MICHIGAN STATE UNIVERSITY

Development and Validation of a Benchtop Cardiovascular Simulator of Arterial Hemorrhage Against a Porcine In Vivo Comparator

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59TH MEDICAL WING

DEDICATION DUTY SERVICE

4DBio³

Uniformed Services University

Disclaimer & COI

Disclaimer

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COI:

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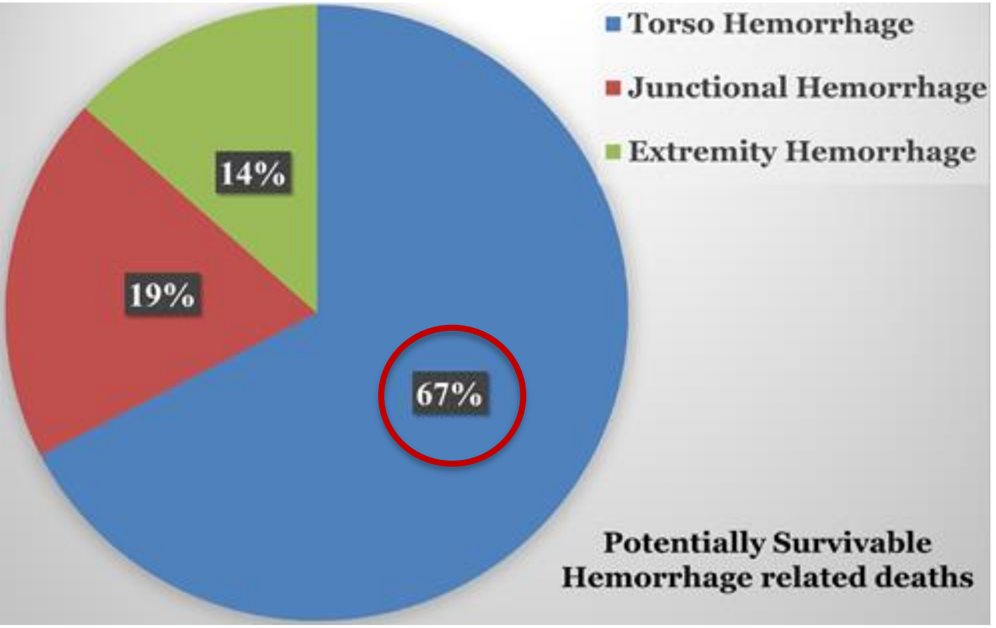
Motivation

Non-Compressible Torso Hemorrhage has a disproportionately high mortality resulting from medium-grade, potentially survivable injuries on the battlefield

Reproduced from *Eastridge, Brian J., et al Journal of trauma and acute care surgery (2012)*



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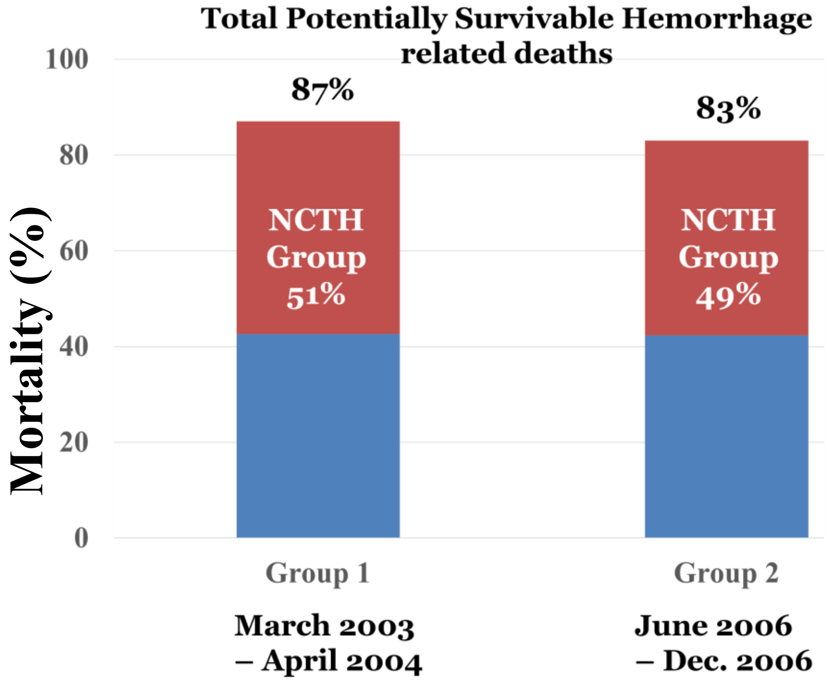

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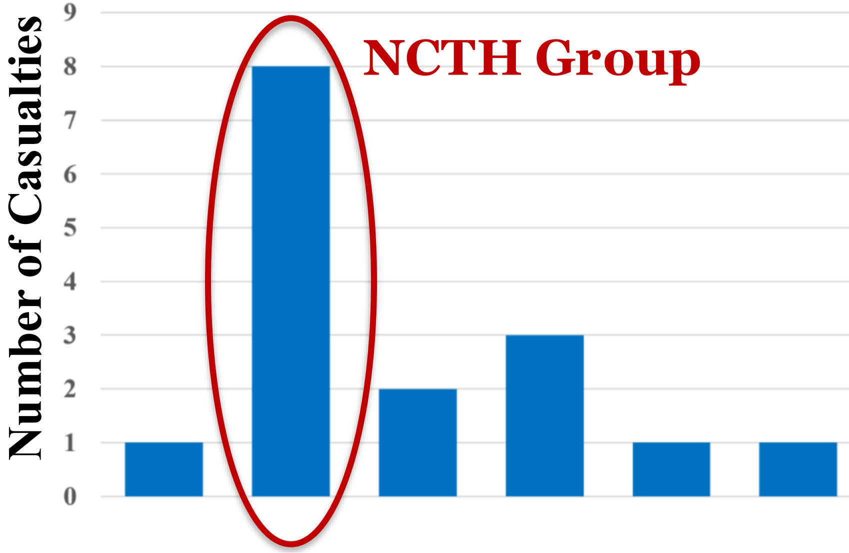
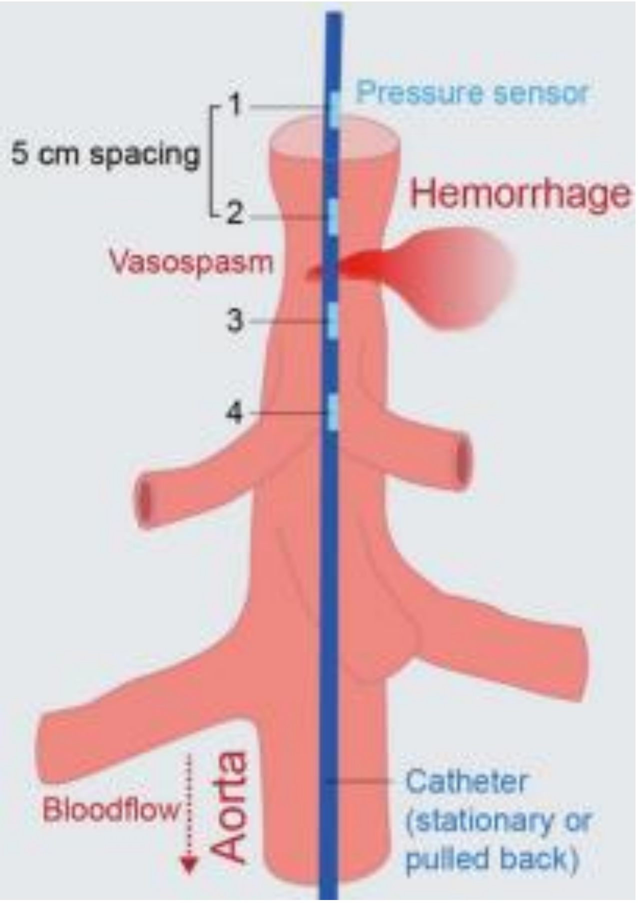
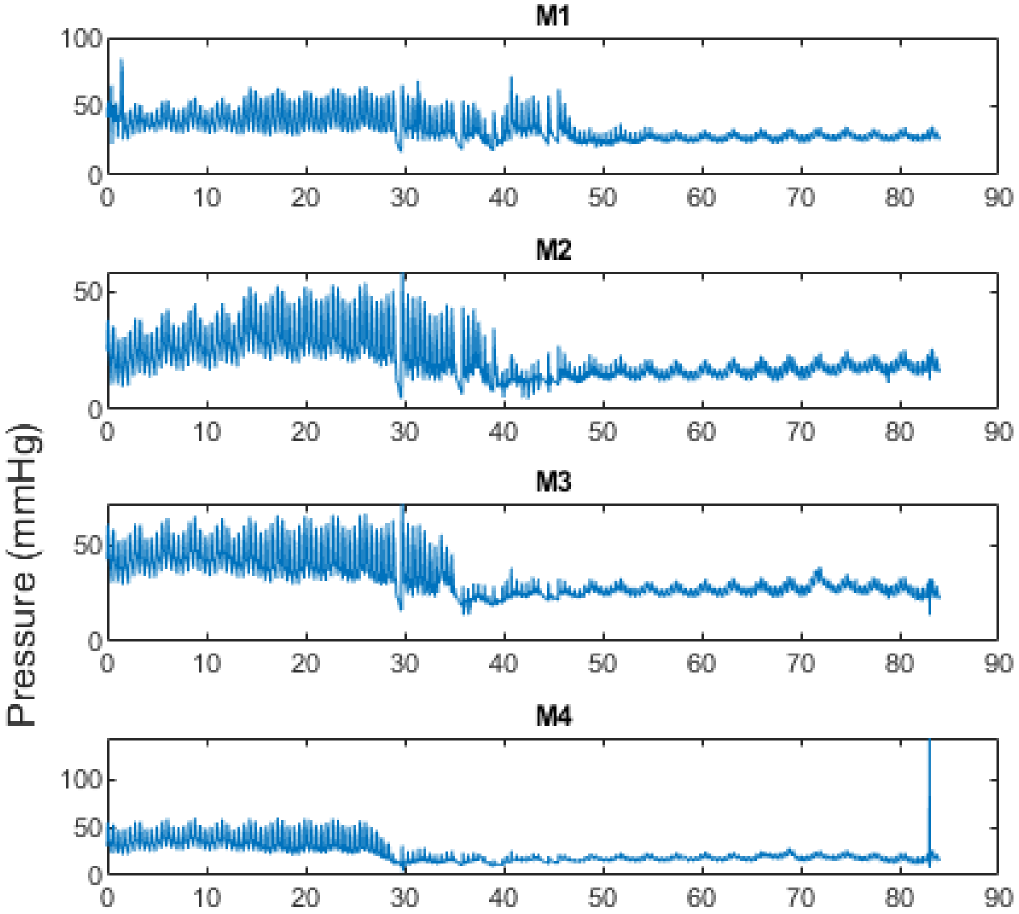


