PROJECT 2: MODELING OF THE TRACHEA

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INTRODUCTION

The trachea is the introduction of the airway. It takes part in forming pressure gradients compared to the outside air in order to bring oxygen into the lungs (inspiration). In expiration, the internal pressure of the trachea is negative. The trachea is a tube of cartilaginous rings posteriorly lined and interspaced with smooth muscle. There are a total of 18-22 rings that eventually branch.

For the purpose of this experiment, the main branches (about 7 cartilage rings) are simulated in normal, healthy context, with tracheomalacia, and with tracheostomy/tracheotomy. Different diseases and procedures change the functionality of the trachea, thus affecting the airway.

Tracheomalacia is a structural abnormality in the cartilaginous rings of the trachea. This leads to an overall weakening of trachea and increases its collapsibility. With structural integrity reduced in both congenital and secondary forms, patients commonly face decreased airflow.[1]

In cases of obstructed airways a tracheotomy, or tracheostomy is performed on a patient. The surgical procedure requires an incision through the anterior side of the neck into the trachea. A breathing tube is sometimes inserted and later removed in some cases in this opening.[2]

It is the objective of this experiment to model examples of tracheal diseases in order to identify how it physiologically affects oxygen received by the lungs. Compliance characterizes tissue expansibility of the tissue and resistance exhibited during breathing.[3] The measurement of this objective will come from compliance calculation and measurement of volumetric deformation from various applied negative internal pressures. Tracheomalacia occurs when abnormal softening of cartilage rings develop into a reduced airway, posterior smooth muscle wall widening, and collapse.[4]

For the simulation, the trachea will be modelled via finite-element modelling. A compliant vessel assumption with linearly elastic material will compose the model structure. Therefore, the relation of initial tracheal volume, tracheal volume, compliance, and negative internal pressure are used in its linear form.

MATERIALS AND METHODS

For the purpose of this model, peak expiration of sheep's trachea was simulated and measured using volumetric deformation functions and pressure loading tools in ANSYS. Peak expiration is defined as applying a negative internal pressure of the cylindrical trachea in the range of -100 to -500 Pa, where the minimum (-500 Pa) estimates heavy exertion. All cartilage rings of the trachea are assumed to have a uniform, circular shape. The trachea is assumed to be isotropic and incompressible composed of linearly elastic materials

The healthy model of the trachea consists of seven, 20 mm diameter cartilaginous rings with width 5mm, connective tissue bands with width 10 mm alternating between cartilaginous rings. The connective tissue was also used in the posterior of the cartilaginous rings to close the cylindrical shape of the modelled trachea. This is to simplify the model, although physiologically there is a muscle lining instead of the connective tissue at the posterior of all rings and connective tissue bands (smooth muscle strip). Both ends of the tracheal cylinder were fixed with fixed internal pressure throughout the trachea.

The corresponding elastic modulus and Poisson's ratio was assigned to each solid component per connective tissue and cartilaginous regions. For the three simulated cases–healthy tracheal expiration, tracheomalacia, and tracheostomy– *Table 1* summarizes the conditions and variations applied to the setup of each model.

Table 1. Material parameters and structure summary of simulated trachea models in ANSYS.

	Cartilage			Connective Tissue			
Tracheal Model Type	Elastic Moduli (MPa)	Poisson's Ratio	Thickness (mm)	Elastic Moduli (kPa)	Poisson's Ratio	Thickness (mm)	Structure
Healthy	2	0.3	1.1	20	0.3	1	Cylindrical - 7 cartilage rings posteriorly connected by connective tissue
Tracheomalacia	0.5	0.3	1.1	20	0.3	1	Same as "Healthy"
tracheostomy	2	0.3	1.1	20	0.3	1	Same as "Healthy"; Third cartilage ring has additional connective tissue block anterior

In the tracheostomy case, there is an anterior connective tissue region in the third ring to estimate a tracheal opening through the neck as a permanent airway.

Trachea are treated as compliance vessels, therefore the relationship $V = V_o + CP$ is used in extracting the compliance from pressure-volume (PV) curves. V is volume in trachea, V_o is the initial trachea volume, C is the compliance, and P is pressure. Compliance was obtained to compare efficiency of respiration given the simulated cases.

RESULTS

Generally, simulated pressure loads showed a gradient that complimented the most volumetric deformation on the anterior surface of the cartilage ring, with increasing deformation to the posterior connective tissue. Little to no deformation was applied to anterior regions of the cartilage rings, with the exception of the tracheostomy.

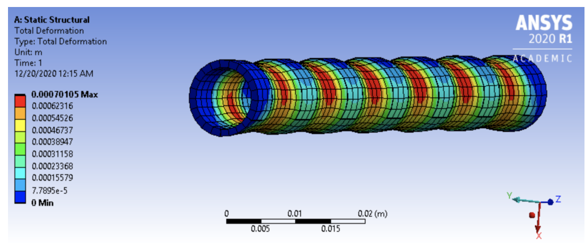

Figure 1. ANSYS simulation of the healthy trachea model at -500 Pa internal pressure.

