Oral presentation | Turbulence simulation (DNS,LES,RANS)

Turbulence simulation(DNS,LES,RANS)-I

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[8-B-01] Scale-Adaptive Airflow Simulations in a Complete Human Airways up to Transitional Bronchioles

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Scale-Adaptive Airflow Simulations in a Complete Human Airways up to Transitional Bronchioles

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1 Introduction

Computational fluid dynamics (CFD) techniques have been playing an important role in providing a better in-dept understanding of flow transport and physical phenomena in the human respiratory system. Currently, Reynolds-averaged Navier–Stokes (RANS) turbulence and large eddy simulation (LES) models are two main approaches for turbulent flow computations in the human respiratory system. While RANS is the most popular turbulence model, the prediction of flow fluctuations is ignored due to its time-invariant features. LES models show better results of velocity fields compared to experimental data than RANS models. Unfortunately, the requirements of computer time, high-resolution grids still make the use of LES challenging, given the limited computational resources. In this study, we assess an alternative hybrid approach between RANS and LES, i.e., HyRANS, which offers the potential to combine the two models' advantages in a complete human respiratory system.

2 Methodology

2.1 Geometry and mesh

The 3D lower respiratory tract was obtained from CT image data. Physiologically realistic small airways were virtually generated beyond CT-resolved regions representing up to terminal airways (~22 Generation). Furthermore, an idealized upper airway geometry was connected to the lower parts to construct a complete human airway geometry (1). An 1D-centerline-based meshing algorithm was applied with diameters and estimated flow rates using the open-source software Gmsh and Tetgen (2). This method guarantees the maximum value of y^+ was in the viscous sub-layer regions.

2.2 Numerical set-up

2.2.1 Turbulence model

Numerical simulations were performed using the open-source software OpenFOAM v11. For LES model, wall-adapting-local-eddy-viscosity (WALE) (3); for HyRANS, scale-adaptive (SA) shear stress transport (SST) model (kOmegaSSTSAS) by Menter (4); for traditional RANS (TraRANS), SST model (kOmegaSST) (5) are employed in this study.

2.2.2 Boundary conditions

A constant flow rate of 20 L/min with a uniform velocity profile is applied at the inlet. There are a total of 615 outlets where a fully developed parabolic velocity profile matching the subject-specific flow rates (6) was imposed. No-slip conditions were adopted at walls. The second-order schemes were used to discretize all the mathematical terms. The simulation was performed in a total of 2 s. It took 1 s for the air to go through the whole lung and the last second was used to average the flow fields. An adaptive time step with an initial value of 10^{-7} s was adopted to satisfy the CFL condition.

2.2 Verification

The numerical framework of HyRANS was validated by comparing the airflows in a constricted tube with previous RANS and LES simulation studies, and with experiments (7). The results from HyRANS were comparable to LES and similar to TraRANS.

3 Summary

At normal breathing condition, the time-averaged velocity fields and secondary flow streamlines are not significantly different between the LES, HyRANS, and TraRANS turbulence models (Fig. 1). However, TraRANS overpredicted the pressure distributions while HyRANS and LES showed similar trends (Fig. 2). More importantly, HyRANS was able to capture a similar TKE to that produced by LES while TraRANS failed to capture TKE by design (Fig. 3). In terms of particle deposition efficiency, HyRANS slightly improved the simulated results compared to TraRANS when referring to LES (Fig. 4). In conclusion, we demonstrated the validity of the HyRANS (SA-SST) model in human respiratory system over LES through flow fields and particle deposition.

