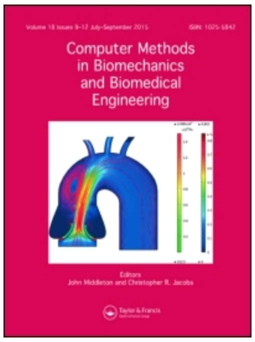

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A new adaptive time step method for unsteady flow simulations in a human lung

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ABSTRACT

The innovation presented is a method for adaptive time-stepping that allows clustering of time steps in portions of the cycle for which flow variables are rapidly changing, based on the concept of using a uniform step in a relevant dependent variable rather than a uniform step in the independent variable time. A user-defined function was developed to adapt the magnitude of the time step (adaptive time step) to a defined rate of change in inlet velocity. Quantitative comparison indicates that the new adaptive time stepping method significantly improves accuracy for simulations using an equivalent number of time steps per cycle.

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KEYWORDS
Adaptive time step; CFD; unsteady flow rate

1. Introduction

An examination of the literature shows that few studies are available for computational simulations using unsteady boundary conditions for modelling of air flow throughout the lung. Calay et al. (2002) using a sinusoidal velocity function as inflow/outflow boundary condition, simulating two ventilation conditions, breathing at rest and at maximum exercise. In each case the time step was constant, 0.005 s at resting and 0.00125 s at maximum exercise. Nowak et al. (2003) used a sinusoidal pressure profile to simulate a respiratory cycle, with an adaptive time step method based on Courant-Friedrichs-Lewy (CFL) number, with a maximum step size of 0.01 s. Zhang and Kleinstreuer (2004) performed simulations under similar conditions, with an adaptive time step between 0.0016 and 0.01 s.

This paper examines a new method for adaptive time step based on uniform changes in values of a variable more relevant (e.g. volume or pressure) than the traditional independent variable (time). This method will be compared with constant time step and adaptive time step (based on the Courant number) methods using experimental data of a forced spirometry test in order to verify its effectiveness.

2. Numerical model

A description of the human bronchial airway geometry, comprising generations 0–16 (G0–G16), and a detailed discussion of the simulation methods used here can be found in Tena (2014) and Tena et al. (2016). The main innovation of this work is an adaptive time-stepping that makes use of the time step as a dependent variable function of a relevant independent flow variable with constant step size (velocity or flow rate, pressure). The ventilation pattern to be simulated is shown in Figure 1.

The forced spirometry (dashed curve) has a range of velocities between 38.02 and −30.77 m/s (reverse flow), in a time of 7.11 s. The rate of change of the velocity is very dependent with the considered time interval, suggesting that time points corresponding to simulation time steps should be clustered closer together when the rate of change in velocity is large and more sparsely when the rate of change is small. This study implemented a custom time-stepping scheme based on a physiologically relevant independent variable (velocity or pressure). The method was implemented into Ansys FLUENT (2015) using user-defined function (UDF) subroutines.

Figure 1 includes a section of the spirometric curve plotting (right inset) showing both a constant time step and a constant velocity step (variable time step). The inputs to the adaptive algorithm are the overall velocity profile for the cycle and the number of steps to be performed during the cycle. The UDF algorithm determines the appropriate constant velocity variation and calculates the corresponding variable time steps. The method has two key advantages. First is clustering of time steps during portions of the cycle for which velocity is rapidly

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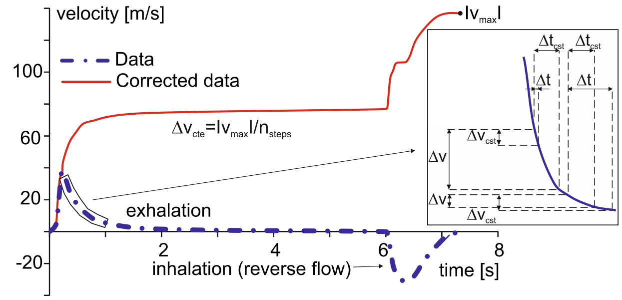

Figure 1. Velocity vs. time (range 38.02 and −30.77 m/s) for a forced spirometry test (dashed curve) and accumulated velocity from absolute increments (red continuous curve). At right, a section of the spirometric curve illustrating the constant time step method and the adaptive time step method which allows a uniform change in velocity during each step.

