CPM Specifications Document Healthy Pulmonary:

OSMSC 0005_0000

May 1, 2013

Version 1

Open Source Medical Software Corporation

1. Clinical Significance & Condition

Pulmonary arteries connect blood flow from the heart to the lungs in order to oxygenate blood before being pumped through the body. The main pulmonary artery (MPA) starts at the right ventricle of the heart and divides into the left (LPA) and right pulmonary arteries (RPA), which branch out into the lungs. The main pulmonary artery in healthy subjects has an average diameter of 2.72 cm. Anatomical differences in MPA diameter have also been documented between genders, with a mean MPA diameter of 2.77 cm for males and 2.64 cm for females [1].

Examples of complications seen in the pulmonary arteries include pulmonary hypertension and pulmonary embolisms. Pulmonary arterial hypertension (PAH) is a chronic disease that occurs when the blood vessels between the heart and lungs narrow and harden, increasing the pressure in the pulmonary arteries [2]. The increased resistance makes it difficult for the heart to pump blood to the lungs, adding strain to and weakening the right ventricle. PAH is a serious condition, with a median survival of less than 3 years if left untreated [3],causing over 15,000 deaths and 260,000 hospital visits in the United States in 2002 [4].

Significant vascular remodeling is observed in PAH patients, with larger proximal pulmonary arteries and more convoluted branches when compared to healthy patients (Figure 1). In a study examining three-dimensional hemodynamics of the pulmonary arteries, PAH patients were found to have an average main pulmonary diameter of 3.5 ± 0.5 cm, where healthy patients had an average of 2.7 ± 0.1 cm [3].

A pulmonary embolism is another condition seen the pulmonary arteries, involving one or more arteries being blocked by a blood clot. The blood clots typically originate elsewhere in the body and travel to the pulmonary arteries. The effects of a pulmonary embolism can be quiet severe, with the first sign being sudden death in 25% of pulmonary embolism cases [5]. However, prompt application of anti-clogging medication can help avoid mortality and further complications [6].

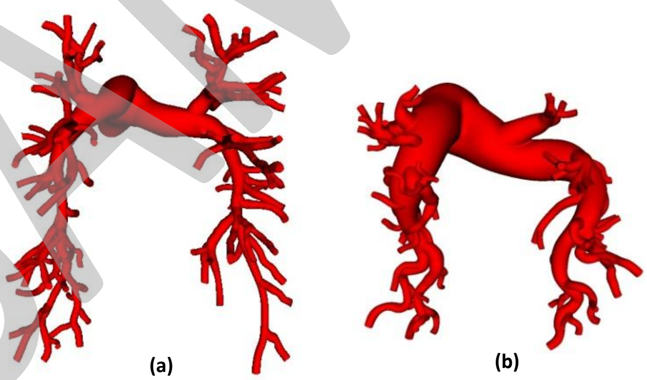


Figure 1 (a) Healthy pulmonary arteries, (b) PAH pulmonary arteries

2. Clinical Data

Patient-specific volumetric image data was obtained to create physiological models and blood flow simulations. Details of the imaging data used can be seen in Table 1. See Appendix 1 for details on image data orientation.

Table 1 – Patient-specific volumetric image data details (mm)

OSMSC ID	Modality	Voxel Spacing			Voxel Dimensions			Physical Dimensions		
		R	A	S	R	A	S	R	A	S
0005_1000	CT	0.5859	0.5859	1.25	512	512	198	300	300	247.5

Available patient-specific clinical data collected can be seen in Table 2.

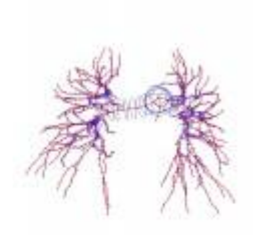
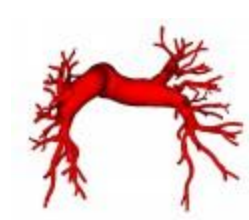
Table 2 – Available patient-specific clinical data

OSMSC ID	Age	Gender
0005_1000	67	F

3. Anatomic Model Description

Anatomic models were created using customized SimVascular software (Simtk.org) and the image data described in Section 2. The models extend from the main pulmonary artery to various levels of branching in the left and right pulmonary arteries. See Appendix 2 for a description of modeling methods. 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: OSMSC0005 subID: 1000 Age: 67 Gender: F				

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
0005_1000	1	100	89.08	345.13	101	591

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. Solver parameters can be seen in Table 5.

Table 5 – Solver Parameters

OSMSC ID	Time Steps Per Cycle	Time Stepping Strategy
0005_1000	1000	Fixed step – 3

5. 2 Inlet Boundary Conditions

The inflow waveform was adapted from Cheng et al. to be an average resting pulmonary artery flow waveform for healthy subjects [7] (Figure 2). See Table 6 for the inflow details.

