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Large eddy simulation of high frequency oscillating flow in an asymmetric branching airway model

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ABSTRACT

The implementation of artificial ventilation schemes is necessary when respiration fails. One approach involves the application of high frequency oscillatory ventilation (HFOV) to the respiratory system. Oscillatory airflow in the upper bronchial tree can be characterized by Reynolds numbers as high as 10^4, hence, the flow presents turbulent features. In this study, transitional and turbulent flow within an asymmetric bifurcating model of the upper airway during HFOV are studied using large eddy simulation (LES) methods. The flow, characterized by a peak Reynolds number of 8132, is analysed using a validated LES model of a three-dimensional branching geometry. The pressures, velocities, and vorticity within the flow are presented and compared with prior models for branching flow systems. The results demonstrate how pendelluft occurs at asymmetric branches within the respiratory system. These results may be useful in optimising treatments using HFOV methods.

1. Introduction

Artificial respiration techniques have been clinically applied to patients suffering from respiratory disorders since the 1950s. One effective method involves applying forced high frequency oscillatory ventilation (HFOV) artificially to the lung. Studies have been made into the dynamics of fluid flow within lung-like geometries at rapid ventilation frequencies, in order to better comprehend and analyse the properties of HFOV. The results of such studies are paramount to the success and efficiency of future treatments in this field.

During the ventilation process, air enters the trachea and travels through the bronchial tree before exhalation reverses the bulk flow via the same geometry. The upper bronchial tree comprises the trachea, where the main air intake enters the lung, and two branches—the left main bronchus and the right main bronchus. The left main bronchus is the longer, more slender, and less vertical of the pair. These bronchi in turn branch out into two and three daughter bronchi respectively, which branch out sequentially ad dimunitum. The generation of the bronchial tree has been studied, and its dimensions have been found to be extremely variable in humans, with the total airway length being the most irregular parameter [1].

At high ventilation frequencies (5–25 Hz), forced artificial respiration is termed HFOV. The ventilation process is typically approximated by applying sinusoidal velocity functions at the trachea entrance to represent inhalation and exhalation [2–4]. Analysing the system in this way demonstrates the phenomenon of pendelluft (transient movement of fluid at the end of an inhalation or exhalation cycle), which is thought to occur when the bronchial passages fill at differing rates. Studies of branching geometries subject to HFOV have shown that pendelluft is a universally important mechanism under these conditions, and must be considered in models of the respiration process [3–6].

Previous studies have simplified the geometry of the bronchial tree for analysis. It has been represented by a single bifurcation, both symmetric [2–4,7] and asymmetric [8], while sequentially bifurcating geometries have also been analysed [9,10]. The usage of such geometries has been justified and validated in each case; however, sequentially bifurcating, asymmetric geometries are a more accurate representation of the physical bronchial tree.

A variety of methods have been utilised to model flow behaviour within an airway. Initially, the system was interpreted as a number of parallel pathways, each with a designated compliance, resistance and inertance. Flow could then be analysed by using the equations governing analogous inductor–capacitor–resistor (LCR) circuits [2,3]. However, these analyses did not consider the nonlinear resistances and variable pressures that occur during the ventilation process. It is more common recently to utilise finite discretisation methods coupled with commercial CFD software [7,9,10]. Comparisons with experimental data have also verified the correctness of finite volume-based models [11].

One division of the methods used in CFD is the field of large eddy simulation (LES). LES is a family of methods used to solve the

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equations governing turbulent flow. LES is a transient analysis; that is, it can be used to analyse systems with time-dependent boundary conditions. Despite this advantage over common Reynolds averaged Navier–Stokes (RANS) methods such as the k–ε model, which only solve for the average velocity field, LES has seen limited use until relatively recently, due to the computational processing power required. LES methods have been used to analyse steady flows of high Reynolds number ($\mathrm{Re} \approx 10^4$) within a single asymmetric bifurcating airway model in both two and three dimensions [8]. The results were compared with verifiable k–ε and laminar approaches. While LES analysis largely agreed with these models, it also captured details of the flow that were ignored by time-averaged methods. Hence, LES is capable of modelling both transient and turbulent flow in a branching geometry, albeit with possible improvements possible in its sub-grid model [8].

It has also been found that geometrical variations are important in determining bulk flow properties; for example, turbulent flow in a three-dimensional geometry was found to be less developed than that in a two-dimensional version of the same geometry, despite having the same Reynolds number [8]. Sharp corners at the branches are also known to skew results, in particular, areas of large vorticity caused by flow separation [20].