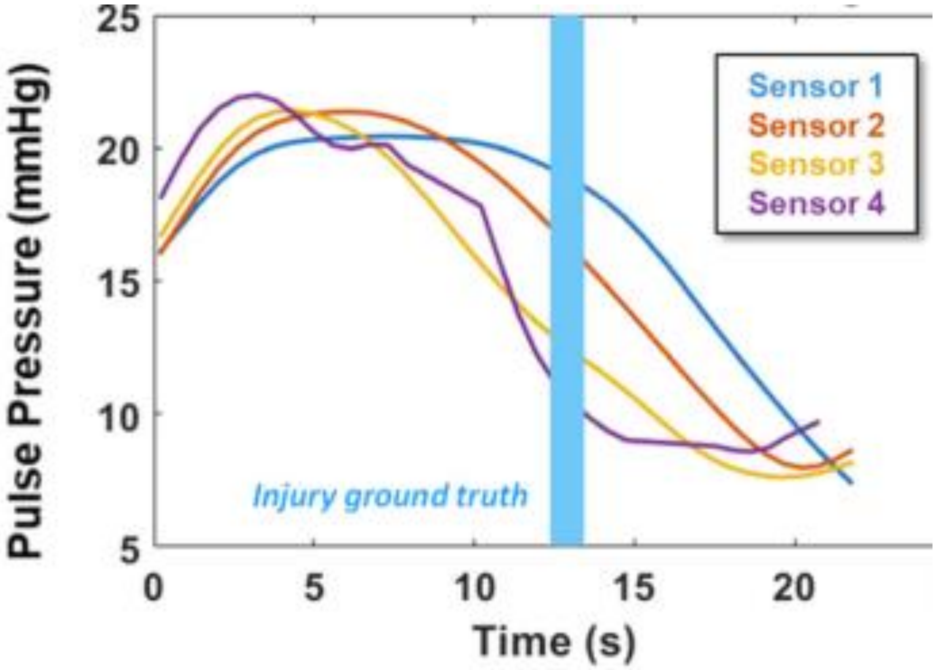
Locate injury on the battlefield → Precise **REBOA** on the battlefield → Prolonged golden hour; Patient transferred to an advanced Trauma care center

Promising *in vivo* Observations

Courtesy: Arshad, Saaid H., et al. "Endovascular Localization of Aortic Injury in a Porcine Model." *IEEE Open Journal of Engineering in Medicine and Biology* (2025).





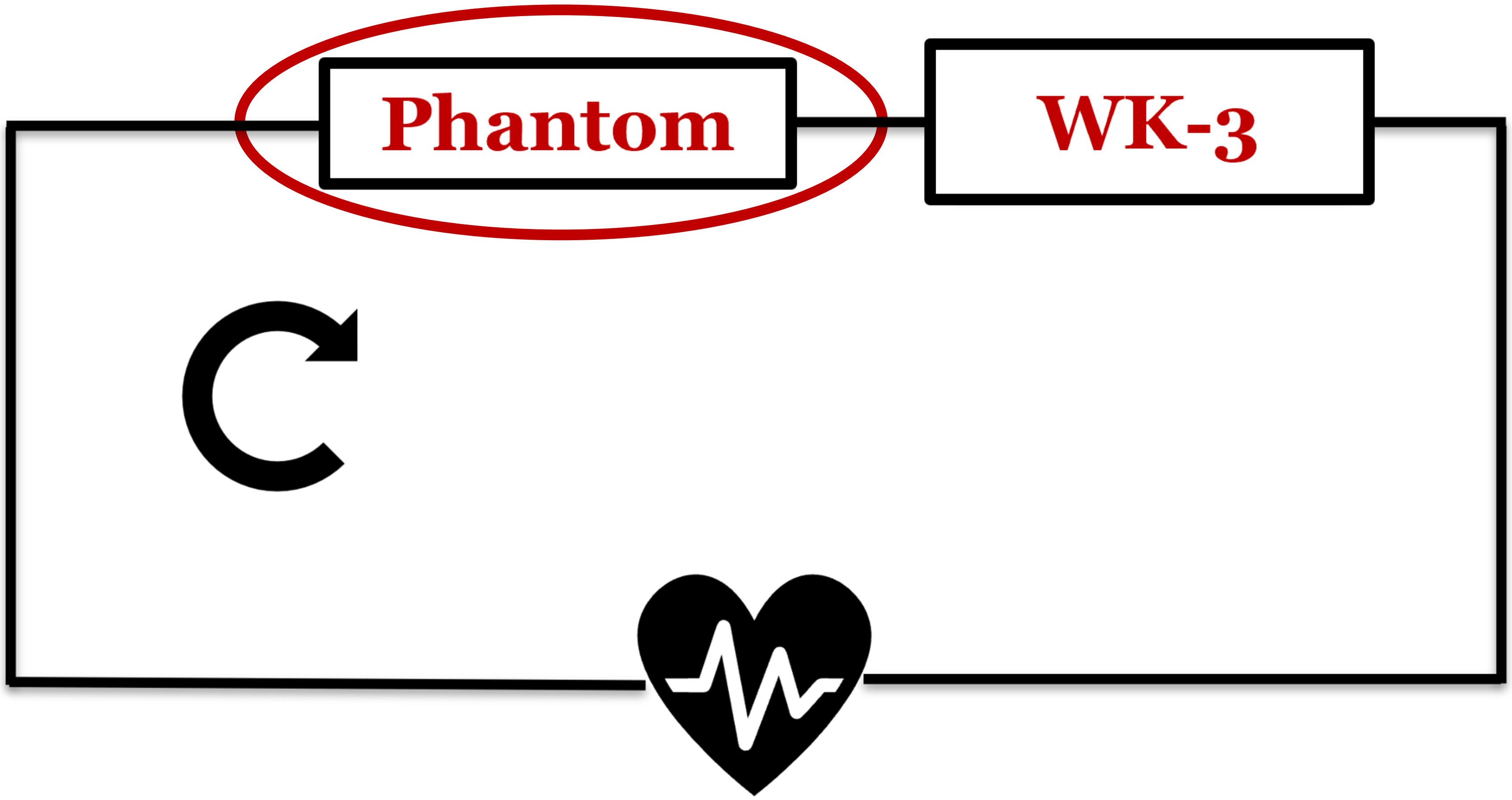


Zone 1 aortic injury localized via a pressure catheter survey along the aorta

Further evaluation requires testing on a rigorous & faithful **in vitro model of hemorrhage**

