Evaluation of the effect of postural and gravitational variations on the distribution of pulmonary blood flow via an image-based computational model

Kelly Burrowes* Peter Hunter† Merryn Tawhai‡

*University of Auckland, k.burrowes@auckland.ac.nz
†University of Auckland, p.hunter@auckland.ac.nz
‡University of Auckland, m.tawhai@auckland.ac.nz

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Evaluation of the effect of postural and gravitational variations on the distribution of pulmonary blood flow via an image-based computational model

K. S. Burrowes, P. J. Hunter, M. H. Tawhai
Bioengineering Institute, The University of Auckland
Private Bag 92019
Auckland, New Zealand

Abstract – We have developed an image-based computational model of blood flow within the human pulmonary circulation in order to investigate the distribution of flow under various conditions of posture and gravity. Geometric models of the lobar surfaces and largest arterial and venous vessels were derived from multi-detector row x-ray computed tomography. The remaining blood vessels were generated using a volume-filling branching algorithm. Equations representing conservation of mass and momentum are solved within the vascular geometry to calculate pressure, radius, and velocity distributions. Flow solutions are obtained within the model in the upright, inverted, prone, and supine postures and in the upright posture with and without gravity. Additional equations representing large deformation mechanics are used to calculate the change in lung geometry and pressure distributions within the lung in the various postures - creating a coupled, co-dependent model of mechanics and flow. The embedded vascular meshes deform in accordance with the lung geometry. Results illustrate a persistent flow gradient from the top to the bottom of the lung even in the absence of gravity and in all postures, indicating that vascular branching structure is largely responsible for the distribution of flow.

I. Introduction

Perfusion of the pulmonary circulation has previously been investigated via direct experiment or through imaging studies. Although such studies have increased our understanding of both the anatomy and functional mechanisms in the lung, such as the effect of body posture and the relative contribution of gravity to blood flow distribution, the underlying structure-function relationships that result in clinical or experimental observations are not entirely understood. Early experimental observations [1] concluded that gravity was the main determinant of blood flow but more recent higher resolution studies have shown gravity to be only a minor factor in the distribution of blood flow in the lung [2]. These experimental studies have demonstrated a persistent blood flow gradient with respect to position in the lung, somewhat independent of body posture and gravitational forces [2].

The transport of blood within the lung is dependent on material properties and the resultant mechanical behavior of the parenchymal tissue to which the vascular trees are tethered. Understanding the interdependence between structure, fluid transport, and mechanical function in the lung has traditionally relied on direct experiment and medical imaging. This approach brings together experiment, imaging, and predictive computational models to enable an increased understanding of the complex pulmonary system.

II. Methods

A. Model Geometry

A semi-automated computerized method was used to construct subject-specific computational models from multi-detector row x-ray computed tomography (MDCT) masks, provided by the Lung Atlas [3], of the lobar surfaces and largest arterial and venous vessels in the human lung. Finite element volume meshes of each of the five lobes (Fig. 1a) were fitted to data point clouds, generated via grayscale information provided by lung surface masks. Approximately 2,500 vessels were identified from the MDCT images for each of the arterial and venous networks (Fig. 1b). A volume-filling branching algorithm was used to 'grow' additional blood vessels into the lobar volumes down to the level of their accompanying respiratory bronchioles, resulting in arterial and venous trees each consisting of around 60,000 vessels (Fig. 1c). The branching, length, and diameter ratios of the vascular trees were found to compare well with anatomical measurements [4].

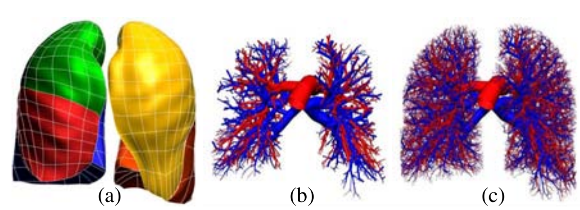

Fig. 1. Finite element models of each of the five lobes (a), and the larger arterial (red) and venous (blue) vessels (b) derived from MDCT data. Additional blood vessels (c) generated into lung volume using a volume-filling branching algorithm.

