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AIRWAY MECHANICS
AND
PULMONARY FUNCTION TESTS

A thesis presented in partial fulfilment of the requirements for the degree of
Doctor of Philosophy in
Physics

at Massey University
Palmerston North
New Zealand

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1999

ABSTRACT

Methods of engineering mechanics were applied to further the theoretical understanding of the elastic deformation of some specific components of the tracheobronchial tree when subject to a transmural pressure difference.

The contribution of the epithelial basement membrane to airway collapse was analysed. The well-known approach based on the physics of a shell was extended to investigate the influence of a non-homogeneous stiffness of the basement membrane on airway collapse. Results were obtained for the fundamental "two-lobe" collapse. These indicate that the critical pressure at which collapse starts depends on the location of the region of maximal stiffness.

A method was presented for analysing asymmetric stress-strain behaviour when the Young modulus of a material is different in compression than in tension. Results indicated that, if the basement membrane were stiffer in compression than in tension, the resulting collapsed structure would be slightly stiffer than in the case of no stiffness difference and thus the airway would be less narrowed and less compliant.

The deformation of the trachea was analysed by using the same theory as used in the study of the folding of the epithelial membrane. Computations were made to investigate (i) a semi-circular "base-shape" as well as more complex, non-circular shapes, (ii) the effect of shortening of the posterior membrane, (iii) localised weakening of the cartilage ring. Good agreement between model predictions and published MRI microscopy data from rabbit tracheas was obtained.

The concepts of fluid mechanics in elastic tubes were used to analyse the effects of airway remodelling on forced expiratory airflow and resistance to airflow. The tracheobronchial tree was modeled as a system of branching, elastic tubes. Flow behaviour through that system of tubes was analysed which allowed the simulation of pulmonary function tests, in particular forced expiration and response to a muscle agonist. Effects of thickening of the airway wall components (adventita, smooth muscle and the submucosa) on exiratory flow and airways resistance, were investigated. Results showed that thickening of the smooth muscle had the strongest effect on expiratory airflow and airway resistance, followed by thickening of the submucosal area. Model results were within a physiologically feasible range.

ACKNOWLEDGEMENTS

The following people have helped me during the course of this work. It is a pleasure to thank them.

Assoc. Prof. Rod K. Lambert, my first supervisor, for his constant support, enthusiasm, expertise and patience during our discussions.

Dr. Craig Eccles, my second supervisor for his assistance with software-related problems.

Dr. Rodger Pack, from Massey University's Institute of Food, Nutrition and Human Health, my third supervisor, for reading the draft of my thesis and his useful advice.

Assoc. Prof. Bob O'Driscoll for his assistance with computer equipment-related problems.

Barbara Moore from University of British Columbia Pulmonary Research Laboratory, Vancouver, Canada for letting me use some of her data.

The Palmerston North Medical Research Foundation for their research grant.

All members of the Institute of Fundamental Sciences for maintaining a pleasant working environment.

Last but not least my parents, who always supported me, although they hated the idea of me going to New Zealand to pursue PhD studies.

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List of symbols

PART I:

F : force

T : tensile force/unit axial length

S : shear force/unit axial length

M : bending moment/unit axial length

P : pressure

κ : curvature

ν : Poisson ratio

E : Young modulus

t : thickness

D : flexural rigidity

s : arc length

R : tube radius

$f(s)$: function indicating dimensionless variation of stiffness distribution

α : stiffness coefficient

θ : angle that tube wall makes with reference direction

P^* : normalised pressure

P^*_{cr} : normalised critical pressure

P^*_c : normalised wall-touching pressure

λ : normalised arc length

n : number of folds

x,y : coordinates of tube wall

A_0 : initial cross-sectional area

A : cross-sectional area

ε : strain

σ : stress

η : ratio between Young moduli

I_A : second moment of area

$\beta(\eta)$: function describing change of flexural rigidity of a composite area

CF : cost function

L_{max} : length at which maximal isometric force was generated

L : posterior membrane length (trachea)

w : width of cartilage ring

a,b : ellipse half radii of cartilage ring

c_s : stretch coefficient

h : arc height

r : radius (intercartilaginous membrane deformations)

PART II:

Raw : airway resistance

FEV_1 : forced expiratory volume in one second

TLC : total lung capacity

VC : vital capacity

RV : residual volume

FRC : functional residual volume

p : pressure

ρ : density

μ : viscosity

z : generation number

U : local average flow speed

$\dot{V}$: volume flow

A : cross-sectional area

f : dissipative pressure loss/unit length

c : wave speed

Re : Reynolds number

L : length of airway

α : specific airway compliance

V : volume

P_o^* : outer adventital perimeter

P^*_{mo} : outer perimeter of airway smooth muscle

P_{bm} : perimeter of basement membrane

D^*_{bm} : maximal diameter of basement membrane

D^*_e : maximal diameter external to smooth muscle

D^*_o : maximal outer diameter

WA_o : outer (adventital) wall area

WA_{sm} : smooth muscle wall area

WA_i : wall area internal to smooth muscle (sub mucosa)

T_N : normalised tension

σ : stress

G : parenchymal shear modulus

PMS : percentage smooth muscle shortening

α,β : coefficients for *PMS* function

dose : (hypothetical) agonist causing smooth muscle shortening