CPM Specifications Document Coronary Arterial Disease (LCX):

OSMSC 0158_0000 0164_0000 0165_0000

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Version 1

Open Source Medical Software Corporation

1. Clinical Significance & Condition

Coronary heart disease (CHD), also known as coronary artery disease is the leading cause of death in the U.S., causing about 25% of total deaths in the U.S [1, 2]. Coronary artery stenosis and occlusion is caused by plague build up, often fatty materials resulting in atherosclerosis, in the arteries supplying blood to heart muscle resulting in ischemia. Coronary Artery aneurysms are also caused by atherosclerosis or other disease; however coronary artery aneurysms are less common with incidence varying from 1.5-5% [3]. The most common sites for coronary aneurysms, in order of highest to lowest frequency are the: (1) proximal Left anterior descending artery (LAD) and right coronary artery (RCA), (2) left main coronary artery (LMCA), (3) left circumflex artery (LCX), (4) and lastly the junction between the RCA and right posterior descending artery (RPD) [4]. Understanding blood flow may serve as the basis for understanding coronary artery disease and aneurysm formation and considering therapeutic options.

2. Clinical Data

Patient-specific volumetric image data was obtained to create physiological models and blood flow simulations. All scans are for the same patient. The data for 0158_0000 is CT and was taken preoperatively. Data for 0164_0000 and 165_0000 is Optical-CT (OCT), a series of individual 2D images, and was taken postoperatively. Data for 0164_000 was taken immediately post-stent and data for 0165_0000 was taken 6 months after stent implantation. Details of the imaging data used can be seen in Table 1. Note that there is no volumetric information for the OCT in Table 1. See Appendix 1 for details on image data orientation.

Table 1 – Patient-specific volumetric image data details (mm). Voxel Spacing, voxel dimensions, and physical dimensions are provided in the Right-Left (R), Anterior-Posterior (A), and Superior-Inferior (S) direction.

OSMSC ID	Surgical State	Modality	Voxel Spacing			Voxel Dimensions			Physical Dimensions		
			R	A	S	R	A	S	R	A	S
0158_0000	Preoperative	CT	0.39	0.39	0.50	512	512	253	199.7	199.68	126.50
0164_0000	Post-Stent	OCT	-	-	-	-	-	-	-	-	-
0165_0000	6 mo. Post-Stent	OCT	-	-	-	-	-	-	-	-	-

Available patient-specific clinical data collected can be seen in **Error! Not a valid bookmark self-reference.**. The date that the data was collected is unknown. Clinical data shown below was used for preoperative and postoperative models.

Table 2 – Available patient-specific clinical data

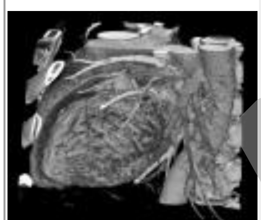
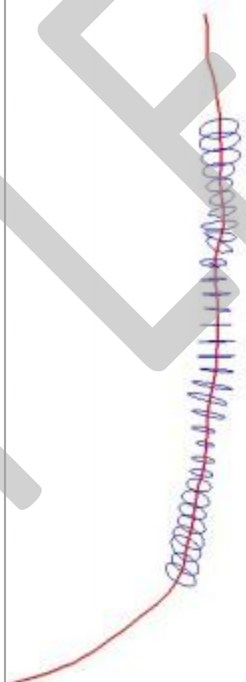
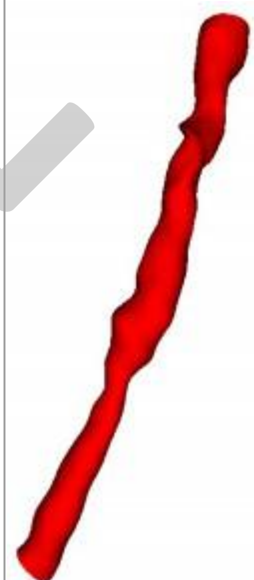
OSMSC ID	Age	Gender	Height (m)	Weight (kg)	Cardiac Output (L/min	Heart Rate	Diastolic Pressure (mmHg)	Systolic Pressure (mmHg)
0158, 0164, 0165	65	M	1.63	49.3	4.21	82	68	131