In plotting the PV curves, the minimum volume (V_o) is supplied by tracheostomy, with 3033 mm^3 compared to 3035 mm^3(*Figure 2, Table 2*).

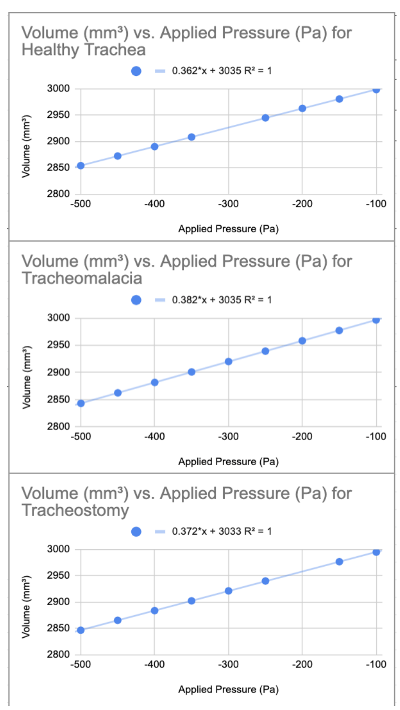

Figure 2. Pressure-Volume curves obtained from healthy, tracheomalacia, and tracheostomy models.

Condition	Applied Pressure (Pa)	Volume, V (mm^3)	Compliance Slope (dV/dP, mm^3/Pa)	Minimal Volume, Vo (mm^3)
Normal	-100	2998.6968		
Normal	-150	2980.7666		
Normal	-200	2962.9526		
Normal	-250	2944.9395		
Normal	-350	2908.4346		
Normal	-400	2890.2225		
Normal	-450	2872.3242		
Normal	-500	2854.0371	0.362	3035
Tracheomalacia	-100	2996.3103		
Tracheomalacia	-150	2977.0692		
Tracheomalacia	-200	2958.1817		
Tracheomalacia	-250	2939.17		
Tracheomalacia	-300	2920.0352		
Tracheomalacia	-350	2900.9282		
Tracheomalacia	-400	2881.6622		
Tracheomalacia	-450	2862.5208		
Tracheomalacia	-500	2843.2325	0.382	3035
tracheostomy	-100	2994.9875		
tracheostomy	-150	2976.7674		
tracheostomy	-250	2940.0742		
tracheostomy	-300	2921.2747		
tracheostomy	-350	2902.324		
tracheostomy	-400	2883.7076		
tracheostomy	-450	2865.2361		
tracheostomy	-500	2846.409	0.372	3033

Table 2. Volume of cylindrical trachea models, their compliance, and tidal volumes via $V = V_o + CP$.

The compliance of the trachea corresponds to how much the trachea can expand. In terms of compliance, the healthy trachea, the tracheostomy, then the tracheomalacia ranked in increasing compliance. Given that compliance is defined as dV/dP, compliance was extracted from the slope of the PV curve as seen in *Figure 2*.

DISCUSSION

The measured volumes show the trend in deformation as pressure decreases (becomes more negative). This translates as to how the trachea physically expands and releases in expiration.

Internal pressure drives tracheal expansion to peak expiration. The stiffness of material informs compliance and the resulting air flow that can be inspired as a result of negative internal pressure. In the scope of the simulation, low stiffness and elastic modulus is associated with high compliance. Based on simulation, compliance is greatest for tracheomalacia, tracheostomy, and then the normal/healthy condition which is expected and supported by small tracheal radius and collapsibility.[5] This is expected and physically supported by the elasticity of connective tissue compared to cartilage. As in *Table 1.,* the lowest elastic moduli corresponds with the highest compliant model.

In terms of error, there is most likely overestimation of volumetric deformation which may impact compliance. Smooth muscle has moduli ranging from about 20kPa to 3kPa in mammals depending on age[6] which can range less than the connective tissue used in place of the smooth muscle strip. If smooth muscle was properly modelled there would likely be increased compliance and greater deformation as the tissue is more elastic. Additionally, the trachea geometry was estimated as a cylinder, but in reality there is more of an ellipsoid appearance which would cause increased volumetric deformation.

In future simulations, the model could use a different approximation of compliance, rather than the linear method used. Adding in a resistance term and taking a nonlinear approach would yield more accuracy and similarity to tracheal physiology as compliance has shown variation with respect to volume in study.[7]

Cartilaginous rings had a much greater elastic modulus than the connective tissue. This resulted in pressure forces greatly affecting the shape of the connective tissue over the cartilage (*Figure 1)*. Thus, the small cartilaginous region replaced with connective tissue in the tracheostomy does not show significant change in tidal volume (>2 mm^3) (*Figure 2*).

References

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