User Manual:
Mock Circulation Loop Design for Simulating Peripheral Radial Pressure Waveforms for Three Hemodynamic States

Tool Reference

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This document provides detailed instruction on the design of our previously published mock circulation flow loop (MCL) setup (Figure 1) for simulating peripheral (radial) blood pressure waveforms. We recommend that you start with reviewing this study [1].

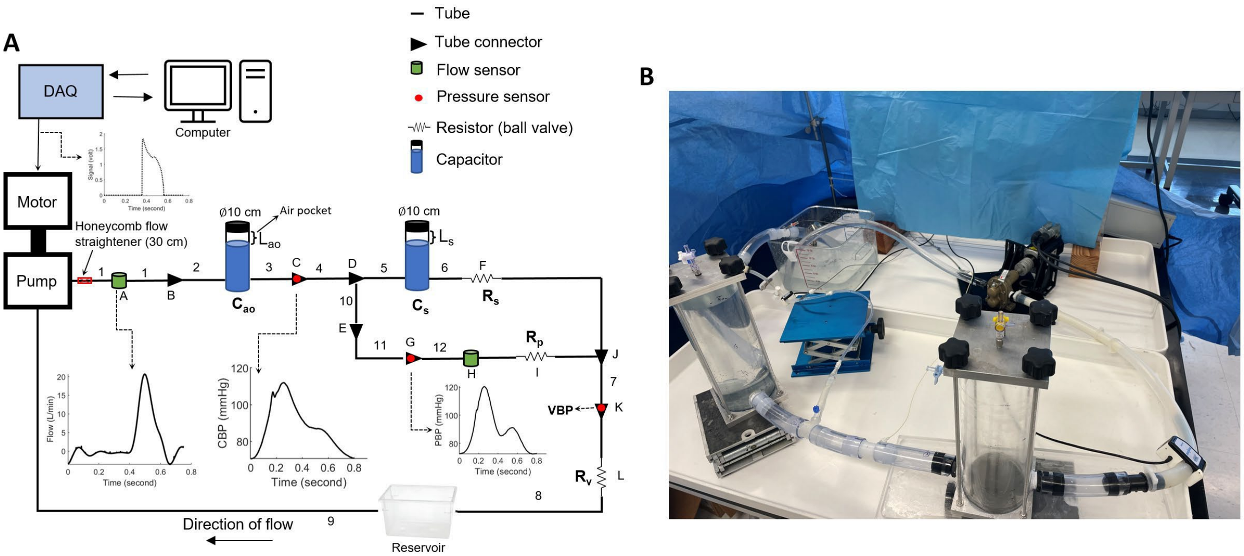


Figure 1. (A) Schematic diagram of the mock circulation loop (MCL). (B) Physical MCL setup. CBP: Central (aortic) blood pressure; PBP: Peripheral (radial) blood pressure; VBP: Venous blood pressure; Rs: Systemic resistance; Rp: peripheral (radial) resistance; Rv: Venous resistance; Cao: Aortic compliance; Cs: Arterial compliance; Lao: Level of air in Cao; Ls: Level of air in Cs; DAQ: Data acquisition hardware.

The MCL consists of physical elements such as high-pressure PVC tubing, flexible silicone tubing, a fluid reservoir, two cylindrical compliance chambers with diameter of 10 cm, and three resistors set at different levels to simulate three physiological states: cardiogenic shock state, normovolemic state, and hyperdynamic state. The capacitors, tubes, and resistors were adjusted to achieve:

1) literature reported hemodynamic values (e.g., cardiac output, peripheral and central (aortic) pressures) for each hemodynamic state [1],
2) literature reported transfer functions between central pressure and peripheral pressure [1].

The average hemodynamic values and transfer function (i.e., the relationship between the central pressure and peripheral pressure) for each hemodynamic state produced by the MCL are described in Table 1 and Figure 2, respectively.

	NV	CS	HD
PR (BPM)	75	90	110
CO (L/min)	4.94	3.03	6.84
CBP (mmHg)			
Systolic	114	74	87
Mean	89	59	59
Diastolic	72	48	42
PBP (mmHg)			
Systolic	123	81	100
Mean	90	61	63
Diastolic	70	49	43
Mean VBP (mmHg)	11	11	10

Table 1. Range of baseline physiologic parameters produced by the MCL. **NV**: normovolemic; **CS**: cardiogenic shock; **HD**: hyperdynamic**;** **PR**: Pulse rate; **CO**: Cardiac output; **CBP**: Central (aortic) blood pressure; **PBP**: Peripheral (radial) blood pressure. **VBP**: venous blood pressure.

