Fluid Dynamics in Three-dimensional Branching Networks with Application to Model Human Bronchial Tree

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Abstract

The present work provides a comprehensive computational study of the complex fluid dynamics in three-dimensional branching networks. Although the geometry for the computations are based on a generalized model of the human bronchial tree, the flow physics described here is generic and is applicable to other naturally occurring or future engineered branching networks as well. Computations have been performed for branching networks comprising up to six generations of branches. Since the number of branches in a network increases rapidly according to the formula $2^n - 1$, computation of six generations of branches (involving 63 branches and 31 bifurcation modules) in one go poses computational challenges that are rarely taken in the literature. Two branching configurations are considered side by side: the most widely studied in-plane configuration in which the centrelines of all generations lie on the same plane, and, the 90° out-of-plane configuration in which the centreline of each generation is rotated with respect to its grandmother generation following a systematic methodology to form a space-filling three-dimensional structure. This makes it possible to establish a quantitative evaluation of the dependence of the fluid dynamics on the three-dimensional arrangement of the same individual branches. The combined effects of flow path curvature in the bifurcation module, flow division at a bifurcation ridge and inertia of the flow result in flow asymmetry even in a geometrically symmetric network. There exists substantial non-uniformity in the fluid dynamic features (e.g. velocity field, pressure field, mass flow distribution or viscous dissipation) over any longitudinal plane or cross-sectional plane of a particular branch as well as that between different branches of any generation. The details of the secondary flow field and the vortical structures in a branched network are also analysed and many subtle features are unearthed. New parameters are formulated for a quantitative description of the overall features of both the primary and the secondary flow field. It is established that, in spite of the complexity of the flow solutions, there also exists a systematic order such that it is possible to ascertain the flow field in all branches of a particular generation by determining the flow field in some systematically selected branches of that generation, indicating a possible route to the saving of computational resource and time. The alteration to the flow field caused by a blockage in an intermediate branch is investigated for varying blockage locations and extents, and two different three-dimensional arrangements of the same individual branches. The unsteady simulations modelling a breathing cycle in humans reveal that the quasi-steady assumption is approximately valid in the neighbourhood of the peak flow rate while unsteady effects are at their maximum during the reversal of direction of the predominant flow. Flow division at a bifurcation generates large asymmetry in the flow field whereas flow combination at the same bifurcation during oppositely directed flow tends to produce more symmetry in the flow field, displaying essential irreversibility of fluid dynamics.

Keywords: branching network, computational fluid dynamics, secondary motion, blockage, oscillatory flow.