Table 6 – Inflow details from waveforms seen in Figure 2

OSMSC ID	Period (second)	Mean Flow (L/min)	Profile Type
0005_1000	1.0	4.9799	Plug

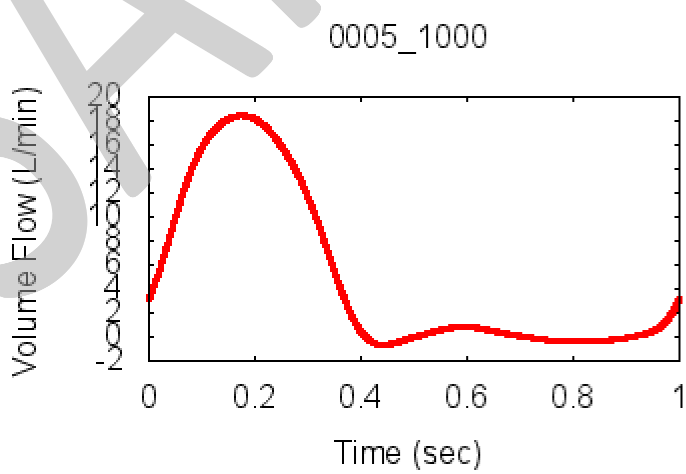


Figure 2 – Inflow waveforms in L/min

5. 3 Outlet Boundary Conditions

Resistance values for exercise conditions were assigned at each outlet, calculated using the outlet area, LPA/RPA flow split, and pulmonary pressures (Table 7). See Exhibit 1 for the applied resistance values.

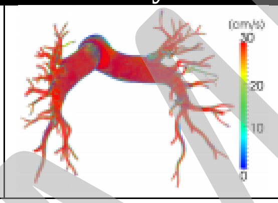
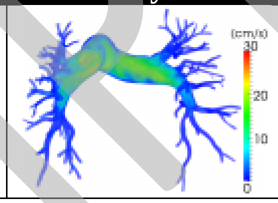
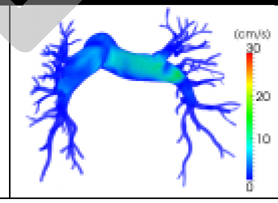
Table 7 – Flow distributions

OSMSC ID	LPA	RPA	Psys (mmHg)	Pdia (mmHg)
0005_1000	45%	55%	24	12

6. Simulation Results

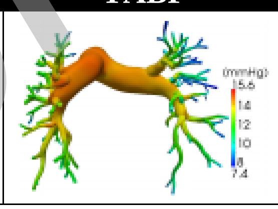
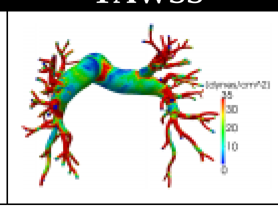
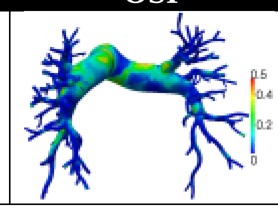
Simulation results were quantified for the last cardiac cycle. Paraview (Kitware, Clifton Park, NY), an open-source scientific visualization application, was used to visualize the results. A volume rendering of velocity magnitude for three time points during the cardiac cycle can be seen in Table 9 for each model.

Table 8 – Volume rendering velocity during peak systole, end systole and end diastole.

OSMSC ID	Peak Systole	End Systole	End Diastole
ID: OSMSC0005 subID: 1000 Age: 67 Gender: F			

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: OSMSC0005 subID: 1000 Age: 67 Gender: F			

7. References

[1] P. D. Edwards, R. K. Bull and R. Coulden, "CT measurement of main pulmonary artery diameter," *The British Institue of Radiology,* vol. 71, pp. 1018-1020, 1998.

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[3] B. Tang, *Quantification of Three-Dimensionsal Hemodynamic Conditions in the Human Abdominal Aorta and Pulmonary Arteries with Application to Shear-Mediated Gene Transcription in Endothelial Cell Culture,* PhD Dissertation, Department of Mechanical Engineering, Stanford University, Stanford, CA, USA, June 2007.

[4] A. Hyduk, J. B. Croft, C. Ayala, K. Zheng, Z.-J. Zheng and G. A. Mensah, "Pulmonary Hypertension Surveillance: United States, 1980-2002," *Morbidity and Mortality Weekly Report ,* vol. 54, no. SS05, pp. 1-28, 2005.

[5] Ceneters for Disease Control and Prevention, "Deep Vein Thrombosis/Pulmonary Emoblism: Data & Statistics," 21 September 2011. [Online]. Available: http://www.cdc.gov/ncbddd/dvt/data.html. [Accessed 24 January 2012].