The NCTH Simulator

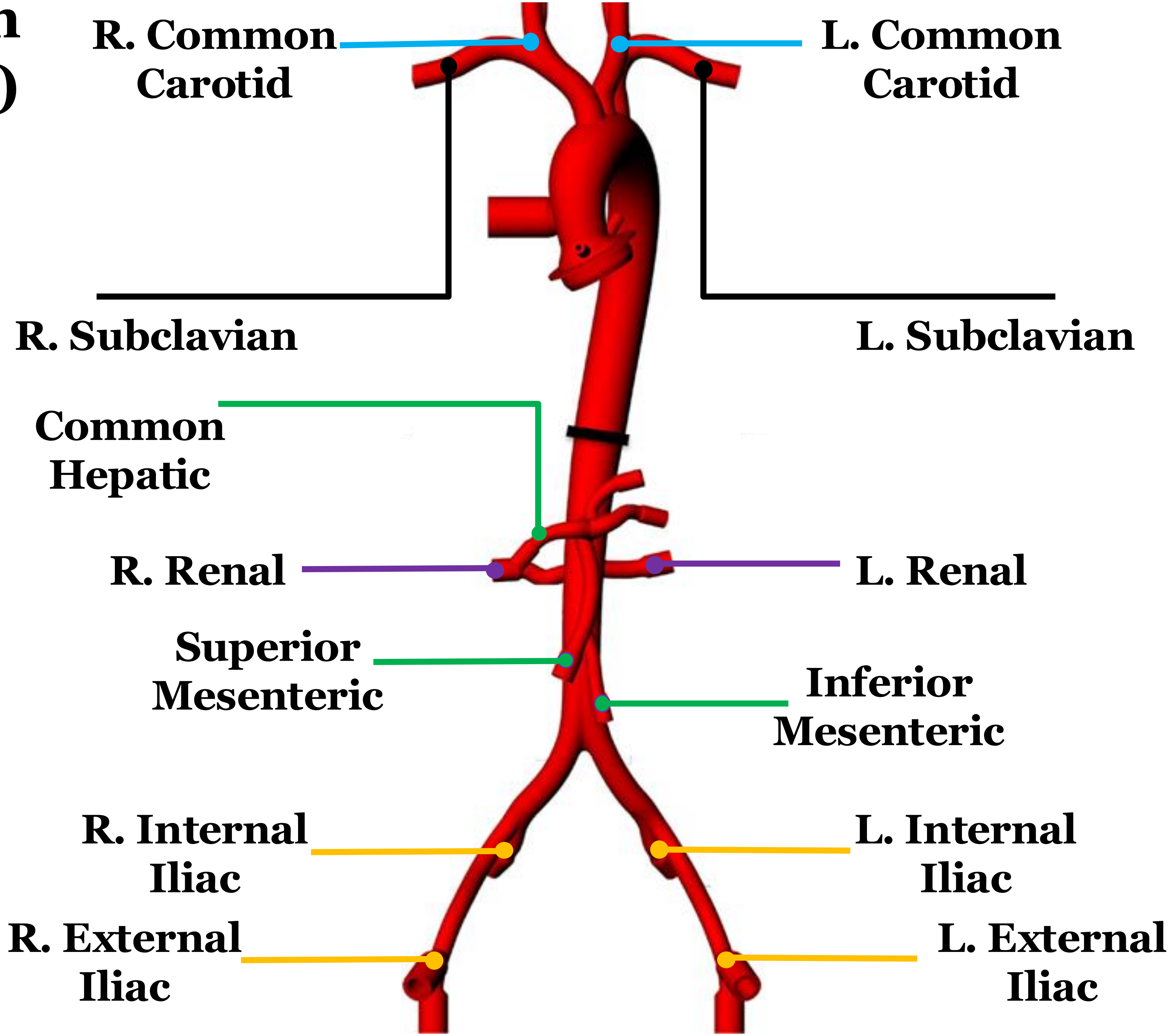
NCTH Simulator



Aortic Phantom (Active Vessels)