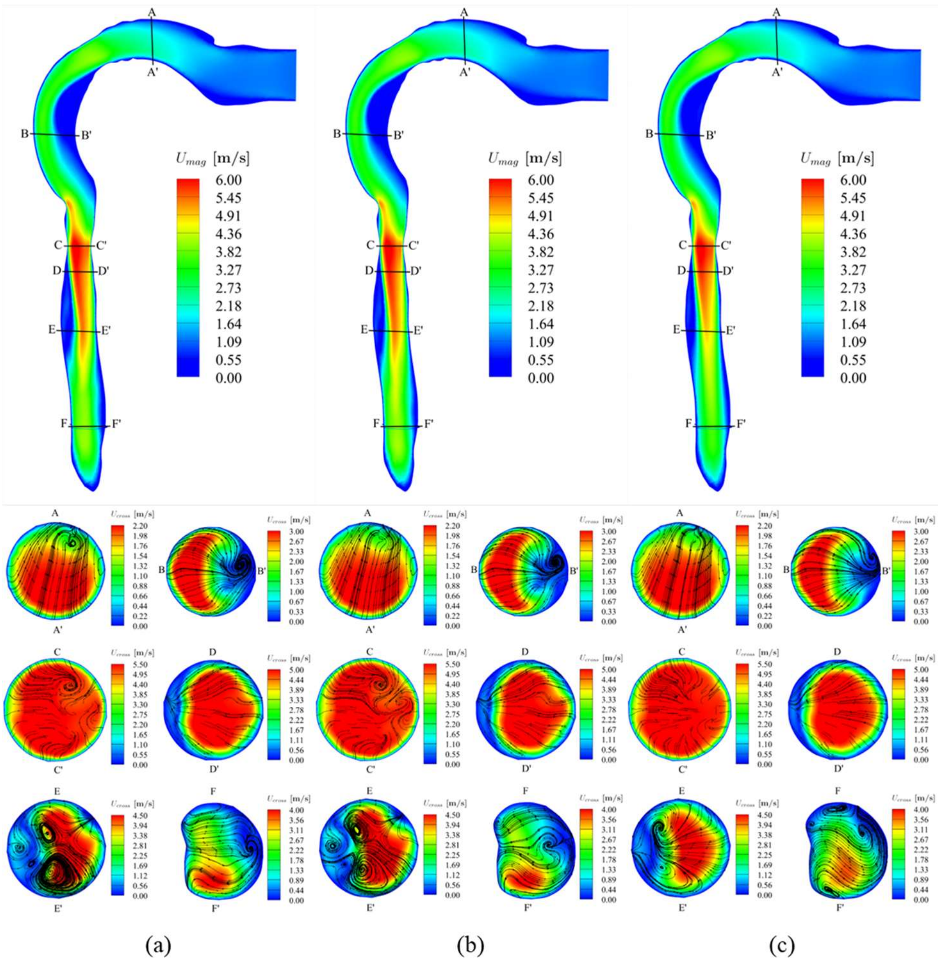


Figure 1: Velocity contour at mid-plane, and axial velocity contour and secondary streams at cross-sections of time-averaged flow fields between (a) LES, (b) HyRANS, and (c) TraRANS.

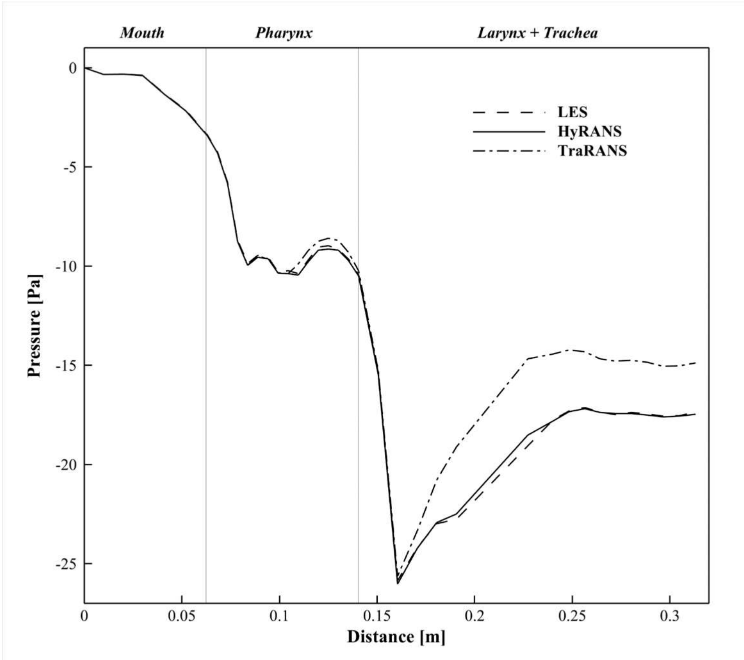
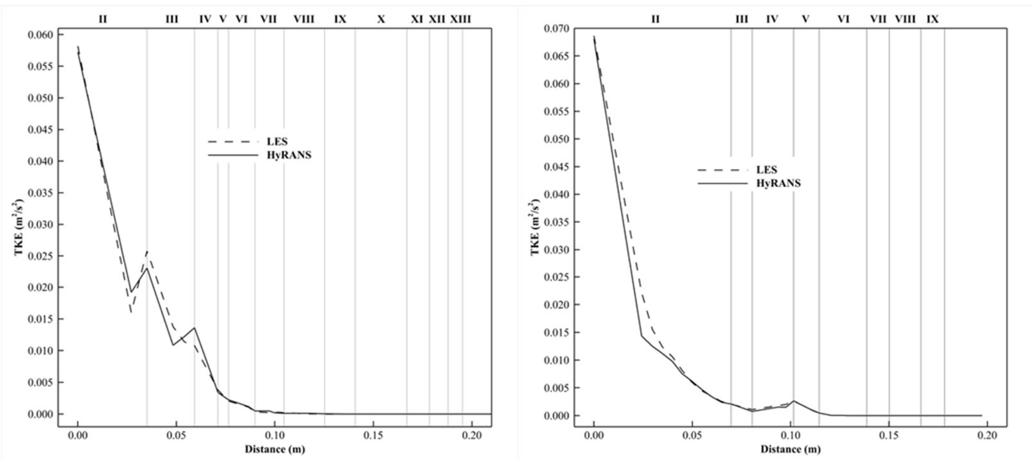


Figure 2: Variation in the pressure along the 1D centerline in the upper airway with LES (dashed), HyRANS (solid), and TraRANS (dashed dot). The gray solid lines divide the grid into the mouth, pharynx, and larynx/trachea regions.



