Computational Modeling of Blood Flow in the Bifurcation of Human Carotid Artery

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Introduction

Develop three-dimensional patient specific computational models of blood hemodynamic in the human carotid arteries based on finite volume method.

To better predict the risk of atherosclerotic plaques (atheromas) formation.
Geometry

CT images:
63 year old female patient
left and right carotid artery (CA)
intravenously applied iodine-based contrast material

CT 5000 Ingenuit PHILIPS
DICOM 512x512 pixels (width x height)
Resolution 0.4873x0.4873x2 mm^3

Geometry reconstruction:
RETOMO software (BETA CAE Systems)

Atheromas were removed manually from the model so that the geometry corresponds to healthy carotid arteries.
Geometry

a) Reconstructed geometry of the left CA  
b) Reconstructed geometry of the right CA.
Mesh

Software: ANSYS ICEM-CFD, hexahedral elements

24,809 elements

49,289 elements

158,576 elements

57,448 elements

Finite volume mesh of the left CA

Finite volume mesh of the right CA
Mesh element size

Software: ANSYS Fluent, transient analysis with a time step $\Delta t = 2 \times 10^{-3}$ s
six periods of the cardiac cycle

a) Computed velocity profiles near left CCA inlet
b) Before bifurcation
c) near ICA outlet for different element sizes (at systolic pressure).
Boundary conditions

Inlet
mass flow rate wave form obtained from cine phase-contrast MR flow velocity measurements (Cebral et al., 2002)

Outlet
two-element Windkessel model implemented in ANSYS Fluent by ANSYS Customization Tool Windkessel

\[ Q_{in} = C \frac{d}{dt}(P_{in} - P_{c}) + \frac{P_{in} - P_{out}}{R} \]

where \( P_i \) and \( Q_i \) are pressure and mass flow at node \( i \)
R is resistance
C is compliance
Boundary conditions

Parameters were first estimated according to the pulse pressure method, then iteratively tuned to achieve agreement with literature.

Used parameters of two-element Windkessel models

<table>
<thead>
<tr>
<th>Parameter (Organ)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$ (ICA)</td>
<td>$2.023e9$ [kg/m$^4$s]</td>
</tr>
<tr>
<td>$C_1$ (ICA)</td>
<td>$7.505e-11$ [m$^4$s$^2$/kg]</td>
</tr>
<tr>
<td>$R_2$ (ECA)</td>
<td>$3.811e9$ [kg/m$^4$s]</td>
</tr>
<tr>
<td>$C_2$ (ECA)</td>
<td>$8.0e-11$ [m$^4$s$^2$/kg]</td>
</tr>
</tbody>
</table>

Mass flow rate waveform used as boundary condition at CCA inlet (black) and computed mass flow rates at ECA outlet (blue) and at ICA outlet (red).
Model of blood

non-Newtonian fluid using the Carreau model implemented in ANSYS Fluent

\[ \mu_{\text{eff}} (\dot{\gamma}) = \mu_{\text{inf}} + (\mu_0 - \mu_{\text{inf}}) \left( 1 + (\lambda \dot{\gamma})^2 \right)^{n-1/2} \]

where

- \( \mu_{\text{eff}} \) is effective viscosity
- \( \dot{\gamma} \) is shear rate
- \( \mu_0 \) is viscosity at zero shear rate
- \( \mu_{\text{inf}} \) is viscosity at infinite shear rate
- \( \lambda \) is relaxation time
- \( n \) is power index

Parameters used for simulation (Johnston et al., 2004)

<table>
<thead>
<tr>
<th>( \mu_0 ) [Pa.s]</th>
<th>( \mu_{\text{inf}} ) [Pa.s]</th>
<th>( \lambda ) [s]</th>
<th>( n ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.56</td>
<td>0.0345</td>
<td>3.313</td>
<td>0.3568</td>
</tr>
</tbody>
</table>
Streamlines with colour marked velocity magnitude for the left CA video
Velocity profiles in individual cross-sections for the left CA video
Flow visualization (diastolic pressure) a) Streamlines with colour marked velocity magnitude for the left CA, b) Velocity profiles in individual cross-sections for the left CA c) Streamlines for the right CA d) Velocity profiles for the right CA.
WSS magnitude distribution for the left CA in global range - video
WSS magnitude distribution for the left CA in range up to 0.4 Pa -video
Visualization of the WSS magnitude distribution (diastolic pressure) a) Left CA in global range b) Left CA in range up to 0.4 Pa c) Right CA in global range d) Right CA in range up to 0.4 Pa.
Computed WSS magnitude at points 1 (left CA) and 2 (right CA)
Wall shear stress (WSS) vector magnitude

\[ |WSS| = |\tau_{ij} \cdot n_i| \]

- \( n_i \) is surface vector normal
- \( \tau_{ij} \) is viscous stress tensor

Time-averaged magnitude of the WSS vector (TAWSS)

\[ TAWSS = \frac{1}{T} \int_0^T |WSS| dt \]

- \( T \) is period of the cardiac cycle

Oscillatory shear index (OSI)

\[ OSI = \frac{1}{2} \left( 1 - \frac{\int_0^T WSS dt}{\int_0^T |WSS| dt} \right) \]
a) TAWSS distribution for the left CA in range up to 0.4 Pa b) OSI for the left CA in global range c) TAWSS distribution for the right CA in range up to 0.4 Pa d) OSI for the right CA in global range

Last solved period of cardiac cycle
Conclusions:

- Three-dimensional patient specific computational models of blood hemodynamic in the human carotid arteries were created.
- Computed results are in good agreement with physiological data published in the literature and the model is capable to predict correctly velocity profiles, WSS magnitude, TAWSS and OSI.
- Locations of low WSS magnitude and TAWSS (<0.4 Pa) and OSI near to 0.5 correspond well to locations where the atheroma began to form.
- Although the process of atheroma formation is generally more complicated and need future research, the developed model may be helpful in guiding future therapeutic strategies.
Acknowledgement:

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Thank you for your attention.