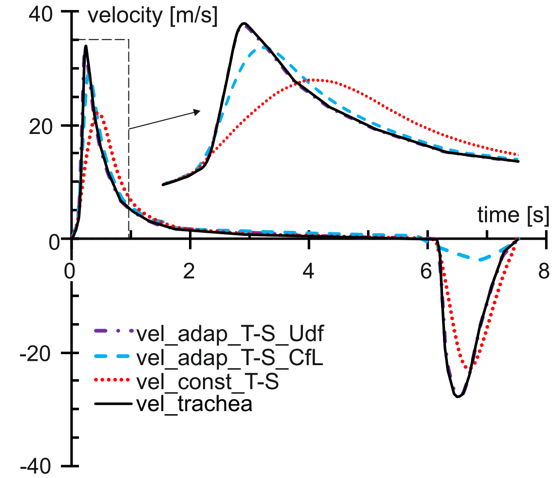

Figure 2. Experimental forced spirometry (continuous curve) and the three-forced spirometry obtained by simulation (dashed curves).

changing. Second is that the total number of time steps taken within each cycle can be specified by the user. Both of these advantages provide a means of reducing computational cost for any simulation compared to using a fixed time step size. In contrast, for an adaptive time step based on the CFL number, the number of steps per cycle cannot be fixed, only the minimum and maximum time step size can be specified.

To implement the method, an accumulated velocity profile is first constructed based on the absolute value of the rate of change of velocity, as illustrated by the red solid curve in Figure 1. The value of the constant velocity step is obtained by dividing the difference of the maximum (end of cycle) and minimum (0, beginning of cycle) accumulated velocity values by the total number of steps to be used per cycle. Once the increment size has been determined, the corresponding non-uniform time step sizes are obtained. In this way, an optimal set of time step sizes for user specified value of total number of steps can be determined a priori for a given velocity flow profile. Further details of this method are available in Tena (2014).

3. Calculation methodology

Three different methods for determination of the time step size were tested: constant time step, adaptive time step based on the CFL number and the newly proposed adaptive time step function based on a fixed velocity step. The comparison between methods was based on the accuracy of each in predicting flow in a forced spirometry test for an equivalent number of time steps per cycle.

The boundary conditions were the time-varying velocity profile at the trachea and a constant pressure-outlet at the lowest generation. Next, the simulations were repeated with a time-dependent pressure difference (G0–G16) as the boundary condition, which was obtained from the corresponding initial simulation. Normalized residuals levels (dividing by the maximum residual value after 5 iterations) were examined. Convergence was accepted with criteria of 0.00001 residuals.

4. Results

The resulting time-dependent velocity distribution predicted by the second set of simulations is compared to the experimental results in Figure 2. It can be observed that the method which best reproduces the velocity distribution is the new adaptive time step method. The ability of the new method to effectively cluster time steps in the most critical portions of the cycle, and the effect on solution accuracy, are apparent. Over the entire cycle, the difference in predicted velocity using the new method vs. the experimental value from the experiment is less than 2%.

5. Summary and conclusions

A new method for adaptive time stepping in respiratory flow simulations was proposed and investigated. The method makes use of a constant step in the relevant dependent variable (velocity-pressure), rather than a constant step in time, to obtain a set of time steps with non-uniform size, clustered during those portions of the breathing cycle in which rapid changes are occurring.

Results showed that the new adaptive time stepping method provided significantly improved accuracy vs. either constant time step size or adaptive time stepping based on CFL number, for simulations using the same number of time steps per cycle. Comparison of the predicted velocity profile to experimental data showed that the new adaptive time-stepping scheme was able to reproduce the results to within 2%, demonstrating its effectiveness for these types of simulations. The method proposed here can be used for future research in similar biological flows, for example cyclic flows in the human circulatory system.

Disclosure statement

The authors declare that no conflicts of interest exist.

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