Blood Fluid Dynamics Simulation in the Aorta-Heart System with Fluid-Structure Interaction (FSI) Methods

Presenter: Wei WEI
Introduction

Blunt aortic injury in Motor Vehicle Crash Accidents (MVCs):

- Second-most common cause to death for victims of blunt chest trauma;
- Up to 15% of deaths related to MVCs;
- About 80% dead at the scene.

(Fox et al., 2015)

Uncertain injury mechanisms:

- Sudden stretch or shear of aorta;
- Entrapment by the surrounding organs;
- Sudden stroke of blood pressure (water hammer);
- The comprehensive effects.
Previous models:

(1) Shah et al., 2007  
Richens et al., 2007  
Lee et al., 2007

(2) Sturla et al., 2013  
Nobari et al., 2013  
Sundaram et al., 2015
Objectives

- Kinematics study on the aorta interacting with the surrounding organs
  -- Integrated with thoracic model
  -- Physiological or deceleration loading
  -- Kinematics validation (acceleration or relative movement)

- Hydrodynamics study on blood flowing in the aorta-heart system
  -- Isolated aorta-heart system
  -- Heart beating (contraction and relaxation)
  -- FSI coupling (LS-DYNA)
  -- Blood flowing validation

- Simultaneously study both kinds of mechanisms
  -- Impact simulation (car crash or thorax strike)
  -- Correlation analysis of aortic responses with kinematics and hydrodynamics
**Geometric model**


Source: CT scan
Geometric model

Table 1. Diameters of different aortic sections

<table>
<thead>
<tr>
<th>Section</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>27.4</td>
<td>27.8</td>
<td>27.1</td>
<td>24.8</td>
<td>24.0</td>
<td>21.9</td>
<td>20.8</td>
<td>18.1</td>
</tr>
<tr>
<td>Reference (mm)</td>
<td>26.8-28.7 (Nevsky et al., 2011)</td>
<td>27.2-29.1 (Nevsky et al., 2011)</td>
<td>24.4-26.4 (Isnard et al., 1989)</td>
<td>20.3-22.1 (Nevsky et al., 2011)</td>
<td>19.3-20.8 (Nevsky et al., 2011)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. The Volume of LV

<table>
<thead>
<tr>
<th>Volume (ml)</th>
<th>Model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>123.2</td>
<td>121-163 (Maceira et al., 2006)</td>
<td></td>
</tr>
</tbody>
</table>
**FE model**

![FE model diagram]

**Materials (LS-DYNA)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material law</th>
<th>Material properties</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>Orthotropic-elastic</td>
<td>$E_a=6.111\text{MPa}$, $E_b=6.111\text{MPa}$, $E_c=6.111\text{MPa}$, $\gamma_a = \gamma_b = \gamma_c = 2.056\text{MPa}$, $\mu=0.4$</td>
<td>Shah, 2007</td>
</tr>
<tr>
<td>Heart</td>
<td>Elastic</td>
<td>$E=10.0\text{MPa}$, $\mu=0.4$</td>
<td>Shah, 2007</td>
</tr>
<tr>
<td>Other vessels and arteries</td>
<td>Elastic</td>
<td>$E=10.0\text{MPa}$, $\mu=0.4$</td>
<td>Shah, 2007</td>
</tr>
<tr>
<td>Blood</td>
<td>Null and Gruneisen equation of state</td>
<td>$\rho=1050\text{kg/m}^3$, Dynamic viscosity=4.5E2 $\text{Pa}\cdot\text{s}$, $K=2.5\text{GPa}$</td>
<td>Einstein et al., 2005 Sundaram et al., 2015</td>
</tr>
</tbody>
</table>

Table. 3 Number of element

<table>
<thead>
<tr>
<th>Type of element</th>
<th>4-node shell</th>
<th>3-node shell</th>
<th>Tetrahedral</th>
<th>Hexahedral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>1,164</td>
<td>11,132</td>
<td>85,035</td>
<td>106,739</td>
</tr>
</tbody>
</table>

**Introduction & objectives**

**Material & Methods**

**Results & Discussion**
Boundary and loading conditions

SPCs:
- Inferior nodes of heart (yellow);
- Posterior nodes of DA (blue);
- Superior nodes of superior arteries (blue).

Loadings:
- Physiological pressure imposed to outlet 1 and 2
- Surface-distributed force applied to LV inner surface (LV volume change)

Pressure input for outlet 1 and 2 (Kim et al., 2009)
Results and discussion
Results and discussion

- Introduction & objectives
- Material & Methods
- Results & Discussion

Left ventricle volume time-history

Left ventricle blood pressure time-history

Peak ejection velocity at section 1
Average blood velocity for different aortic sections
Results and discussion

Flow rate for different aortic sections
Wall shear stress (WSS)

\[ WSS = \mu \left( \frac{\delta u}{\delta x} \right)_{x=0} \]

- \( \mu \): dynamic viscosity
- \( u \): velocity
- \( X \): distance

Section averaged wall shear stress (WSS) time-history
Conclusion

LV volume and blood pressure ➞ Enough blood into aorta within appropriate period

Blood velocity and flow rate ➞ Feasibility of studying hydrodynamics with FSI

Section averaged WSS ➞ Possibility of studying WSS effects on aortic pathologies and injuries with FSI

Future work

Integrating this isolated model with thoracic model;

Validating the relative movement of the aorta to the surrounding organs;

Simulation of car crash conditions or other scenarios;

Parameter analysis of the kinematics and hydrodynamics on aortic injury risks.
Thank you!