STUDY OF CARDIOVASCULAR HEMODYNAMICS USING VASCULARSIM

Aim:

To understand the fundamentals of hemodynamics using a lumped parameter model of the cardiovascular system

Objectives:

- Observe the change in Cardiac Output with respect to change in Heart Rate.
- Observe the change in Cardiac Output and Venous Return with respect to change in Peripheral Resistance (Hand grip).
- Compute Pulse Wave Velocity in the arterial tree

Materials Required:

VascularSim Software, Tool for plotting (MATLAB).

Theory:

The cardiovascular system has lent itself for modelling due to our understanding of the hydraulics principles on which it is based (Davis, 1991) . VascularSim, a software being developed by TouchLab at IITM aims to use a model of the cardiovascular system to teach the concepts of hemodynamics with a visual tool. A simpler version of the model is shown in Figure 1, for a more intuitive understanding of the theory.

Closed loop model –

The cardiovascular system can be divided in to the following major regions – the right heart, the pulmonary circulation, the left heart and the systemic circulation. Figure 1 shows a simple electrical analogue of these regions. The arteries and the veins in the systemic and pulmonary circulations are represented by capacitances. Similarly, the heart chambers are also represented by capacitors, however these are time varying to emulate the contraction and relaxation. The flow resistance offered by the blood vessels

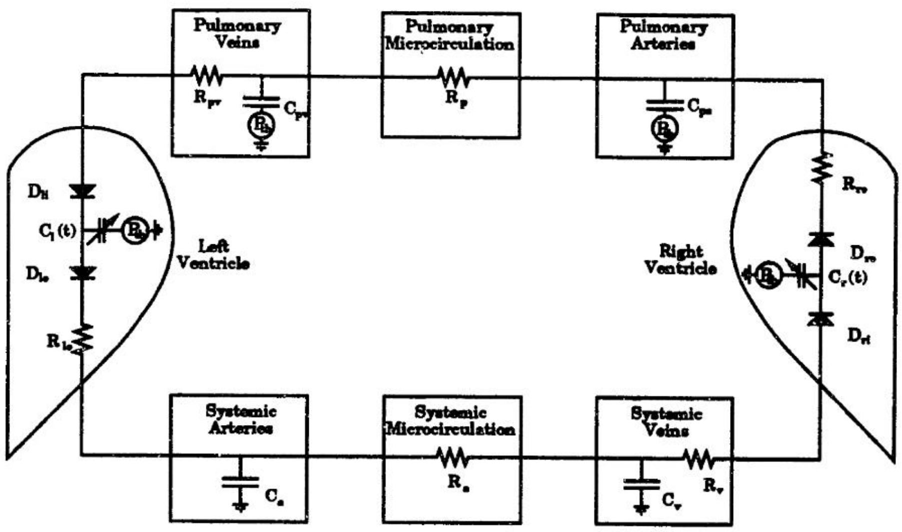


Figure 1

Electric Analogue of a simplified Cardiovascular model

(taken from *Davis, T. L. (1991). Teaching physiology through interactive simulation of hemodynamics*) (arteries, veins, arterioles, venules, capillaries) are modelled as electrical resistance. Finally, the valves are modelled as diodes.

The pressure across each 'capacitance' and the flow through each 'resistance' can be computed by getting state equations using the Kirchoff's laws. The differential equations are then numerically solved using a Runge Kutta Variable step method. Using these computed values, other parameters of the hemodynamics can also be derived.

Stroke Volume (SV, mL/beat) = Total volume of blood ejected from the left heart in one beat.

Cardiac Output (CO, mL/min) = Total volume of blood ejected from left heart in one minute

$$= SV \times HR$$

Venous Return (VR, mL/min) = Total volume of blood entering the right heart in one minute

Typically, since the cardiovascular system is closed-loop, the VR will be equal to CO, at most delayed by a few beats. The stroke volume can be computed by integrating the left ventricular outflow over a single beat. Since the heart rate is known, the Cardiac Output can be computed for that beat. Similarly, the Venous Return can also be computed.