B. Blood Flow Solution

By constraining the velocity profile over the cross-section of each vessel a reduced form of the Navier-Stokes equations can be derived to determine the pressure (p), radius (R), and velocity (V) distribution within the arterial and venous vascular geometries using (1,2) [5,6].

$$\frac{\partial R}{\partial t}+V\frac{\partial R}{\partial x}+\frac{R}{2}\frac{\partial V}{\partial x}=0$$
(1)

$$\frac{\partial V}{\partial t}+(2\alpha-1)V\frac{\partial V}{\partial x}+2(\alpha-1)\frac{V^2}{R}\frac{\partial R}{\partial x}+\frac{1}{\rho}\left[\frac{\partial p}{\partial x}+\rho g\cos\Theta\right]=$$
$$-2\frac{\nu\alpha}{\alpha-1}\frac{V}{R^2}$$
(2)

where t denotes time, Θ is the vertical angle between the gravitational vector and the vector of the vessel centerline, and g, the acceleration due to gravity, has a value of 9.81 m.s^{-2} (1G) or 0 m.s^{-2} (0G). The vessel cross-section velocity profile parameter, α, defines a parabolic velocity profile and has a value of 1.1 in all simulations in this study. The term ρ (blood density) is 1.05x10^{-6} kg.mm^{-3}, and ν (the kinematic viscosity of blood) is 3.2 mm^2.s^{-1} for all simulations in this study. A relationship between vessel radius and pressure is also defined by (3).

$$p(R)=G_0\left[\left(\frac{R}{R_0}\right)^{\beta}-1\right]$$
(3)

where G_0 and β are constants fitted to experimental data.

Solutions are obtained with and without the inclusion of gravitational forces in the upright vascular models in order to assess the effect of gravity on flow distribution. Flow solutions within the vascular models in the prone, supine, and inverted postures are also compared.

C. Mechanics Model

The lung is modeled as a homogeneous, compressible, non-linear elastic body using finite deformation theory to obtain mechanics solutions [7]. The mechanics solution boundary conditions are derived from frictionless contact between the deformable lung mesh and the rigid thoracic cavity mesh. Displacements of the rigid contact body determine the gross geometry of the deformable lung, but the lung is free to slide within the cavity. The gravity force is included in the solution.

D. Coupled Mechanics-Flow

The arterial and venous geometries are embedded within the lung volume to achieve the coupled mechanics-flow system. After a mechanics solution is obtained for the lung tissue, the new geometry of the vascular meshes can be obtained, by maintaining consistent ξ coordinates of the embedded vascular mesh with respect to the lung volume. The change in length of vessels influences fluid velocity and vessel stiffness. The mechanics solution also provides information on the external pressure applied by the lung on the blood vessel walls, thereby constraining vessel radius and affecting internal fluid pressure.

Solution of the flow equations provides a prediction of the blood pressure distribution within the lung, which is used to recalculate the mechanics solution. An iterative solution procedure is implemented until convergence of the mechanics and flow solutions is reached.

III. Results

A. Blood Flow Solution

The pressure solutions in the arterial and venous networks at TLC (total lung capacity), including gravity, are displayed in Fig. 2a and b, respectively. A clear gradient of increasing pressure from the top to the bottom of the lung, due to gravitational forces, can be seen.

Terminal solution values were isolated from the arterial and venous vascular models. These results were averaged within 1 and 50 mm slices in order to mimic different resolution data. The model demonstrated significant heterogeneity of tissue perfusion in isogravitational planes (1mm slice averages), but also showed a distinct gradient of blood flow due to gravitational forces, Fig. 3. These flow results at different resolutions unify previous experimental measures [1,2] that may have been interpreted as contradictory.

Flow results in the various postures showed a persistent gradient of flow resulting from the vascular branching structure, namely regions of decreased flow in both the apical and basal regions of the lung, Fig. 4.

B. Mechanics Solution

Solution of the finite deformation theory provides estimates for the distribution of pressure exerted on the blood vessels by the deformation of the lung. The resulting pressure fields derived from contact mechanics solutions are displayed in the lung model in a supine posture at TLC with and without gravity in Fig. 5.