Active Vessel Count = 13

5 Regional Circulations



Cerebral

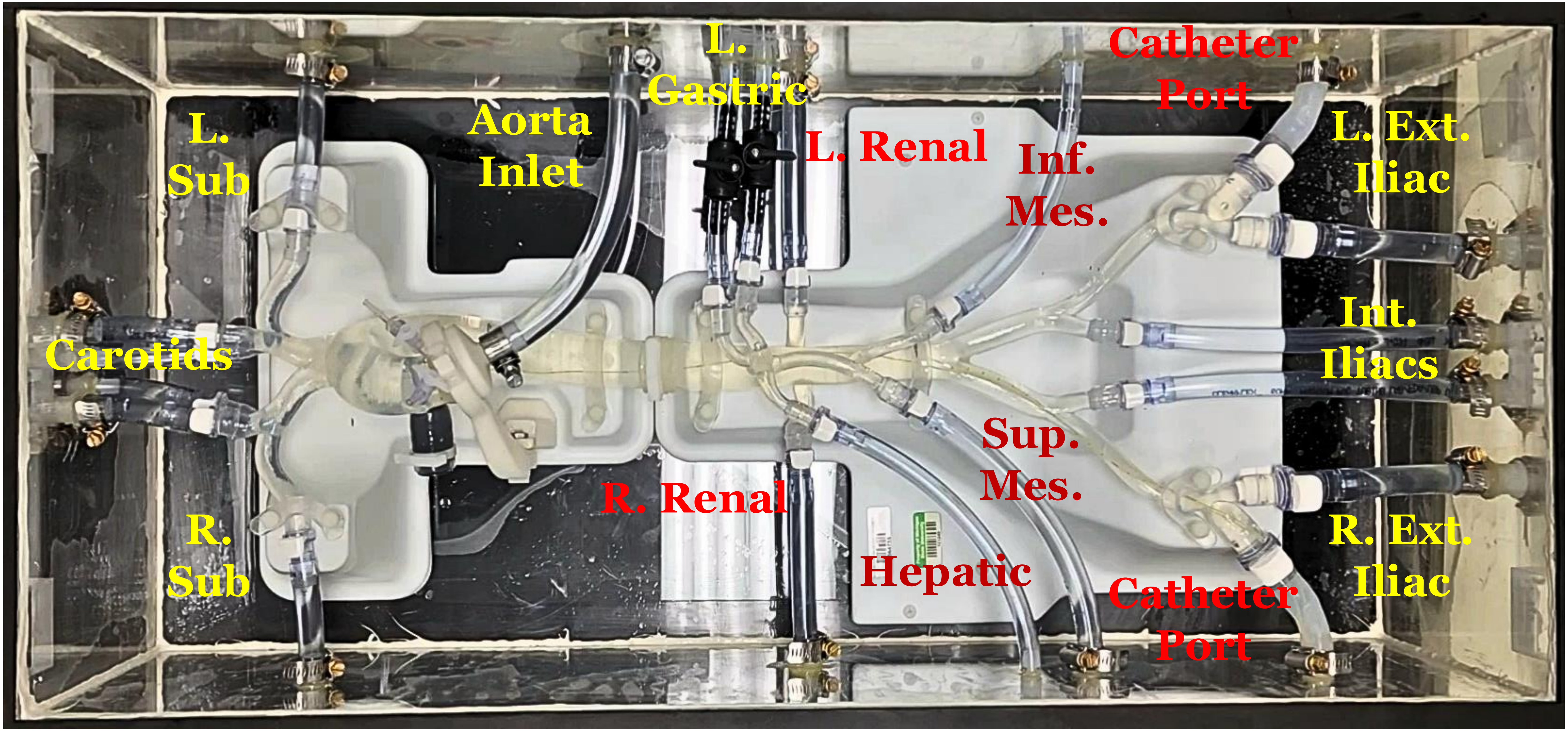
Upper Limbs

Renal

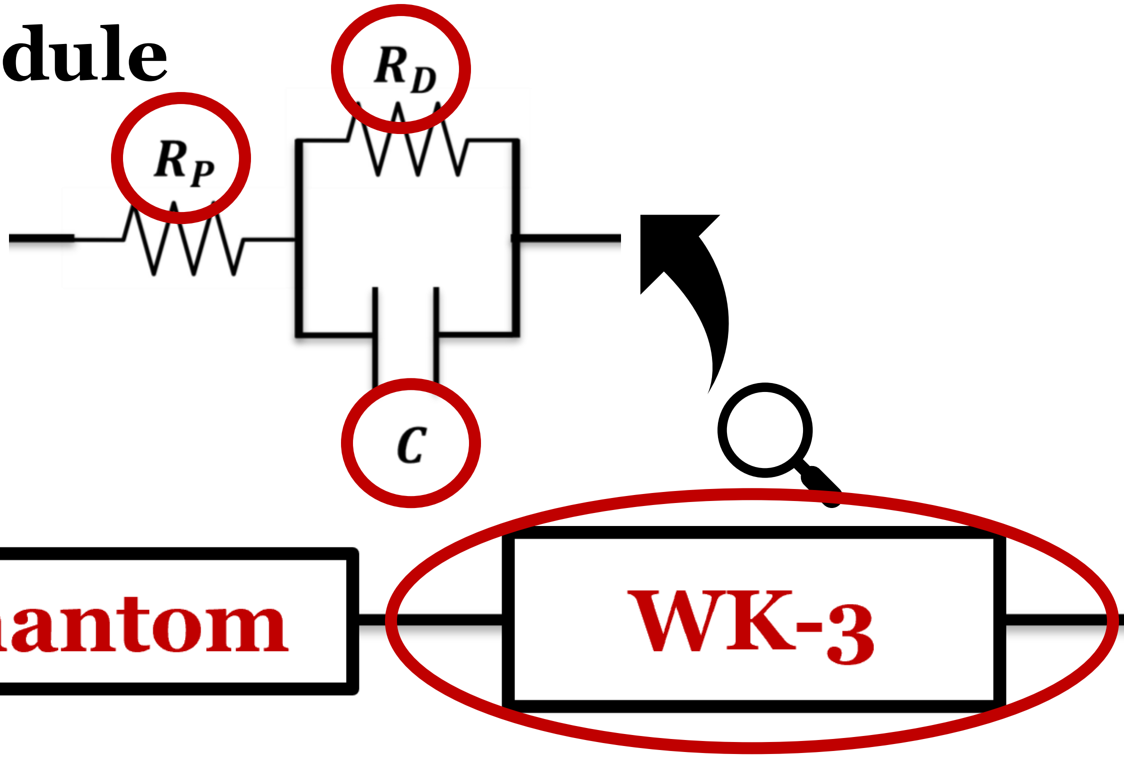
Splanchnic

Lower Body

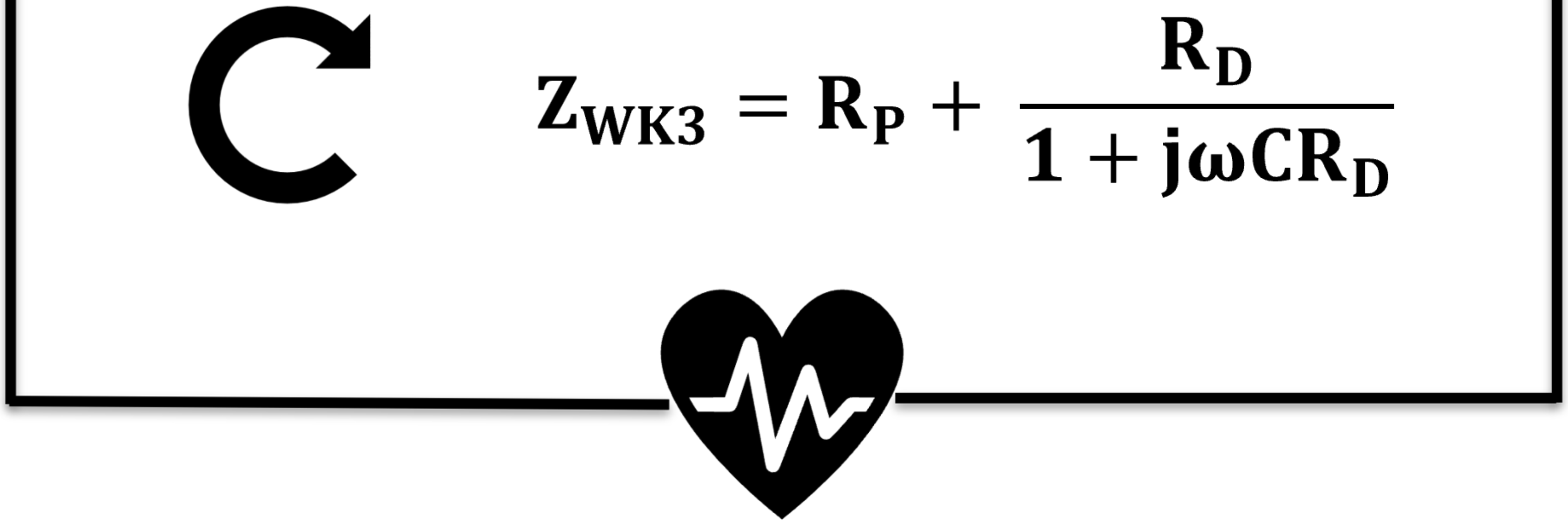
Aortic Phantom



Windkessel Module



$$Z_{WK3} = R_P + \frac{R_D}{1 + j\omega C R_D}$$



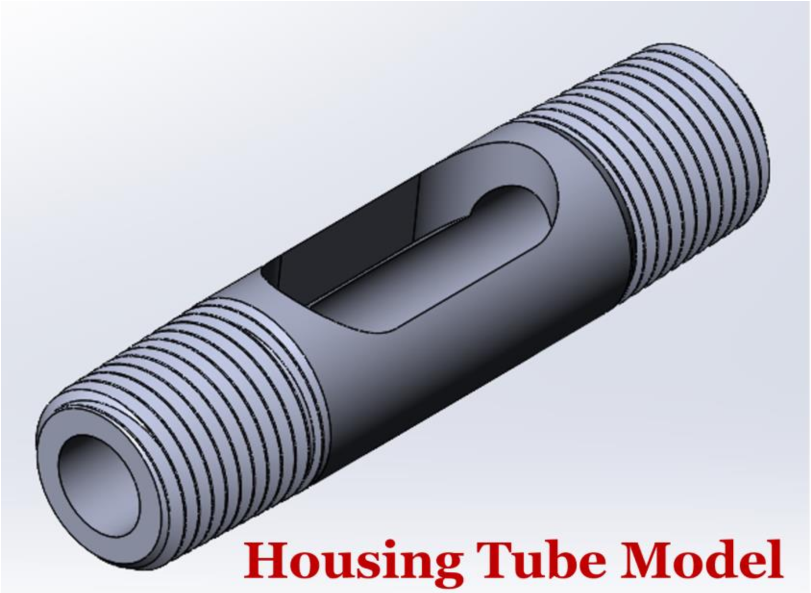
R_P – Resistance of proximal vessels

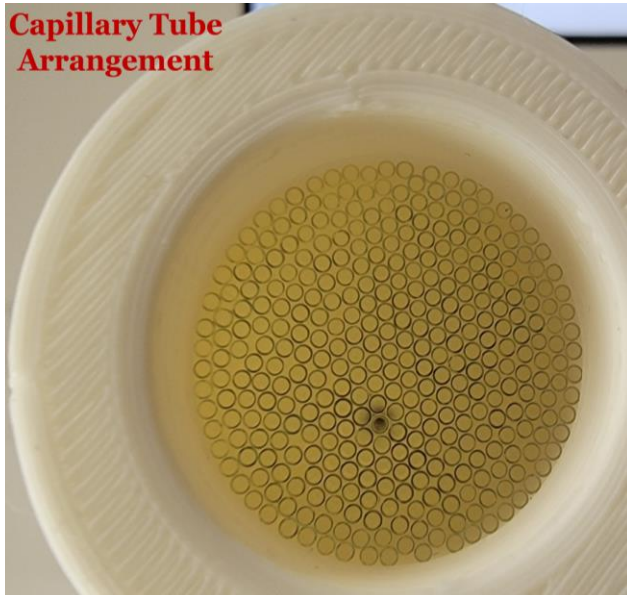
C – Vessel compliance or distensibility

R_D – Resistance of distal arterioles & capillaries

Windkessel Module