Arterial tree model –

While the previous model looks at the full circulation, the arterial tree model looks in detail at the arteries alone. The entire arterial tree is divided into 128 segments, each represented by an RLC circuit. The R and C components have the same role as before, while the 'L', called the inertance plays the role of the inertia of the blood already present in the blood vessel. This model is an open loop where the pressure in the following vessels (capillaries and veins) is assumed to be negligible.

As the heart beats, a pulse travels through the walls of the arteries. Due to the impedance to the blood flow, as delay begins to accumulate, distal to the heart. This delay can be seen in the systolic peak getting shifted. Since the approximate distance from the heart is known and the delay can be measured, pulse wave velocity can be measured.

PWV = distance from heart/shift in systolic peak

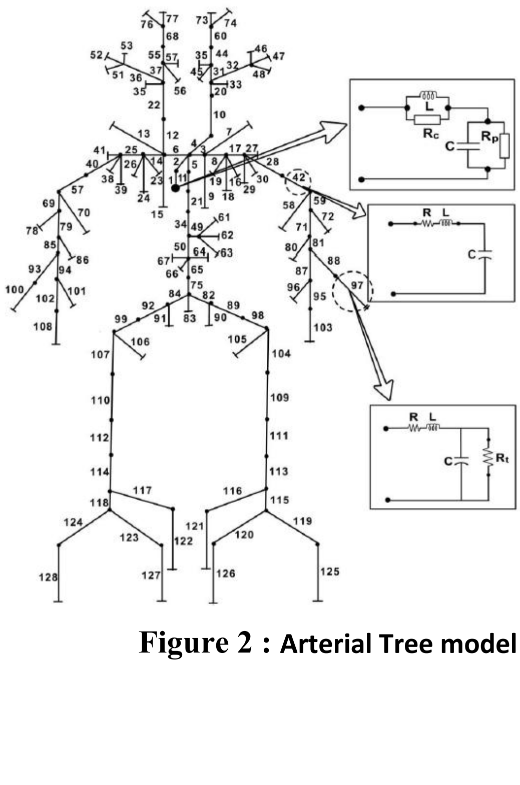


Figure 2 : Arterial Tree model

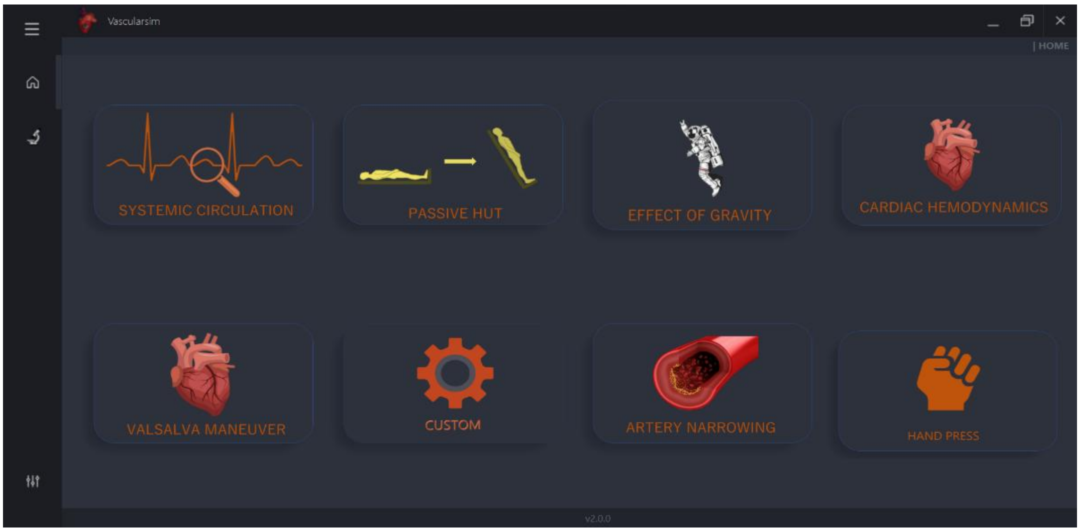


Figure 3 : VascularSim GUI

Procedure:

- Load the VascularSim GUI, go to Cardiac Hemodynamics
- Press start to begin running the model and change the graph as required. The graph can be paused to note down the observations.
- Compute the CO and VR as described above.
- Change the HR and repeat for various values of HR (60 - 200).
- Load the GUI again, Go to Hand Press.
- Change the Peripheral resistance and compute the CO and VR as above.
- Load the GUI again, Go to systemic circulation.
- Press start to begin running the model.
- Pause the model after enough pulses have been simulated and note the time at which the peak occurs in each segment.
- Compute the pulse wave velocity using a reference provided in the appendix.