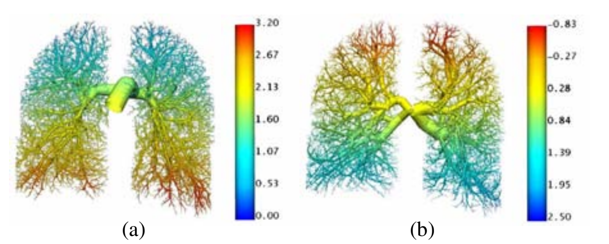

Fig. 2. Pressure solutions in the arterial (a) and venous (b) networks at TLC (total lung capacity), including gravity. These results display a clear gradient of increasing pressure from the top to the bottom of the lung due to hydrostatic forces. Solution spectrums have units kPa.

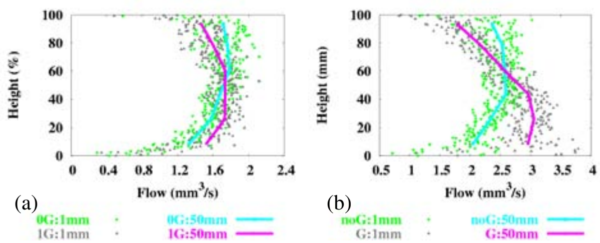

Fig 3. Flow solutions at all terminal locations in the arterial (a) and venous (b) models with (1G) and without (0G) gravity, averaged within 1 and 50mm slices.

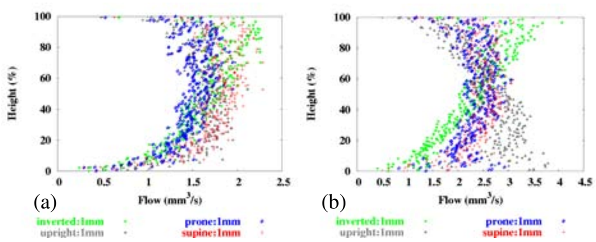

Fig 4. Flow solutions at all terminal nodal locations in the arterial (a) and venous (b) models in various postures (upright, inverted, prone, and supine) averaged within 1 mm slices.

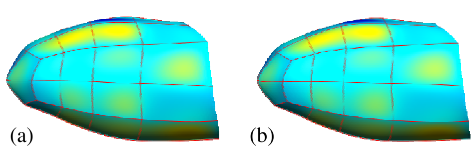

Fig. 5. Lung surface pressures calculated using contact mechanics in a normal human lung in the supine posture with (a) and without (b) gravity.

IV. Discussion

West's zonal flow model [1], in which gravity is named the main determinant of regional vascular perfusion, leads to a number of predictions with respect to blood flow distribution. For example, the zonal model implies that flow within isogravitational planes (equal height and hydrostatic pressure) is uniform, reversal of posture should result in reversal of the flow gradient, heterogeneity should only occur in line with gravity, increased pressure, for example during exercise, should result in more uniform flow throughout the lung. Another major prediction of this zonal model is that in the absence of gravity blood flow distribution should become uniform. Experimental procedures have disproved a lot of these hypotheses with the advent of higher resolution flow data and microgravity experiments [2]. Model results clearly display a large amount of heterogeneity within isogravitational regions, and the persistence of a flow gradient in the absence of gravity, indicating that factors other than hydrostatic pressures affect blood flow distribution.

Coupling of the mechanics and flow sub-systems enables incorporation of tissue density, deformation of blood vessels, gravity, and the effect on flow in different postures and lung volumes, allowing more realistic predictions of pulmonary perfusion and mechanics to be made.

V. Conclusions

Model predictions demonstrated a persistent flow gradient, namely an increasing flow from apical to basal regions and a decreased flow in the most basal regions of the lung, under all gravitational and postural conditions. These results suggest that the vascular geometry largely determines the distribution of flow. Coupling of mechanics and blood flow models provides the potential to yield more realistic computational predictions for both lung mechanics and blood flow distributions.

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