(a) (b)

Figure 3: Variation in the TKE along the 1D centerline in the (a) RLL and (b) LLL airway paths between LES (dashed line) and HyRANS (solid line). The gray solid lines indicate the generation numbers (Roman numerals). Generations after XIII and IX were skipped for the RLL and LLL airway paths, respectively.

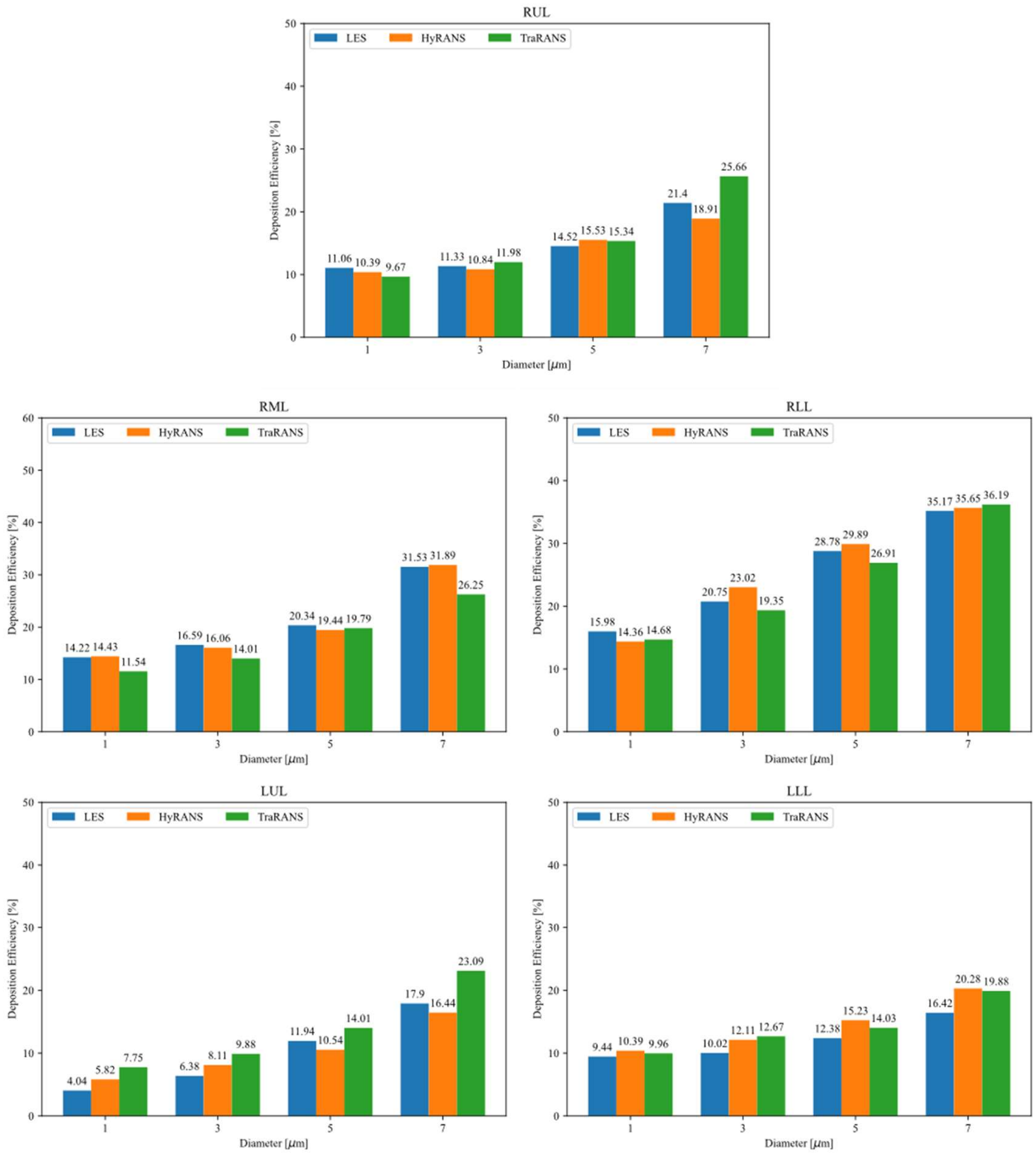


Figure 4: *Comparison of variation in the particle deposition efficiency based on particle size (1, 3, 5, and 7 μm) in five lung sub-lobes including the RUL (top), RML (middle left), RLL (middle right), LLL (bottom left), and LUL (bottom right) between LES, HyRANS, and TraRANS turbulence models.*

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