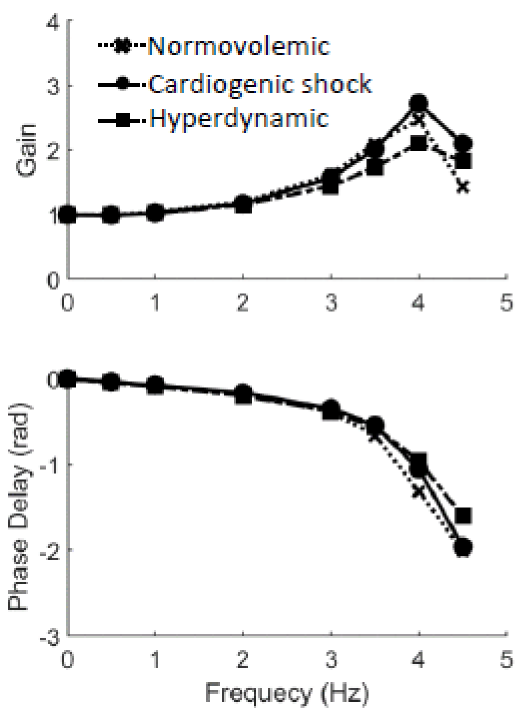


Figure 2. The MCL characterization results. Central aortic to peripheral pressure transfer functions for the normovolemic, cardiogenic shock, and hyperdynamic states.

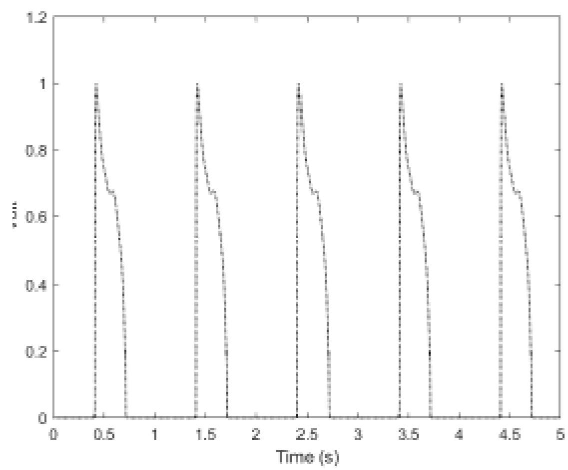


Figure 3. Example input signal to the servomotor for generating transient central flow waveforms for 5 seconds. The input signal should be scaled and resampled for generating desired central flow waveforms with different cardiac periods (i.e., pulse rate).

A gear pump (e.g., Dayton 4KHH8, Grainger, Inc., Lake Forest, IL) coupled to a servo motor (e.g., AKM42E- ANCNC-00, Kollmorgen Corporation, Radford, VA) and servo drive (e.g., AKD-P00306-NBAN-000, Kollmorgen Corporation, Radford, VA) were used for generating pulsatile central flow waveforms. The gear pump is a positive displacement pump for which the flow output should not depend on the downstream pressure. Unlike piston pumps, gear pumps can run continuously and do not need valves for controlling the direction of the flow. The servo motor provides smooth motion and was controlled using a servo drive that accepts an analog voltage up to 10 Volt for controlling the rotor speed. We have included a voltage signal (V_{int} in Vint.csv; V_{int} is normalized and has a cardiac period of 1 second) that can be used for generating semi-triangular aortic flow waveforms. This initial input voltage should be linearly scaled ($\alpha \times V_{int}$, where α is the scaling factor) and resampled (we used the "resample" command in MATLAB 2021 for adjusting the cardiac period) to achieve the desired average central flow rates and pulse rates (Table 1). The resultant voltage signal has the duration of one cardiac cycle (this period depends on the pulse rate) and can be concatenated for simulating multiple cardiac cycles (Figure 3). Here, we simulated the baseline of each hemodynamic state using the MCL for 120 seconds (Table 1).