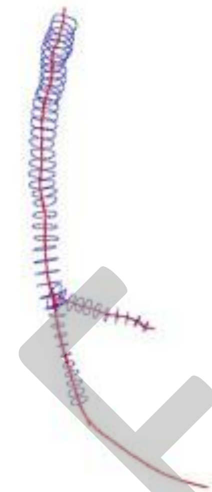
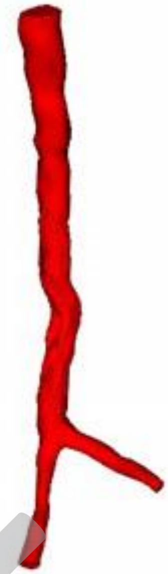
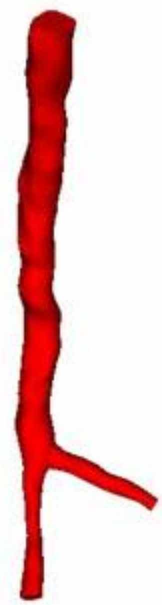
3. Anatomic Model Description

Anatomic models were created using customized SimVascular software (Simtk.org) and the image data described in Section 2. Models include the left coronary circumflex (LCX). Models 0164 and 0165 also include the second obtuse marginal artery (OM2) and distal LCX (dLCX). See

Table 3 for a visual summary of the image data, paths, segmentations and solid model constructed.

Table 3 – Visual summary of image data, paths, segmentations and solid model.

OSMSC ID	Image Data	Paths	Paths and Segmentations	Model
ID: OSMSC0158 subID: 0000 Preoperative Age: 65 Gender: M				

ID: OSMSC0164 Post-stent subID: 0000 Age: 65 Gender: M				
ID: OSMSC0165 6 mo. post-stent subID: 0000 Age: 65 Gender: M				

Details of anatomic models, such has number of outlets and model volume, can be seen in Table 4.

Table 4 – Anatomic Model details

OSMSC ID	Inlets	Outlets	Volume (cm^3)	Surface Area (cm^2)	Vessel Paths	2-D Segmentations
0158_0000	1	1	0.0808	1.912	1	33
0164_0000	1	2	0.1721	3.9025	4	53
0165_0000	1	2	0.1981	3.5293	4	-1

4. Physiological Model Description

In addition to the clinical data gathered for this model, several physiological assumptions were made in preparation for running the simulation. See Appendix 3 for details.

5. Simulation Parameters & Details

5. 1 Simulation Parameters

See Appendix 4 for information on the physiology and simulation specifications. See Table 5 for solver Parameters.

Table 5- Solver Parameters

OSMSC ID	Time Steps per Cycle	Time Stepping Strategy
0158_0000	1000	residual_control 1 min_iter 3 max_iter 4 criteria 0.01
0164_0000	1000	residual_control 1 min_iter 3 max_iter 4 criteria 0.01
0165_0000	1000	residual_control 1 min_iter 3 max_iter 4 criteria 0.01

5. 2 Inlet Boundary Conditions

A canine pulsatile blood flow waveform contour obtained from the left anterior descending coronary artery was scaled and prescribed to the LCX inlet of the models [5]. The flow to the LCX was determined assuming that the coronary arteries receive 5% of the flow and the left coronaries receive 84% of the total coronary flow. It was then assumed that the LCX received 33% of the flow that goes to the left coronaries. See Table 6 for the period and prescribed cardiac output for each simulation. Prescribed inflow waveforms for each simulation are shown in Figure 1.

Table 6 – Period and Cardiac Output from waveforms seen in Figure 1

OSMSC ID	Period (s)	Cardiac Output (L/min)	Profile Type
0158, 0164, 0165	0.731	4.21	Womersley