The present paper describes the analysis of high frequency (25 Hz) oscillating ventilation within an asymmetric double bifurcating airway, using large eddy simulation. The LES modelling process is outlined in Section 2. Details of the relevant physical assumptions, the geometric parameters, modelling, boundary and initial conditions, and the validation of the CFD software are included. The results, including velocity profiles and vorticity contours, are displayed in Section 3. Discussion of these results and the conclusions drawn from them are presented in Sections 4 and 5 respectively.

2. LES modelling

Our aim was to analyse a representative model of the air flow during the respiration cycle of an adult human patient using a respirator with very high ventilation frequencies. A frequency of 25 Hz, corresponding with the upper limit of typical HFOV respiration equipment was selected for analysis. The fluid is assumed to be incompressible, as the flow speed is very low sub-sonic. The air is therefore treated as isothermal, and modelled using the ideal gas equation of state. Fluid properties are shown in Table 1.

2.1. Flow domain

The geometry used was a rigid branching model based on the human upper bronchial tree, namely, the trachea, main bronchi, and their respective daughter bronchi. This geometry is shown in Fig. 1. The major geometric parameters of the model are tabulated in Table 2. Bronchial dimensions were selected to represent an adult human whilst conserving cross-sectional area at each branch.

The finite volume model can only give a limited representation of the ventilation process, as it is an approximation of the upper regions of the bronchial tree. A more accurate model would include further branching and further geometric variations. Nevertheless, due to the similarity in the structure of further generations of bifurcations within the physical bronchial tree, it seems reasonable to assume that modelling the upper portion of the bronchial tree may result in flow patterns that are representative of lower branches, albeit on a larger scale.

Table 1
Fluid properties.

Temperature, T	25 (°C)
Pressure, P	101 (kPa)
Density, ρ	1.184 (kg/m^3)
Viscosity, μ	1.82×10^{-5} (kg/ms)

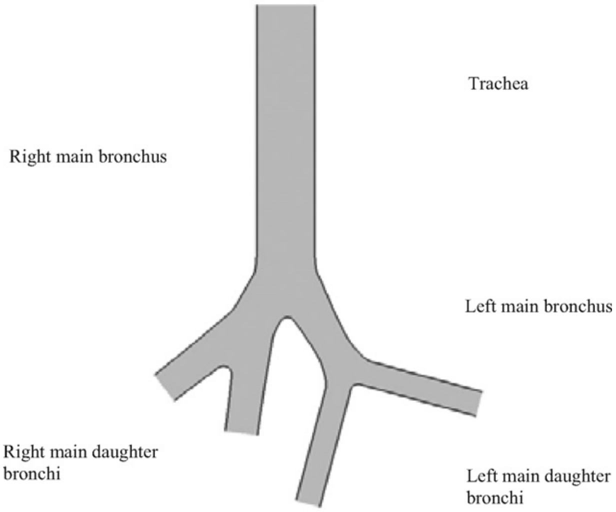

Fig. 1. The simulated branching geometry. Dimensions for each section are given in Table 2.

2.2. Large eddy simulation

Large eddy simulation is one of a family of methods used to solve the unsteady equations governing turbulent fluid flow. The LES process calculates the effect of small eddies using a sub-grid scale model whilst also calculating the large scale motion of the flow using filtered versions of the Navier–Stokes equations [12]. A solution is achieved by numerically evaluating this series of partial differential equations, discretising the non-linear terms [13,14].

Popular traditional turbulent flow models utilising Reynolds averaged Navier–Stokes (RANS) methods such as the k–ε and renormalisation group (RNG) k–ε methods have been used to simulate flows [8]. However, these solve for the average velocity field in the flow, and are therefore of limited use in analysing transient flows. LES is less detailed than the computationally expensive direct numerical simulation (DNS) methods [8]. LES was selected for this study as it can be used to analyse transient flows with a sufficient degree of accuracy without being prohibitively expensive.

A structured, tetrahedral mesh was applied to the geometry, using the advanced (ICEM) meshing module within the ANSYS software. A small number of exponential mesh inflation layers were used to create smaller elements near the walls of the trachea and bronchi in order to more completely resolve the boundary layer flow. Full details of the mesh are given in Table 3.

The LES algorithm using the Smagorinsky sub-grid-scale model within ANSYS CFX 11.0 was used to analyse the flow, using a high resolution advection scheme [15] and a second order backward Euler transient scheme [16]. The time step was chosen to be 0.0004 s, a value that produced stable and satisfactory results, and the total solution period was 0.4 s. This comprised ten ventilation

Table 2
Geometric parameters.

	Diameter (mm)	Length (mm)	Angle (°)
Trachea	25	110	0
Right main bronchus	20	25	30
Left main bronchus	15	50	30
Right daughter bronchi	16	50	22.5
Left daughter bronchi	10	50	45