A mixture of 40% glycerol solution and 60% water, which has a dynamic viscosity and density similar to those of human blood, was used as the working fluid. The setup for each hemodynamic state is the same, except the compliance chambers and resistors were configured to the appropriate compliance and resistance values for each respective state (Table 2). Each capacitator was tuned by changing the level of its air pocket (thus changing the air volume). Details regarding the exact tubing measurements and locations of the physical elements are listed in Tables 2, 3, and 4 and visually represented in the MCL schematic (Figure 1). A honeycomb flow straightener was placed right after the pump to uniform the initial flow. The flow straightener and long tube after the pump decreased flow turbulence and resulted in improved flow signal quality during high flow rate conditions (e.g., hyperdynamic state). Ultrasound transit time flow meters (TS410 and T402, Transonic Systems Inc., Ithaca, NY) with a low pass filter of 10 Hz and ME-16 PXL and ME-6 PXL flow probes (Transonic Systems Inc., Ithaca, NY) were used to measure instantaneous flow rates at the pump outlet (i.e., central flow) and peripheral radial branch (i.e., peripheral flow), respectively. Pressure signals were recorded at different locations as shown in the schematic diagram of the MCL (Figure 1) using a pressure recording unit (Millar PCU-2000, Millar, Inc., Houston, TX) and pressure catheters (Mikro-Tip SPC-370 and MPR-500, Millar, Inc., Houston, TX). All data were acquired at a sampling rate of 1000 Hz and then passed through a low pass filter with cut-off frequency of 55 Hz to remove high frequency artifacts, powerline disturbances and noises.

	NV	CS	HD
Capacitance (air level in *mm*)			
Lao	235	235	167
Ls	29	29	27
Resistances (*mmHg.min/L*)			
Rs	~16.4	~16.5	~7.2
Rv	2.2	3.6	1.5

Table 2. Range of physical elements for simulating each hemodynamic state and baseline physiologic parameters produced by the MCL. Both cylinders have a diameter of 10cm and area of 78.54cm^2. **NV**: normovolemic; **CS**: cardiogenic shock; **HD**: hyperdynamic; **Rs**: Systemic resistance; **Rv**: Venous resistance (refer to Figure 1). (*Note: We adjusted the peripheral radial resistance (Rp) to achieve a mean peripheral pressure (PBPmean) as close as possible to mean central pressure (CBPmean)*).

ID (see figure 1)	**Element**	**Specifications**
A	ME-16PXL Flow Probe	66.5cm from the pump's outlet.
B	¾" – 1" connector	Straight reducer (e.g., https://www.mcmaster.com/5047K29/)
C	CBP (Millar pressure catheter)	Insert pressure catheter to read pressure (see appendix).
D	Peripheral Loop Start	See appendix.
E	Cone Reducer	See appendix.
F	Rs	Pinch valve placed 39cm from the Cs.
G	PBP (Millar pressure catheter)	Wye Connector for inserting pressure catheter to read pressure (e.g., https://www.mcmaster.com/5372K886/).
H	ME-8PXL Flow Probe	7.5cm from the PBP.
I	Rp	Pinch valve placed 10cm from ME-8PXL Flow Probe.
J	Peripheral Loop End	See appendix.
K	VBP (Millar pressure catheter)	Insert pressure catheter to read pressure (see appendix).
L	Rv	Pinch valve placed 10cm from the VBP.
	Working Fluid	Glycerin solution: 60% Water and 40% Glycerin—99%

Table 3. Specifications of the connectors, pressure readers, and resistors used for physical set-up of MCL. **CBP**: Central (aortic) blood pressure; **PBP**: Peripheral (radial) blood pressure. **VBP**: venous blood pressure. **Rs:** Systemic resistance; **Rp:** peripheral radial resistance; **Rv:** Venous resistance (refer to Figure 1).

ID (see figure 1)	Material	Inner diameter (in)	Thickness (in)	Length (in)
1	Silicone; Shore 50A	3/4	1/8	18.9
2	PVC	1	3/16	5.4
3	PVC	1	3/16	5.7
4	PVC	1	3/16	4.3
5	PVC	1	3/16	5.5
6	PVC	1	3/16	14.1
7	PVC	1	3/16	7.3
8	PVC	1	3/16	11.4
9	PVC	3/4	1/8	11.8
10	Silicone; Shore 50A	7/16	3/32	3.2
11	PVC	5/32	1/32	17.0
12	PVC	1/4	1/16	9.1

Table 4. Material and measurements for tubing in the MCL (refer to Figure 1).