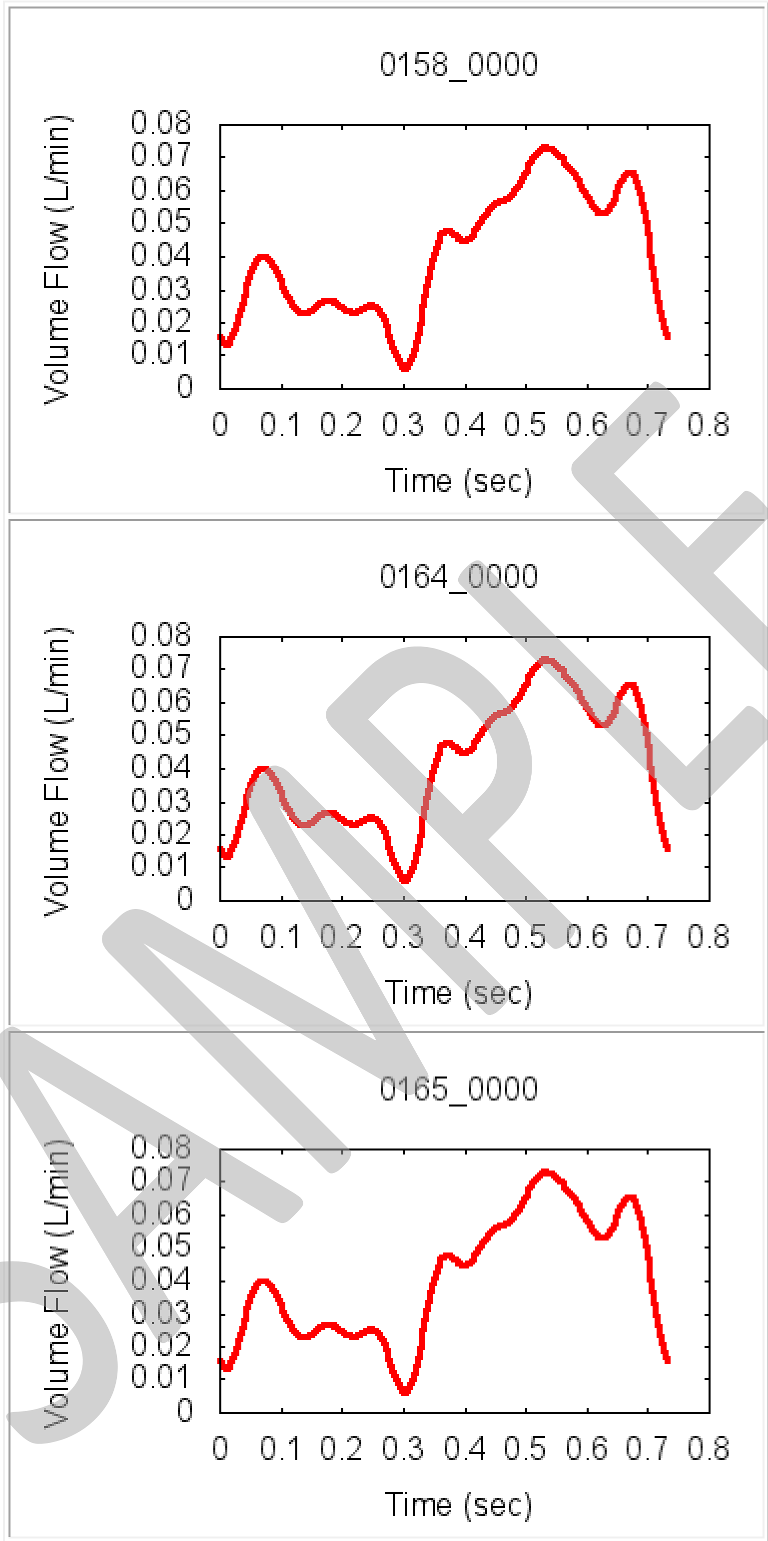


Figure 1 – Inflow waveforms in L/min

5. 3 Outlet Boundary Conditions

A three element Windkessel model was applied at the aorta outlet for each model. For more information refer on RCR parameters to Exhibit 1 and Appendix 5. To define the parameters in the Windkessel model the mean flow to each outlet was calculated. For 0164 and 0165 flow split to the dLCX and OM2 were calculated assuming that wall shear stress was the same for both outlet arteries. For more information you may refer to the publication featuring these models [5]. Flow distributions are shown in Table 7.