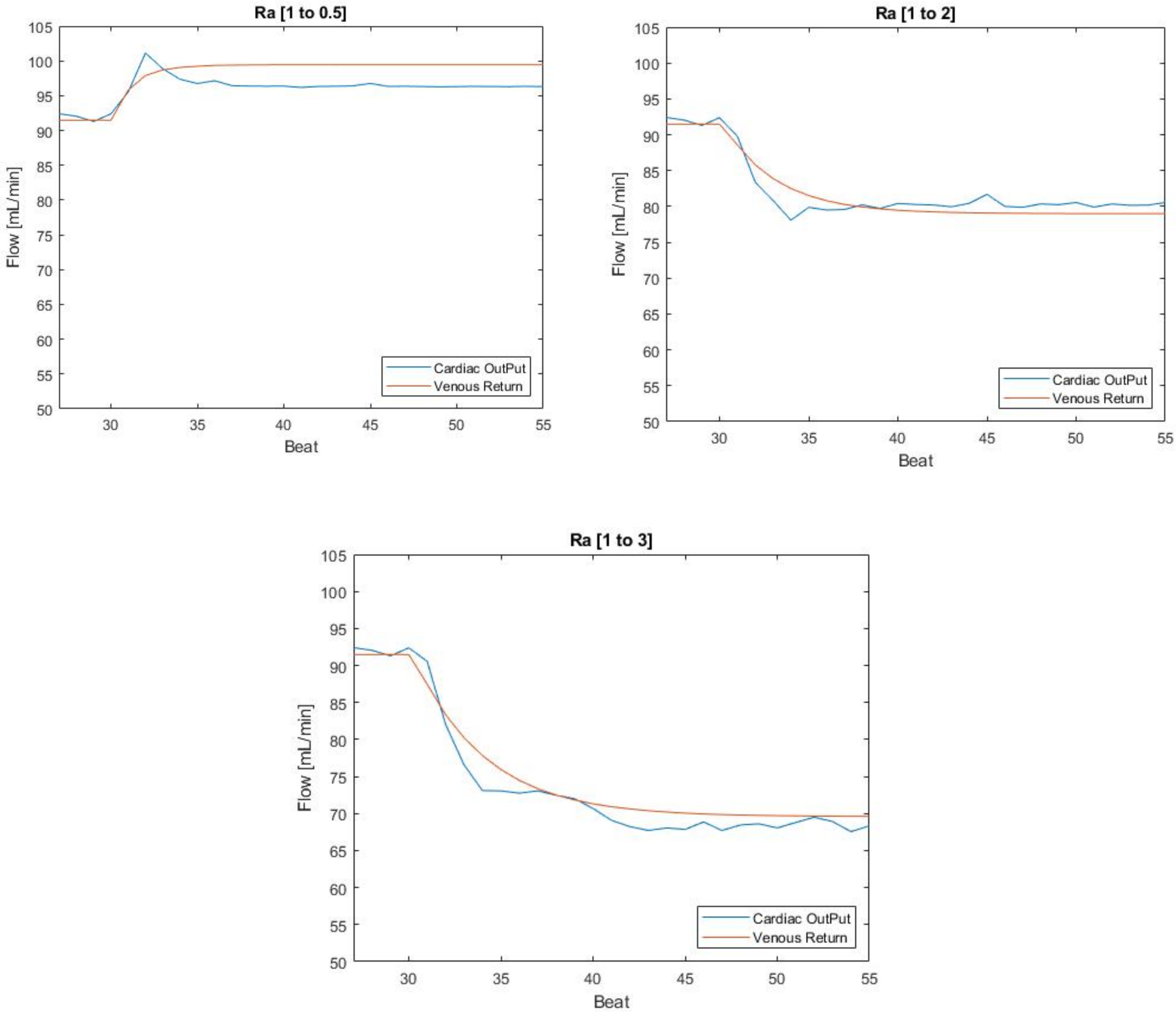
Observations:

Varying HR

Sr No	HR [beat/min]	CO [mL/min]	VR [mL/min]
1	72	5676	5651
2	100	5656	5650
3	120	5238	5325
4	150	4495	4612
5	180	2597	2571

Varying Ra

Sr No	Ra	CO [mL/min]	VR [mL/min]
1	1	5676	5651
2	0.5	6169	6169
3	2	4886	4847



(a) (b)

(c)

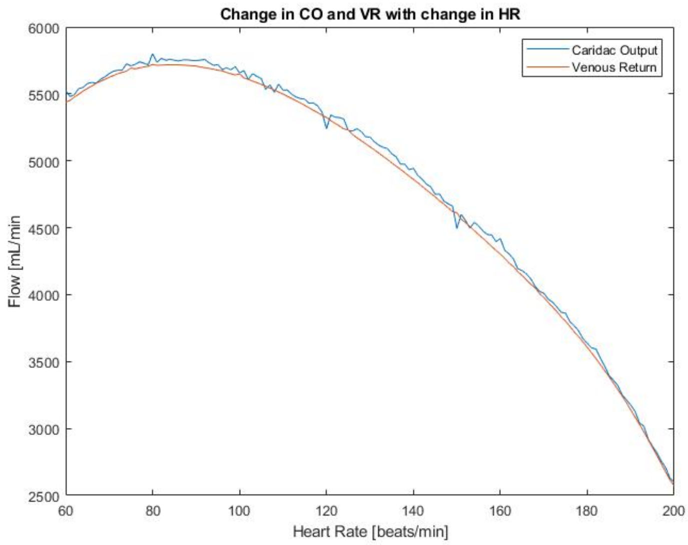
Figure 4

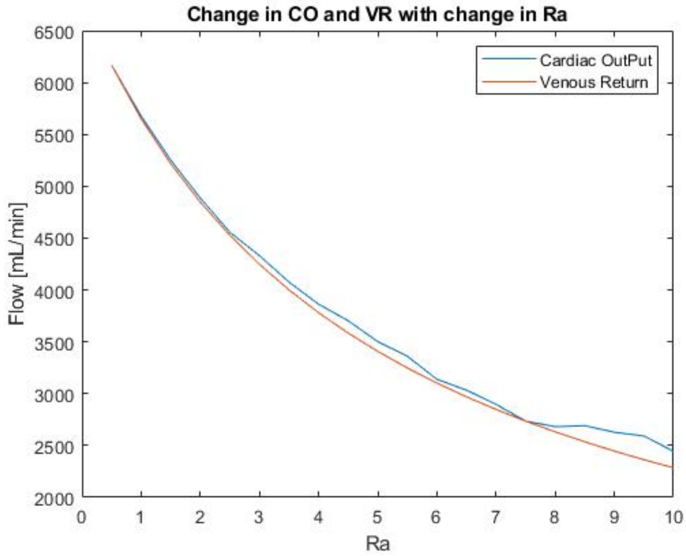
Transient Response of CO and VR after sudden change in Ra. (a) change of Ra from 1 to 0.5. (b) change of Ra from 1 to 2. (c) change of Ra from 1 to 3