Resistor Module

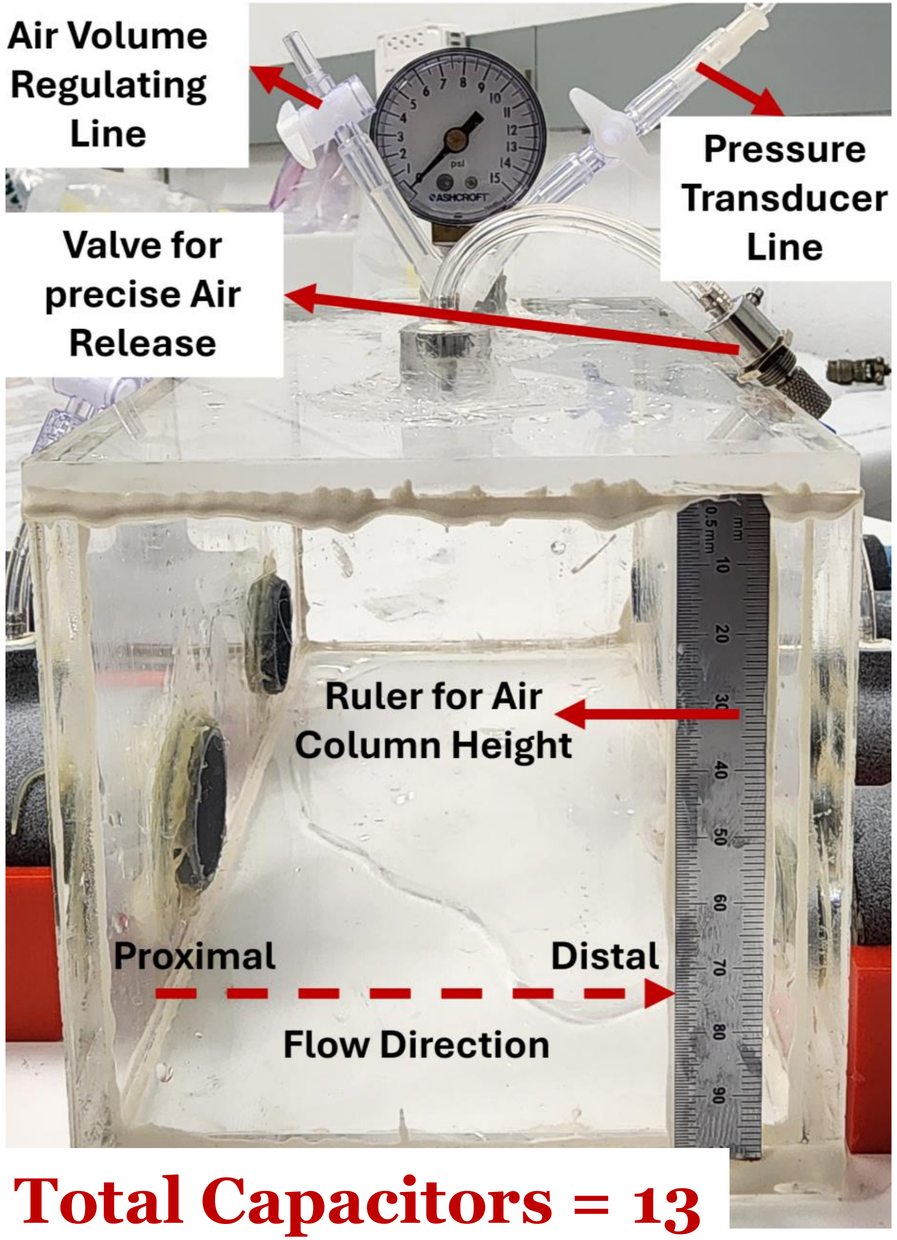




Capillaries parallelly stacked and glued

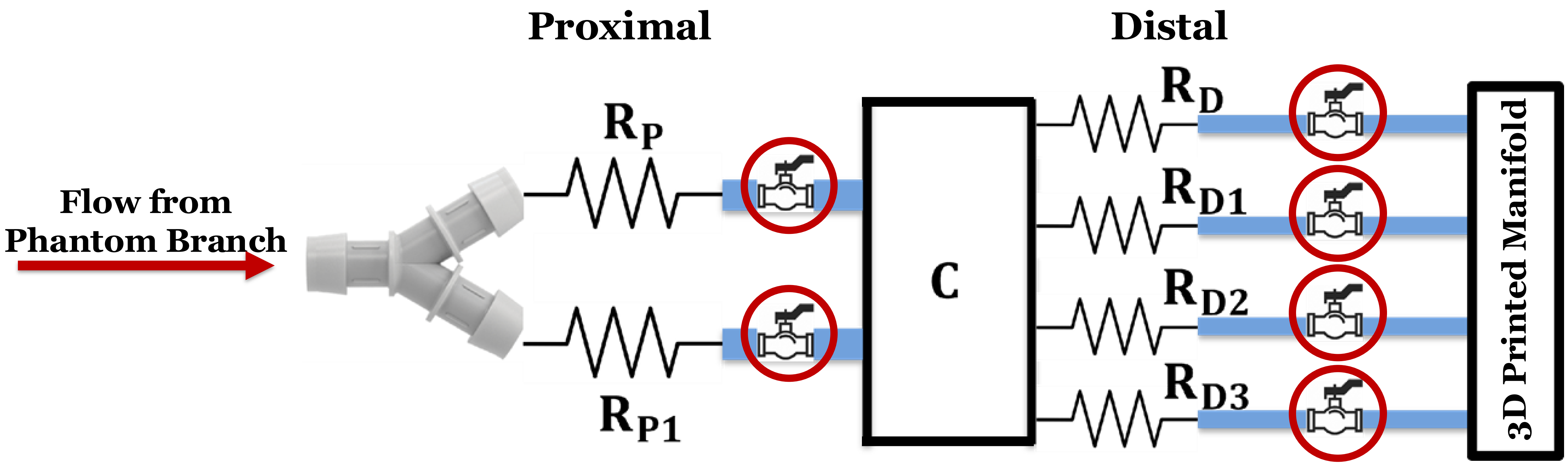
Total Resistors Fabricated = 76

Capacitor Module



Total Capacitors = 13

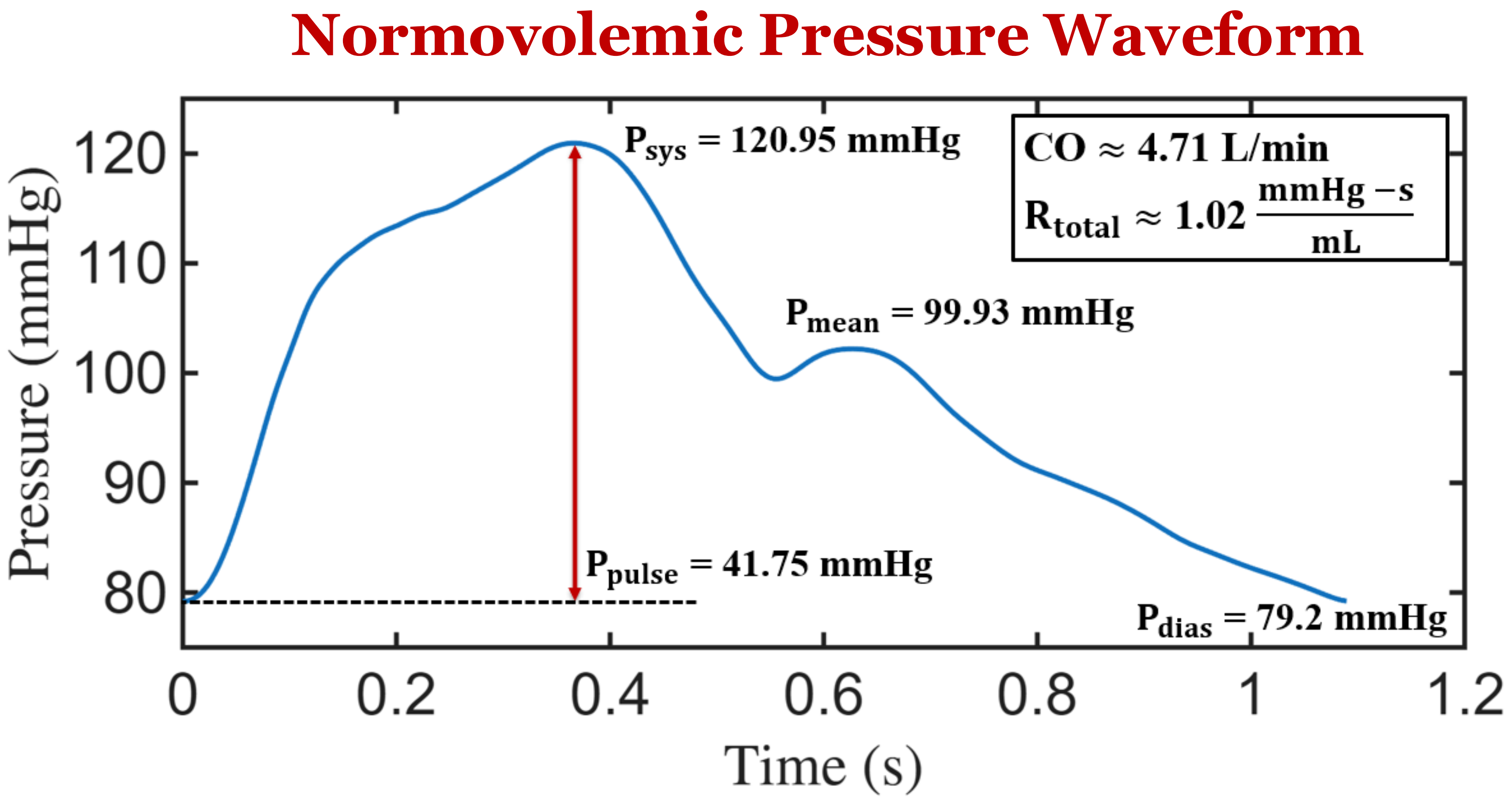
Windkessel Module – Assembly

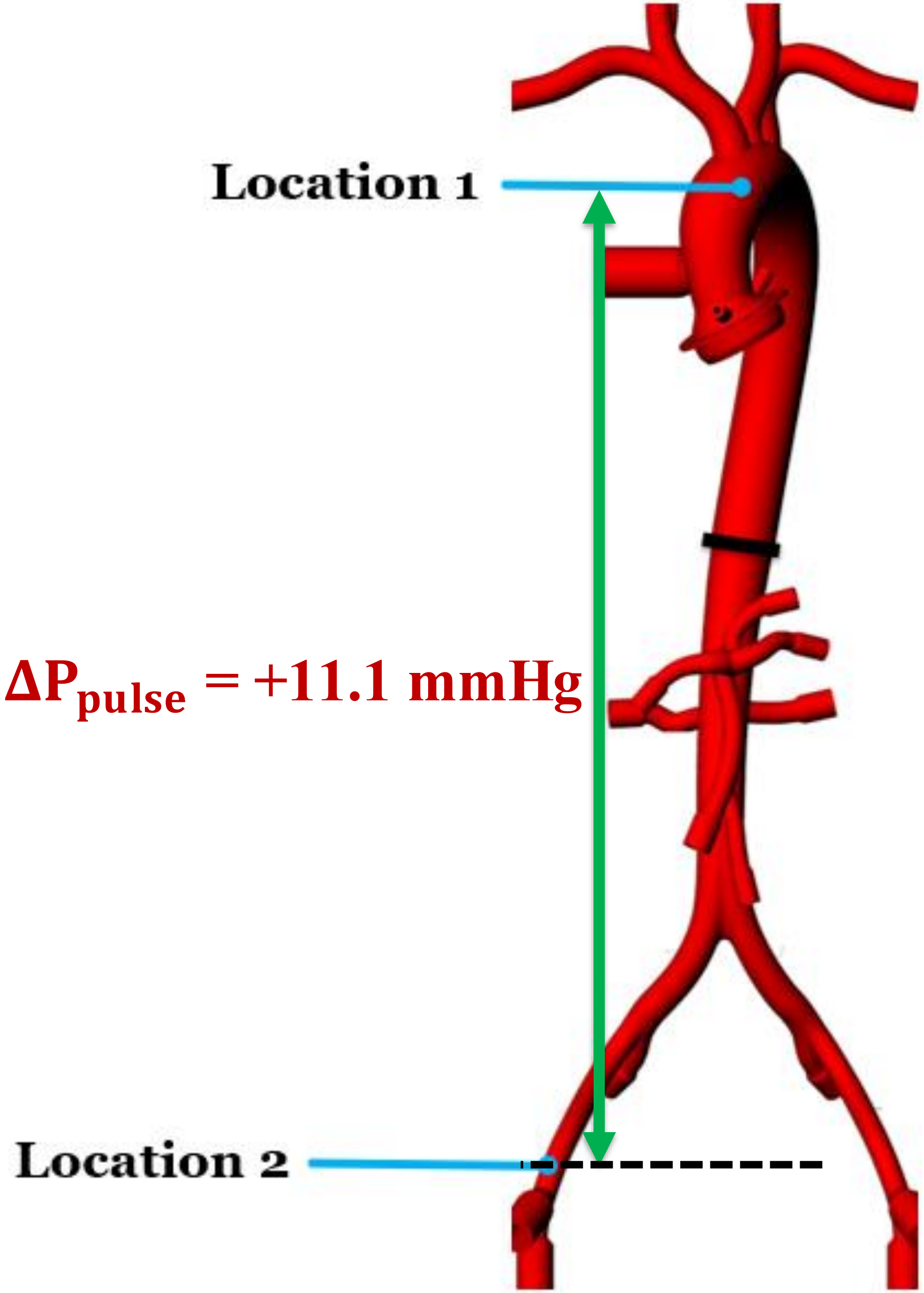


- Full-port ON/OFF valves adjust the vascular tone (vasoconstriction or vasodilation) in real time – Effortless resistance level changing
- Each assembled WK-3 or impedance module connects to a branched vessel of the phantom