Table 7 – Flow distributions

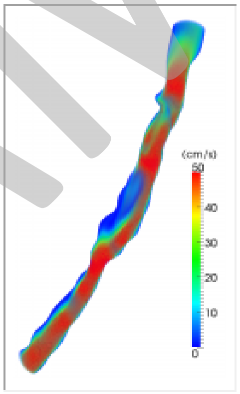
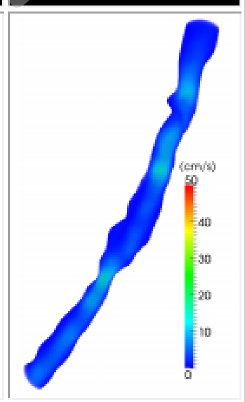
OSMSC ID	dLCX Flow	OM2 Flow
0158_0000	-	-
0164_0000	0.46	0.54
0165_0000	0.46	0.54

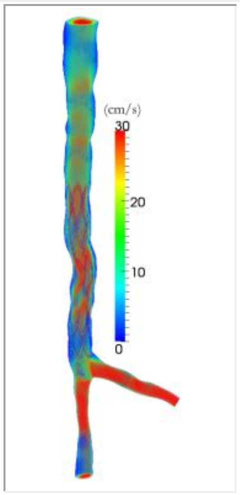
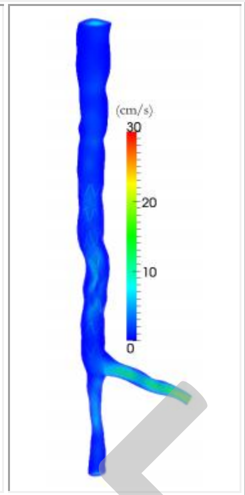
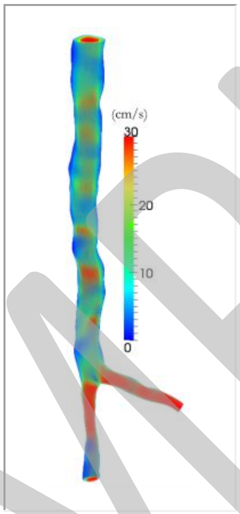
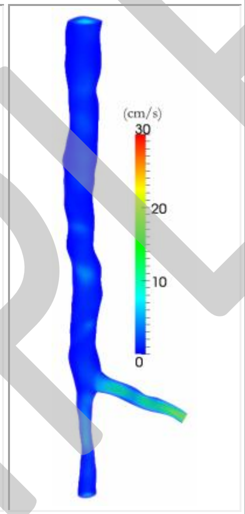
6. Simulation Results

Simulation results were quantified for the last cardiac cycle. Paraview (Kitware, Clifton Park, NY), an open-source scientific visualization application, was used to visualize the results. A volume rendering of velocity magnitude for two time points during the cardiac cycle can be seen in

Table 8 for each model.

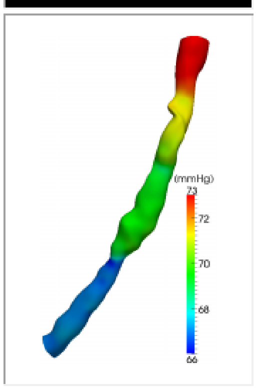
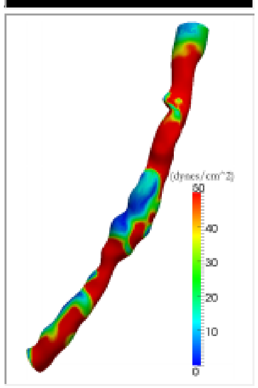
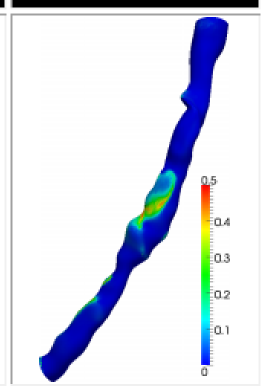
Table 8 – Volume rendering velocity at the point of maximum and minimum volumetric flow. All renderings have the scale below with units of cm/s

