An Efficient Computational Model for Respiratory Gas Exchange

Wendy Kang, Alys Clark, Merryn Tawhai
Auckland Bioengineering Institute, The University of Auckland, New Zealand

Motivation

Problem
- A computational model that can predict respiratory system response to pathology has many clinical applications, but current models are either too simplistic to represent structural heterogeneity, or too complex to solve rapidly.

Aims
- To develop an efficient model to predict patient response in ‘real-time’ for clinical application.
- Require structural & functional detail to describe heterogeneity & matching of ventilation (V) & perfusion (Q) and nonlinear binding of O₂ to haemoglobin (Hb). To investigate to what extent structure & biophysical equations are required to capture spatial & temporal gas exchange function.

Full Model

- A 3D anatomically structured element model of the human airways [1] coupled to 32000 acini at terminal branches (Fig 1).
- Finite deformation elasticity for soft tissue coupled to airways resistance & tissue compliance for V distribution [2].
- Multi-scale model for Q distribution [3].
- Advection-Diffusion Equation (ADX) and gas exchange (Eqn1) is solved for every acinus at each time step for multiple breath till equilibrium.

\[
\frac{dP_{O2}}{dt} = \frac{T_{AC}}{\sigma_0V_0} (1 + \frac{V / Q}{\sigma_0})^{-1} (P_{A02} - P_{B02})
\]

- The Model predicts physiologically consistent distribution of \(P_{O2}\) for normal conditions (Fig 2).

Gas Exchange Simplification

- We investigated the effect that an empirical equation (Eqn 2) fitted to \(P_{B02}\) profile (Fig 3) instead of using gas exchange equation (Eqn 1) has on alveolar-arterial oxygen partial pressure \(P(A-a)O2\) drift:

\[
P(t) = a + \frac{b}{t^{exp}}
\]

- As seen in Fig3, empirical equation can model \(P_{B02}\) profile and save computational time by nearly 80% (Table1).

Geometric Simplification

- We investigated the impact of grouping increasing numbers of acini together to create a simplified geometry.
- Neighbouring acini are successively grouped together as lumped units, with their V & Q averaged.
- Asymmetric conducting airways leading to acini are replaced with symmetric airways, but anatomical dead space kept constant.
- Sequences of acini reducs \(P(A-a)O2\) as seen in Fig 4.
- Sharp decrease at Horsfield order 7, below which averaging had ‘minimal’ effect on \(P(A-a)O2\). Optimal unit of V is ~7, consistent with literature [4].

Numerical Methods

- Lagrange-Galerkin method (LGM) with split operator approach used to solve ADX equation.
- Functional Separation of geometric structure, diffusion only solved for Pelet number<2.
- Adaptive time stepping using predictor-corrector scheme implemented, 2nd order Adam-Bashford as predictor.

Model Predictions

- Modified model is able to capture a large extent of spatial information in \(P_{O2}\) distribution (Fig 5). Gradient is preserved, though slice mean is slightly higher & variance is smaller.
- Modified model compare well with full model at ~2mmHg \(P(A-a)O2\), at ~60% less computation time.

Comparison with MIGET

- We simulated ‘virtual MIGET’ using our model, to compare with MIGET experiments.

Comparison of prescribed V & Q distribution with virtual MIGET derived V/Q plot show good agreement for emphysema affected lung

Conclusion

- We have developed an efficient model that gives good prediction of normal lung and a diseased lung condition.
- Trade off between loss of information against computational expense must be considered for specific applications.
- A functionally determined ‘Optimal unit of ventilation is ~7 units.

References