Results

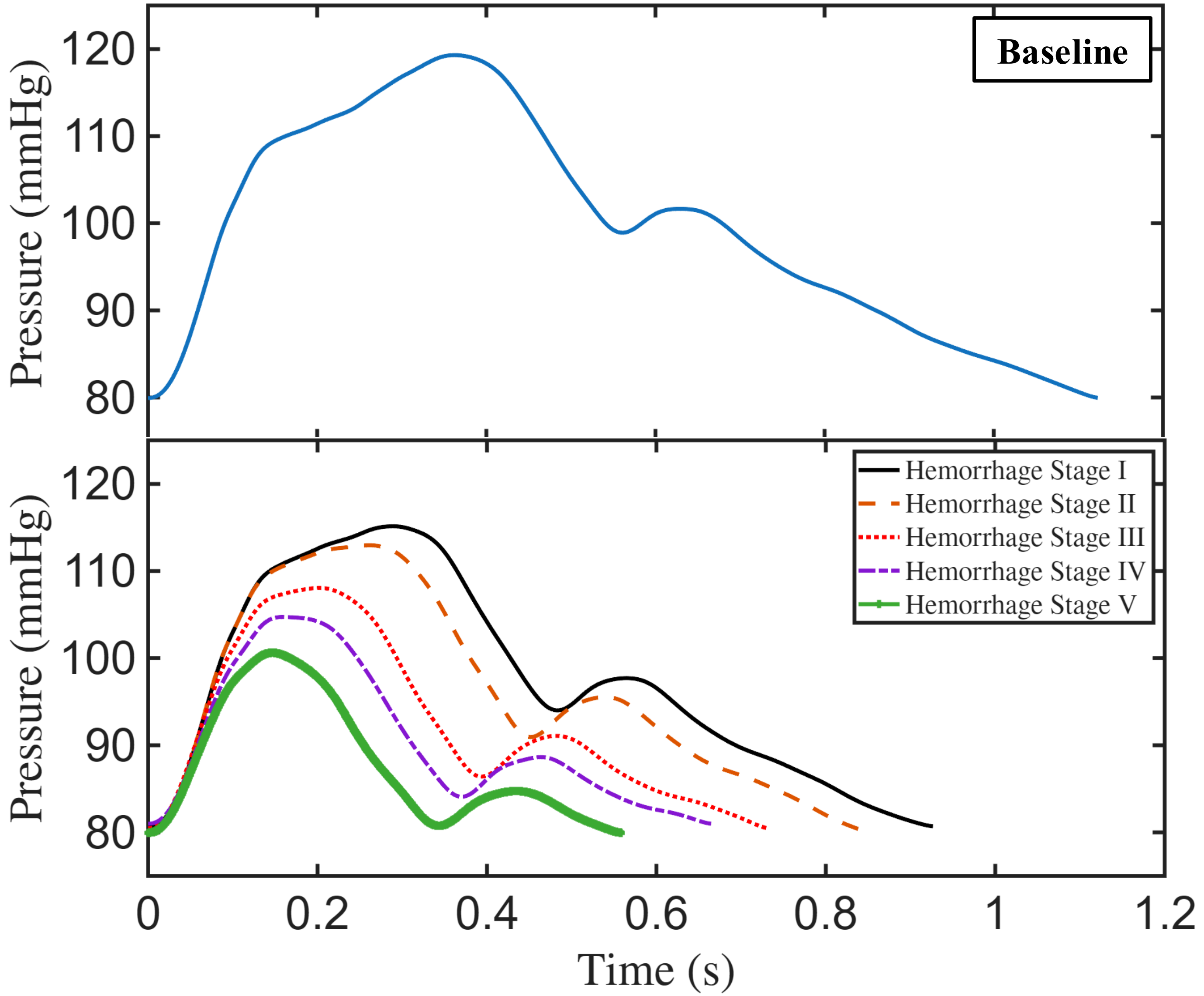
Normovolemic Characterization

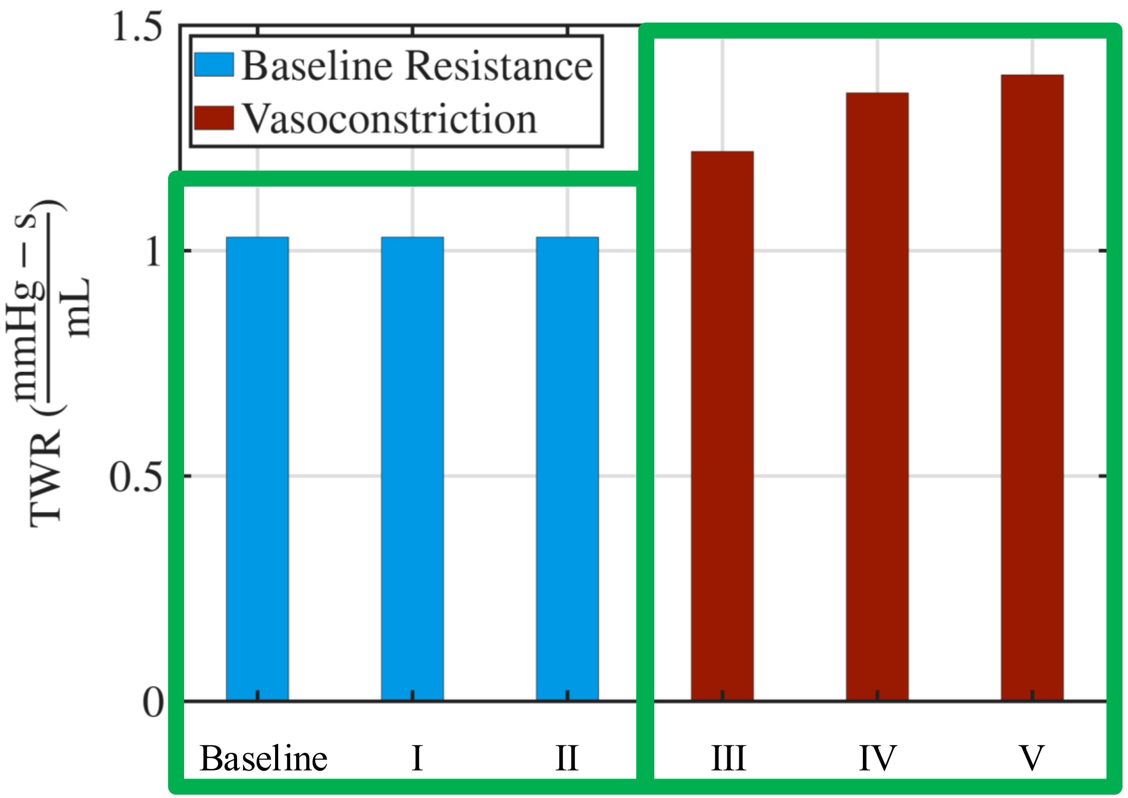




Coefficient of Variation (CV) across 23 consecutive cardiac cycles < 1%; **High Repeatability**