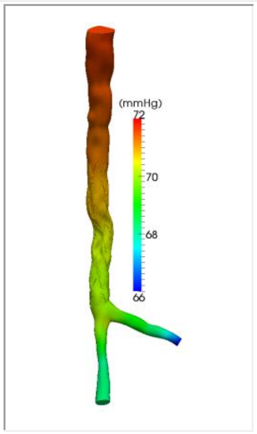
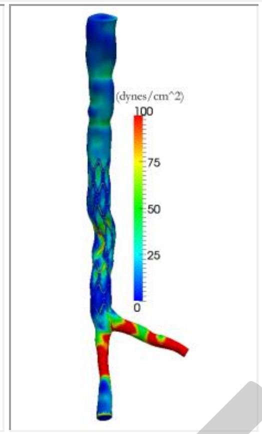
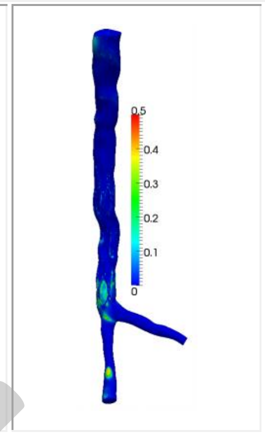
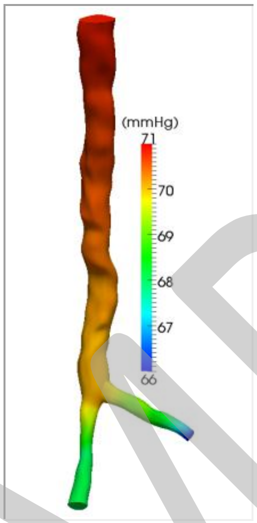
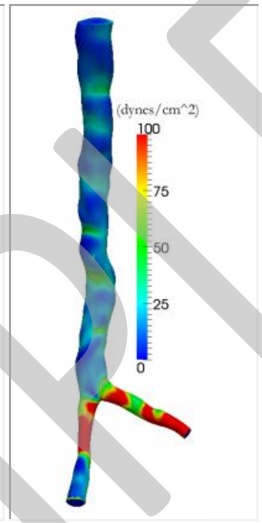
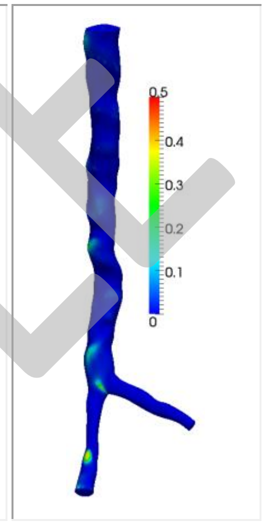
OSMSC ID	Sim High	Sim Low
ID: OSMSC0158 subID: 0000 Age: 65 Gender: M		

ID: OSMSC0164 subID: 0000 Age: 65 Gender: M		
ID: OSMSC0165 subID: 0000 Age: 65 Gender: M		

Surface distribution of time-averaged blood pressure (TABP), time-averaged wall shear stress (TAWSS) and oscillatory shear index (OSI) were also visualized and can be seen in Table 9.

Table 9 – Time averaged blood pressure (TABP), time-average wall shear stress (TAWSS), and oscillatory shear index (OSI) surface distributions

OSMSC ID	TABP	TAWSS	OSI
ID: OSMSC0158 subID: 0000 Age: 65 Gender: M			

ID: OSMSC0164 subID: 0000 Age: 65 Gender: M			
ID: OSMSC0165 subID: 0000 Age: 65 Gender: M			

7. References

[1] American Heart Association, "Coronary Artery Disease -The ABCs of CAD," 14 February 2012. [Online]. Available: http://www.heart.org/HEARTORG/Conditions/More/MyHeartandStrokeNews/Coronary-Artery-Disease---The-ABCs-of-CAD_UCM_436416_Article.jsp#.T3yHFat8B8E. [Accessed 4 April 2012].

[2] Centers for Disease Control and Prevention, "Healthy, United States, 2010: With Special Feature of Death and Dying," U.S Government Printing Office, Washington, DC, 2011.

[3] M. Syed and M. Lesch, "Coronary artery aneurysm: a review," *Prog Cardiovasc,* vol. 40, no. 1, pp. 77-84, 1997.