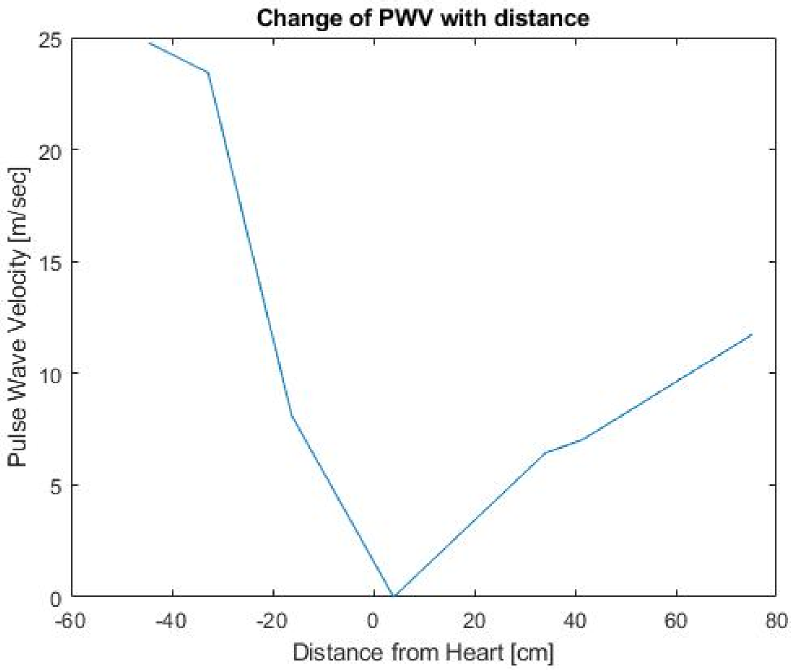
Pulse Wave velocity

Artery	Distance from heart	Peak Shift	PWV
Cerebral Artery	44.6	11.024	24.778
Carotid Artery	32.8	11.02	23.429
Subclavian Artery	16.2	11.026	8.1
Ascending Aorta	4	11.006	0
Brachial Artery	34.2	11.059	6.453
Abdominal Artery	41.4	11.065	7.017
Ulnar Artery	75.1	11.07	11.734
Femoral Artery	74.3	11.07	11.609

Results:







Inferences:

- Increase in heart rate reduces the cardiac output and venous return, due to the heart not being able to fully relax and fill with blood.
- Increase in microcirculation resistance (Ra) reduces the cardiac output and venous return, because of the resulting effect in blood flow velocity.
- Sudden changes in Ra, due to vascular restriction or relaxation, causes a transient change in CO and VR. The settling time is proportional to the difference in value between the previous and current Ra.
- Pulse Wave velocity (PWV) increases as distance from the heart increases. However, other factors, such as diameter and stiffness of the artery, also play a role.