Non-Compressible Torso Hemorrhage



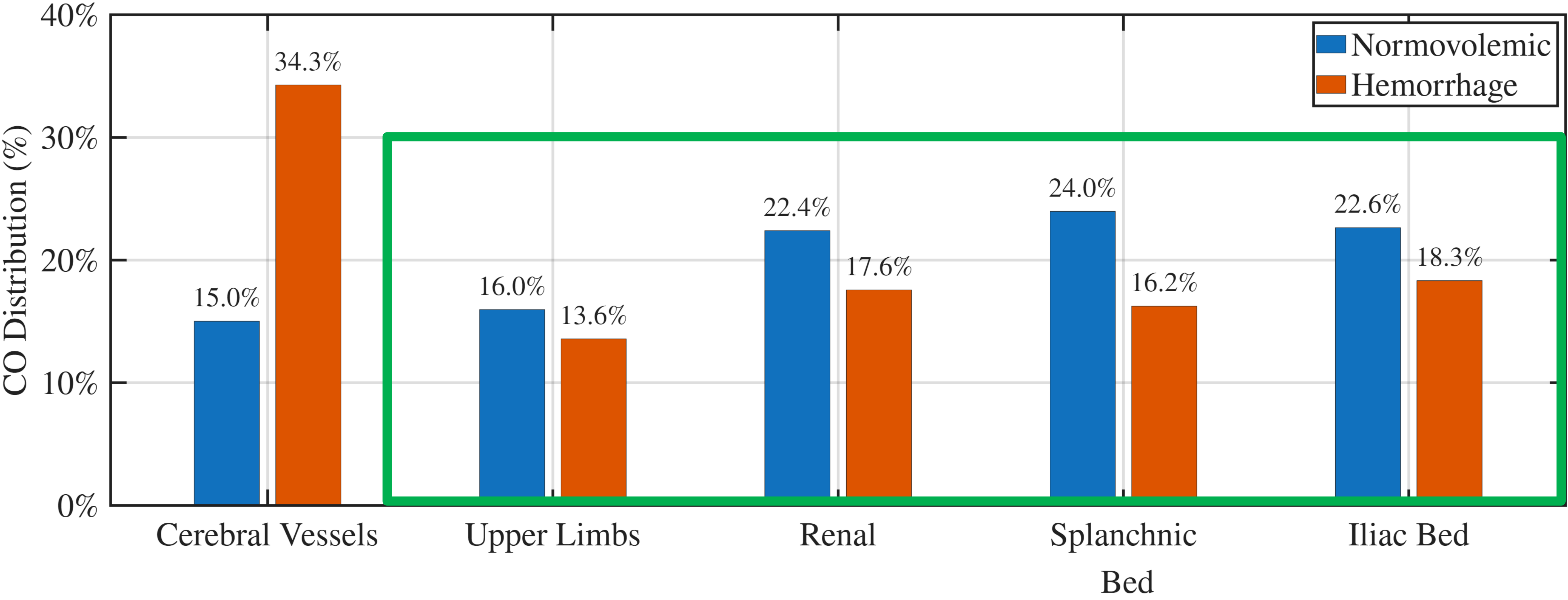


38% reduction in CO reduced the mean pressure by only 11%

Diastolic Floor maintained at normovolemic levels

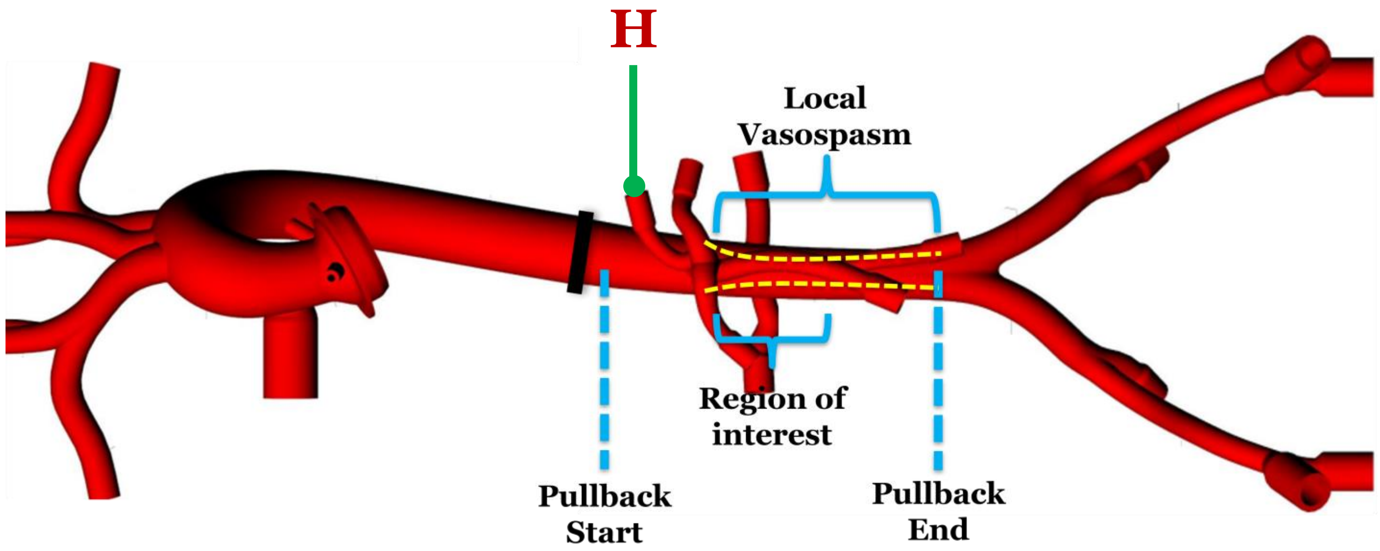
Strong In Vivo Compensatory Response

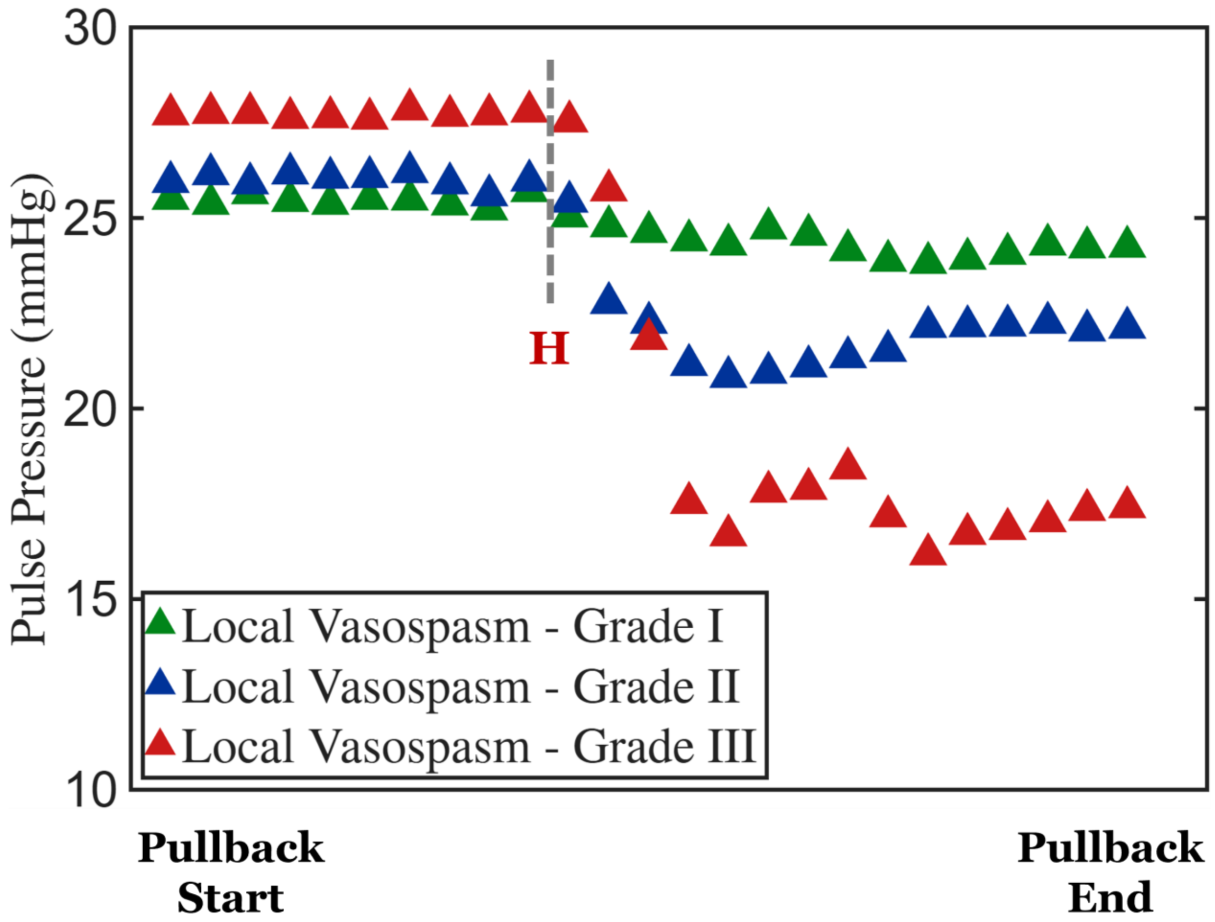
Normovolemic and Hemorrhagic CO (%) Distribution



Disproportionate hemorrhagic vascular tone led to the preferential redistribution of cardiac – withdrawal from visceral beds and towards the cerebral beds

