Numerical simulation of sniff in the respiratory system

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Introduction

- Purpose of the nose
- Improvement of the computational hardware
- Realistic tool
Goals

- Complex flow, well suitable for HPC
- Not so many study and literature about this field
- Better understand the flow in the upper human airway
- Improve numerically the particle tracking and particle deposition
- Obtain precise location of the specific particle deposition
Applications

- Aid in surgical planning
- Improve understanding of healthy and pathological physiology
- Help pharmaceutical company to improve products (spray)
- Reduce the target location and reduce the quantity of product
Anatomy and nomenclature

Introduction to the anatomy of the human respiratory airways:

- Septum
- Nasopharynx
- Vestibule
- Olfactory slit
- Middle meatus
- Middle turbinate
- Lower turbinate
- Lower meatus
- Nasal valve
- Naris
- Main airway
- Nasal valve
- Pharynx
- Larynx
- Trachea
- Branch
Data acquisition: Medical images

Computed Tomography (CT) dataset comprises of axially acquired images: 512×512 pixel matrix with 0.39×0.39 mm pixel size, overlapped image slices with 1.3 mm slice thickness and 0.7 mm spacing.
Geometry definition
Mesh I
Three mesh resolutions: 8M, 44M and 350M elements.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Nodes</th>
<th>Elements</th>
<th>Time-steps(s)</th>
<th>Element size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>$2 \times 10^6$</td>
<td>$8 \times 10^6$</td>
<td>$1 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Medium</td>
<td>$14 \times 10^6$</td>
<td>$44 \times 10^6$</td>
<td>$1 \times 10^{-5}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Fine</td>
<td>$110 \times 10^6$</td>
<td>$350 \times 10^6$</td>
<td>$5 \times 10^{-6}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Prism parameter, example for medium mesh: - first thickness layer : 6 $\mu$m  
number of layer : 13 , growth ratio : 1.2, total height : 0.3 mm  
Value of $Y+$ at the wall: 0.5
Boundary condition: Sniff waveform

10th order polynomial is used, based on data fitting with experimental results*

Alya System

High Performance Computational Mechanics
Multiphysics - Multiscale
Portable to many platforms
Highly parallel
Fluid, solid, electromagnetism, chemistry, heat transfer, Lagrangian particles, etc.

Alya is one of the two CFD codes of the PRACE benchmark suite
Governing Equation: Navier-Stokes solver in Alya

Variational multiscale finite element (VMS)
+ SGS convection tracking
+ SGS time tracking

- Variational principle
  - Weak form for $u$
  - $u \approx u_h$
  - Multiscale splitting $u = u_h + \tilde{u}$
  - Weak form for $u_h$
  - Weak forms for $u_h$ and $\tilde{u}$
  - Galerkin
  - Stabilization method
  - Approx. for $\tilde{u}$, Galerkin for $u_h$

- Unstable Eq. for $u_h$
- Stable Eq. for $u_h$
- Stable Eq. for $u_h$

Galerkin  GLS/SUPG, etc  Variational multiscale
Governing Equation: Navier-Stokes solver in Alya

Monolithic

\[
M^{-1} \begin{bmatrix} A_{uu} & A_{up} \\ A_{pu} & A_{pp} \end{bmatrix} \begin{bmatrix} u \\ p \end{bmatrix} = M^{-1} \begin{bmatrix} b_u \\ b_p \end{bmatrix}
\]

Complex preconditioner vs Simple preconditioner

Fractional scheme

\[
M_u^{-1} A_{uu} u^{k+1} = M_u^{-1} (b_u - A_{up} p^k)
\]
\[
M_p^{-1} Q z = M_p^{-1} r^k
\]
\[
M_u^{-1} A_{uu} v = M_u^{-1} A_{up} z
\]

One system vs Three coupled systems
Blue Waters (NCSA)
4.2 Billions element mesh
Turbulent combustion in a kiln
Portability and scalability of Alya

Lindgren - Cray XE6
Sweden

Jugene - Blue Gene/P
Germany

Curie - BullX
France
Results: Pressure drop

Pressure drop of different sections of the respiratory system
Results: Mean flow

Mean velocity of a few cross sections (0.1 s until 0.15 s).
Results: the laryngeal jet

Iso-surface of the laryngeal jet
Flow distribution on the plane in the middle of nasal cavity (0.1 s until 0.15s).

- Greater flow rate in the left cavity, approximately proportional to the area.
- Little flow goes to the upper septum region, where the olfactory cleft is located.
Results: Turbulence fluctuation

rms velocity fluctuations of a few cross sections (0.1 s until 0.15s).
Iso-surface of the Q-criterion in the throat (time=0.2s)
Result: Coherent structure

Isosurface of Q-criterion and streamlines in the right cavity on the left and Iso-surface of Q-criterion of the nasopharynx region on the right (time=0.2s).
Energy spectra in four different locations, three lines denote the slopes of -5/3, -10/3 and -7, as noticed on the spectrum figures.
Videos and Questions