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[7] C. Cheng, R. Herfkens, C. Taylor and J. Feinstein, "Proximal pulmonary artery blood flow characteristics in healthy subjects measured in an upright posture using MRI: the effects of exercise and age," *Journal of Magnetic Resonance Imaging,* vol. 21, pp. 752-758, 2005.

Exhibit 1: Simulation Resistance Values

Table 10 – Resistance Values and Pressure Offset in cgs and mmHg

ID	Face Name	Rp	Po
2	LPA_01	6497	7.0
3	LPA_02	7928	7.0
4	LPA_03	4464	7.0
5	LPA_04	3077	7.0
6	LPA_05	3212	7.0
7	LPA_06	4881	7.0
8	LPA_07	4269	7.0
9	LPA_08	7308	7.0
10	LPA_09	19617	7.0
11	LPA_10	19659	7.0
12	LPA_11	10766	7.0
13	LPA_12	6613	7.0
14	LPA_13	4644	7.0
15	LPA_14	10547	7.0
16	LPA_15	4457	7.0
17	LPA_16	5619	7.0
18	LPA_17	4610	7.0
19	LPA_18	3185	7.0
20	LPA_19	6001	7.0
21	LPA_20	11025	7.0
22	LPA_21	5822	7.0
23	LPA_22	23520	7.0
24	LPA_23	16702	7.0
25	LPA_24	6290	7.0
26	LPA_25	6555	7.0
27	LPA_26	6514	7.0
28	LPA_27	16772	7.0
29	LPA_28	5319	7.0
30	LPA_29	8165	7.0
31	LPA_30	4732	7.0
32	LPA_31	12513	7.0
33	LPA_32	25928	7.0
34	LPA_33	19974	7.0
35	LPA_34	4068	7.0
36	LPA_35	14136	7.0
37	LPA_36	16784	7.0
38	LPA_37	22804	7.0
39	LPA_38	32221	7.0
40	LPA_39	8985	7.0
41	LPA_40	8331	7.0
42	LPA_41	15158	7.0
43	LPA_42	11098	7.0
44	LPA_43	10223	7.0
45	LPA_44	20256	7.0
46	LPA_45	12810	7.0
47	LPA_46	3848	7.0
48	LPA_47	14875	7.0
49	LPA_48	23634	7.0
50	LPA_49	11613	7.0
51	LPA_50	7508	7.0

ID	Face Name	Rp	Po
52	RPA_01	2293	7.0
53	RPA_02	2083	7.0
54	RPA_03	1634	7.0
55	RPA_04	2902	7.0
56	RPA_05	2323	7.0
57	RPA_06	2251	7.0
58	RPA_07	4353	7.0
59	RPA_08	2140	7.0
60	RPA_09	1401	7.0
61	RPA_10	5024	7.0
62	RPA_11	4448	7.0
63	RPA_12	5694	7.0
64	RPA_13	4412	7.0
65	RPA_14	2961	7.0
66	RPA_15	3408	7.0
67	RPA_16	2031	7.0
68	RPA_17	3880	7.0
69	RPA_18	3968	7.0
70	RPA_19	5431	7.0
71	RPA_20	6890	7.0
72	RPA_21	903	7.0
73	RPA_22	3674	7.0
74	RPA_23	3652	7.0
75	RPA_24	3772	7.0
76	RPA_25	5057	7.0
77	RPA_26	6152	7.0
78	RPA_27	1945	7.0
79	RPA_28	2498	7.0
80	RPA_29	3278	7.0
81	RPA_30	2099	7.0
82	RPA_31	3847	7.0
83	RPA_32	2309	7.0
84	RPA_33	2675	7.0
85	RPA_34	5205	7.0
86	RPA_35	3563	7.0
87	RPA_36	3317	7.0
88	RPA_37	8632	7.0
89	RPA_38	5687	7.0
90	RPA_39	2881	7.0
91	RPA_40	1650	7.0
92	RPA_41	5483	7.0
93	RPA_42	4274	7.0
94	RPA_43	3504	7.0
95	RPA_45	10829	7.0
96	RPA_46	9936	7.0
97	RPA_47	4558	7.0
98	RPA_48	2059	7.0
99	RPA_49	3717	7.0
100	RPA_50	14629	7.0
101	RPA_51	1662	7.0

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).

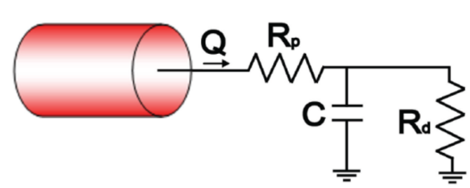

Figure 3 - Windkessel model

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.

