-81.
3. Ghadiali S. N., Banks J., and Swarts J. D., 2002, "Effect of Surface Tension and Surfactant Administration on Eustachian Tube Mechanics," J Appl Physiol, vol. 93, pp. 1007-1014.
4. Ghadiali S. N., Swarts J. D., and Federspiel W. J., 2002, "Model-based Evaluation of Eustachian Tube Mechanical Properties Using Continuous Pressure-Flow Rate Data," Ann Biomed Eng, vol. 30, pp. 1064-1076.

ACKNOWLEDGEMENTS

This work was support by a grant from the NIH/NIDCD DC005345