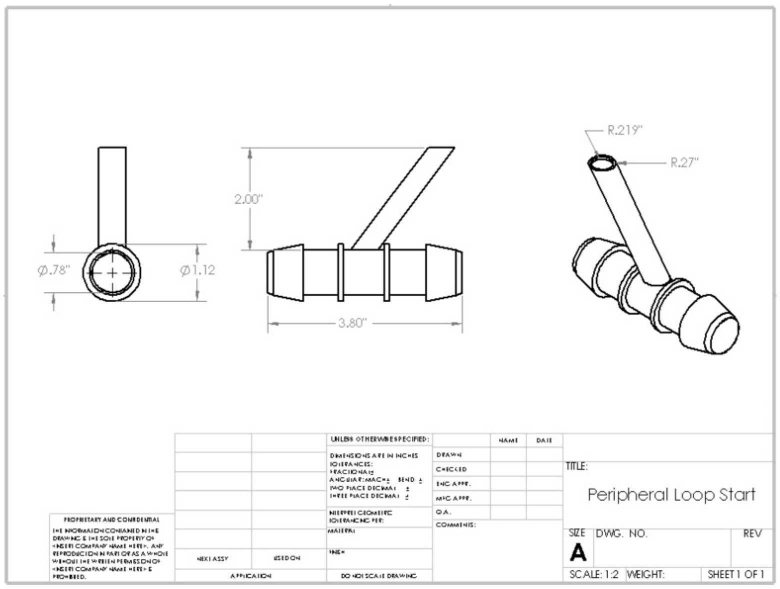
We adjusted the peripheral radial resistance (Rp) to achieve a mean peripheral pressure (PBP_{mean}) as close as possible to mean central pressure (CBP_{mean}). Results are highly dependent on the location of each element in the MCL and the air level of capacitors (i.e., air pocket level) and resistance values. Particularly, the transfer functions generated from this loop are highly sensitive to air volume in the second compliance chamber (C_S: systemic arterial capacitance) and location of central pressure catheter. It was observed that if the systemic arterial capacitance is lower/higher than the recommended value or the central pressure catheter is placed in a different location, it can result in a different transfer function between peripheral and central pressures. This will affect the peripheral and central pressure waveform morphologies. (*Note: The pressure transducers should be zeroed every time the compliances are changed in any of the chambers to compensate for the change in the hydrostatic pressure.*).

Reference

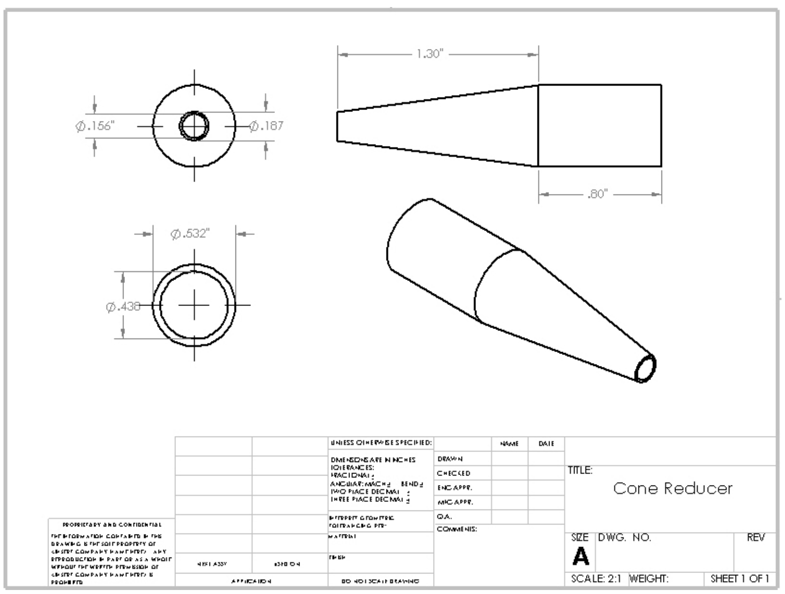
[1] *Farahmand M, Bodwell E, D'Souza GA, Herbertson LH, Scully CG.* ***Mock circulatory loop generated database for dynamic characterization of pressure-based cardiac output monitoring systems****. Comput Biol Med. 2023 Jun;160:106979. doi: 10.1016/j.compbiomed.2023.106979. Epub 2023 May 3. PMID: 37167657.*

Appendix

Peripheral Loop Start (ID: D)



Cone Reducer (ID: E)



Peripheral Loop End (ID: J)