[4] J. W. Newburger, "Diagnosis, Treatment, and Long-Term Management of Kawasaki Disease: A Statement for Health Professionals From the Committee on Rheumatic Fever, Endocarditis and Kawasaki Disease, Council on Cardiovascular Disease in the Young, American Heart Association," *Circulaton,* vol. 110, pp. 2747-2771, 2004.

[5] L. M. Ellwein, H. Otake, T. J. Gundert, B.-K. Koo, T. Shinke, Y. Honda, J. Shite and J. F. LaDisa JR, "Optical Coherence Tomography for Patient-specific 3D Artery Reconstruction and Evaluation of Wall shear Stress in a Left Circumflex Coronary Artery," *Cardiovascular Engineering and Technology,* pp. 212-227, 2011.

Exhibit 1: Coronary Simulations Boundary Conditions

Information on how RCR values were obtained is included in Appendix 5. RCR values for the final simulations are shown in the tables that follow.

Table 10 – RCR Values for 0158_0000 in cgs

OSMSC ID	Solver ID	Face Name	Rp	C	Rd
0158_0000	2	outflow	24301	1.08E-06	107056

Table 11 – RCR values for 0164_0000 in cgs

OSMSC ID	Solver ID	Face Name	Rp	C	Rd
0164_0000	3	lcx	30279	4.7E-07	272511
0164_0000	2	om2	44082	6.1E-07	187927

Table 12 – RCR values for 0165_0000 in cgs

OSMSC ID	Solver ID	Face Name	Rp	C	Rd
0165_0000	3	lcx	30279	4.7E-07	272511
0165_0000	2	OM2	44082	6.1E-07	187927

Appendix

1. Image Data Orientation

The RAS coordinate system was assumed for the image data orientation. Voxel Spacing, voxel dimensions, and physical dimensions are provided in the Right-Left (R), Anterior-Posterior (A), and Superior-Inferior (S) direction in all specification documents unless otherwise specified.

2. Model Construction

All anatomic models were constructed in RAS Space. The models are generated by selecting centerline paths along the vessels, creating 2D segmentations along each of these paths, and then lofting the segmentations together to create a solid model. A separate solid model was created for each vessel and Boolean addition was used to generate a single model representing the complete anatomic model. The vessel junctions were then blended to create a smoothed model.

3. Physiological Assumptions

Newtonian fluid behavior is assumed with standard physiological properties. Blood viscosity and density are given below in units used to input directly into the solver.

Blood Viscosity: 0.04 $g/cm \cdot s^2$
Blood Density: 1.06 g/cm^3

4. Simulation Parameters

Conservation of mass and Navier-Stokes equations were solved using 3D finite element methods assuming rigid and non-slip walls. All simulations were ran in cgs units and ran for several cardiac cycles to allow the flow rate and pressure fields to stabilize.

5. Outlet Boundary Conditions

5.1 Resistance Methods

Resistances values can be applied to the outlets to direct flow and pressure gradients. Total resistance for the model is calculated using relationships of the flow and pressure of the model. Total resistance is than distributed amongst the outlets using an inverse relationship of outlet area and the assumption that the outlets act in parallel.

5.2 Windkessel Model

In order to represent the effects of vessels distal to the CFD model, a three-element Windkessel model can be applied at each outlet. This model consists of proximal resistance (R_p), capacitance (C), and distal resistance (R_d) representing the resistance of the proximal vessels, the capacitance of the proximal vessels, and the resistance of the distal vessels downstream of each outlet, respectively (Figure 1).

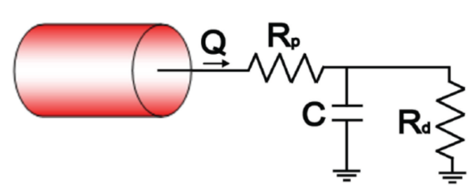


Figure 2 - Windkessel model

First, total arterial capacitance (TAC) was calculated using inflow and blood pressure. The TAC was then distributed among the outlets based on the blood flow distributions. Next, total resistance (R_t) was calculated for each outlet using mean blood pressure and PC-MRI or calculated target flow ($R_t = P_{mean}/Q_{desired}$). Given that $R_t = R_p + R_d$, total resistance was distributed between R_p and R_d adjusting the R_p to R_t ratio for each outlet.