		Left	Right	Length L (cm)	Radius R (cm)	Wall thickness (h cm)	$E \times 10^{6}2$ dyn/cm	f_0 (Hz)
Ascending aorta	1			4·0	1·45	0·163	4	34·7
Aortic arch	2			2·0	1·12	0·132	4	16·7
Aortic arch	5			3·9	1·07	0·127	4	36·6
Thoracic aorta	11			5·2	1·00	0·120	4	27·6
Thoracic aorta	21			5·2	0·95	0·116	4	27·8
Thoracic aorta	34			5·2	0·95	0·116	4	27·8
Abdominal aorta	50			5·3	0·87	0·108	4	27·5
Abdominal aorta	65			5·3	0·57	0·080	4	29·3
Abdominal aorta	75			5·3	0·57	0·080	4	29·3
Coeliac artery	49			1·0	0·39	0·064	4	167·8
Gastric artery	61			7·1	0·18	0·045	4	29·2
Splenic artery	62			6·3	0·28	0·054	4	28·9
Hepatic artery	63			6·6	0·22	0·049	4	29·6
Renal artery	64			3·2	0·26	0·053	4	58·4
Superior mesenteric	66			5·9	0·43	0·069	4	28·1
Gastric artery	67			3·2	0·26	0·053	4	58·4
Inferior mesenteric	83			5·0	0·16	0·043	4	42·9
Common carotid (L)	4			8·9	0·37	0·063	4	19·2
Common carotid (L)	10			8·9	0·37	0·063	4	19·2
Common carotid (L)	20			3·1	0·37	0·63	4	55·1
Common carotid (R)	12			8·9	0·37	0·063	4	19·2
Common carotid (R)	22			8·9	0·37	0·063	4	19·2
Left subclavian artery	3			3·4	0·42	0·067	4	48·6
Brachiocephalic artery	6			3·4	0·62	0·086	4	45·4
Common iliac		82	84	5·8	0·52	0·076	4	27·3
External iliac		89	92	8·3	0·29	0·055	4	21·3
*Internal iliac		90	91	5·0	0·20	0·040	16	74·1
External iliac		98	99	6·1	0·27	0·053	4	30·1
Femoral artery		104	107	12·7	0·24	0·050	8	21·1
Profundis artery		105	106	12·6	0·23	0·049	16	30·3
Femoral artery		109	110	12·7	0·24	0·050	8	21·1
Popliteal artery		111	112	9·4	0·20	0·047	8	30·2
Popliteal artery		113	114	9·4	0·20	0·050	4	22·0
Anterior tibial artery		115	118	2·5	0·13	0·039	16	181·5
Anterior tibial artery		119	124	15·0	0·10	0·020	16	24·7
Anterior tibial artery		125	128	15·0	0·10	0·020	16	24·7
Posterior tibial artery		116	117	16·1	0·18	0·045	16	25·7
Posterior tibial artery		121	122	16·1	0·18	0·045	16	25·7
*Peroneal artery		120	123	15·9	0·13	0·039	16	28·5
*Peroneal artery		126	127	15·9	0·13	0·019	16	28·5
Carotid (internal)		31	37	5·9	0·18	0·045	8	49·6
External carotid		32	36	11·8	0·15	0·042	8	26·3
*Superior thyroid artery		33	35	4·0	0·07	0·020	8	78·3
*Lingual artery		43	56	3·0	0·10	0·030	8	106·9
Internal carotid		44	55	5·9	0·13	0·039	8	54·4
*Facial artery		45	54	4·0	0·10	0·030	16	113·4
*Middle cerebral		46	53	3·0	0·06	0·020	16	159·4
Cerebral artery		47	52	5·9	0·08	0·026	16	80·0
*Opthalmic artery		48	51	3·0	0·07	0·020	16	147·6
Internal carotid		60	68	5·9	0·08	0·026	16	80·0
*Superficial temporal		73	77	4·0	0·06	0·020	16	119·6
*Maxilliary artery		74	76	5·0	0·07	0·020	16	88·6
*Internal mammary		7	15	15·0	0·10	0·030	8	21·4
Subclavian artery		8	14	6·8	0·40	0·066	4	24·7
Vertebral artery		9	13	14·8	0·19	0·045	8	19·2
*Costo-cervical artery		16	26	5·0	0·10	0·030	8	64·2
Axilliary artery		17	25	6·1	0·36	0·062	4	28·2
*Suprascapular		18	24	10·0	0·20	0·052	8	29·9
*Thyrocervical		19	23	5·0	0·10	0·030	8	64·2
*Thoraco-acromial		27	41	3·0	0·15	0·035	16	133·4
Axillary artery		28	40	5·6	0·31	0·057	4	31·7
*Circumflex scapular		29	39	5·0	0·10	0·030	16	90·7
*Subscapular		30	38	8·0	0·15	0·035	16	50·0
Brachial artery		42	57	6·3	0·28	0·055	4	29·1
*Profunda brachi		58	70	15·0	0·15	0·035	8	18·9
Brachial artery		59	69	6·3	0·26	0·053	4	29·7
Brachial artery		71	79	6·3	0·25	0·052	4	29·9
*Superior ulnar collateral		72	78	5·0	0·07	0·020	16	88·6
*Inferior ulnar collateral		80	86	5·0	0·06	0·020	16	95·6
Brachial artery		81	85	4·6	0·24	0·050	4	41·1
Ulnar artery		87	94	6·7	0·21	0·049	8	42·2
Radial artery		88	93	11·7	0·16	0·043	8	25·9
Ulnar artery		95	102	8·5	0·19	0·462	8	33·9
Interossea artery		96	101	7·9	0·09	0·028	16	58·5
Radial artery		97	100	11·7	0·16	0·043	8	25·9
Ulnar artery		103	108	8·5	0·19	0·046	8	33·9

The table contains the lengths of all the arterial segments. (Avolio, 1980)

References:

Avolio, A. P. (1980). Multi-branched model of the human arterial system. *Medical and Biological Engineering and Computing*.

Davis, T. L. (1991). *Teaching physiology through interactive simulation of hemodynamics.* Cambridge: MIT.

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