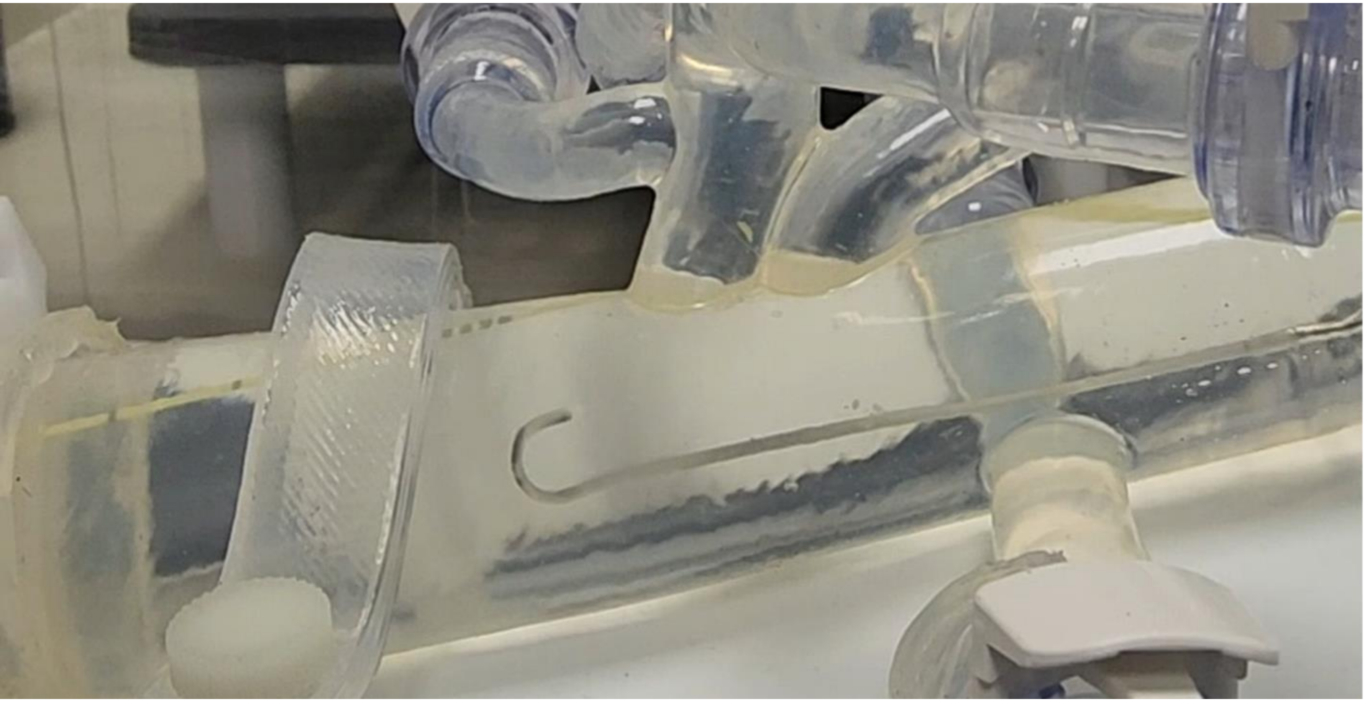
Endovascular Localization of Aortic Hemorrhage

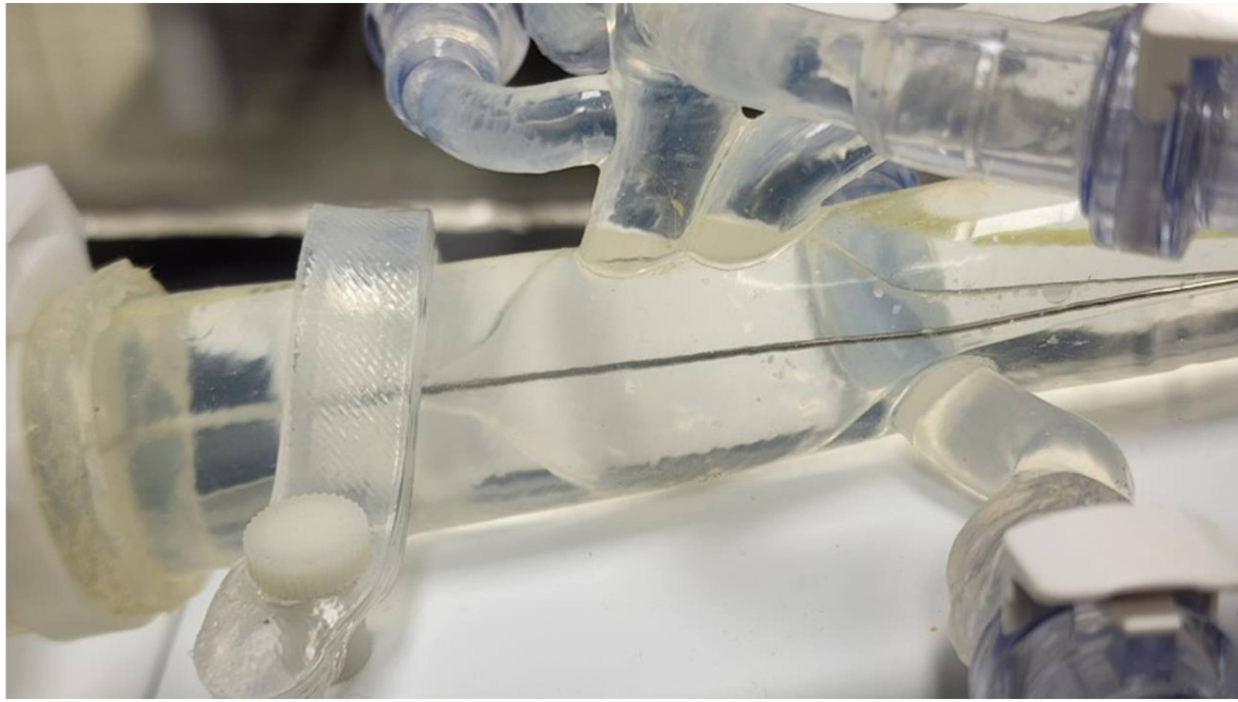




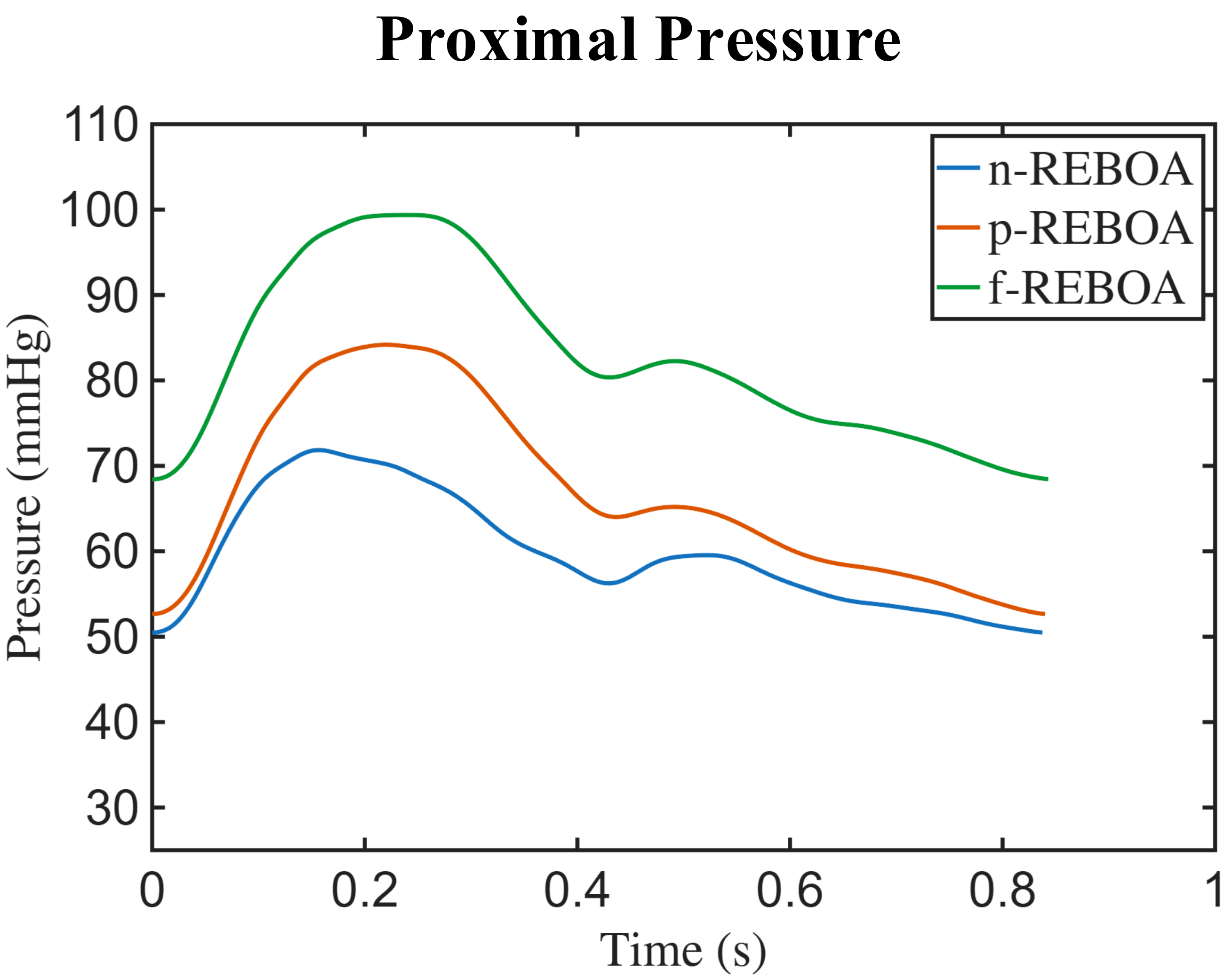
- ➢ Catheter pullback established a Pulse Pressure based hemorrhage localization signature
- ➢ Pulse Pressure reduction (Localization signature) increased with local vasospasm severity

Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA)

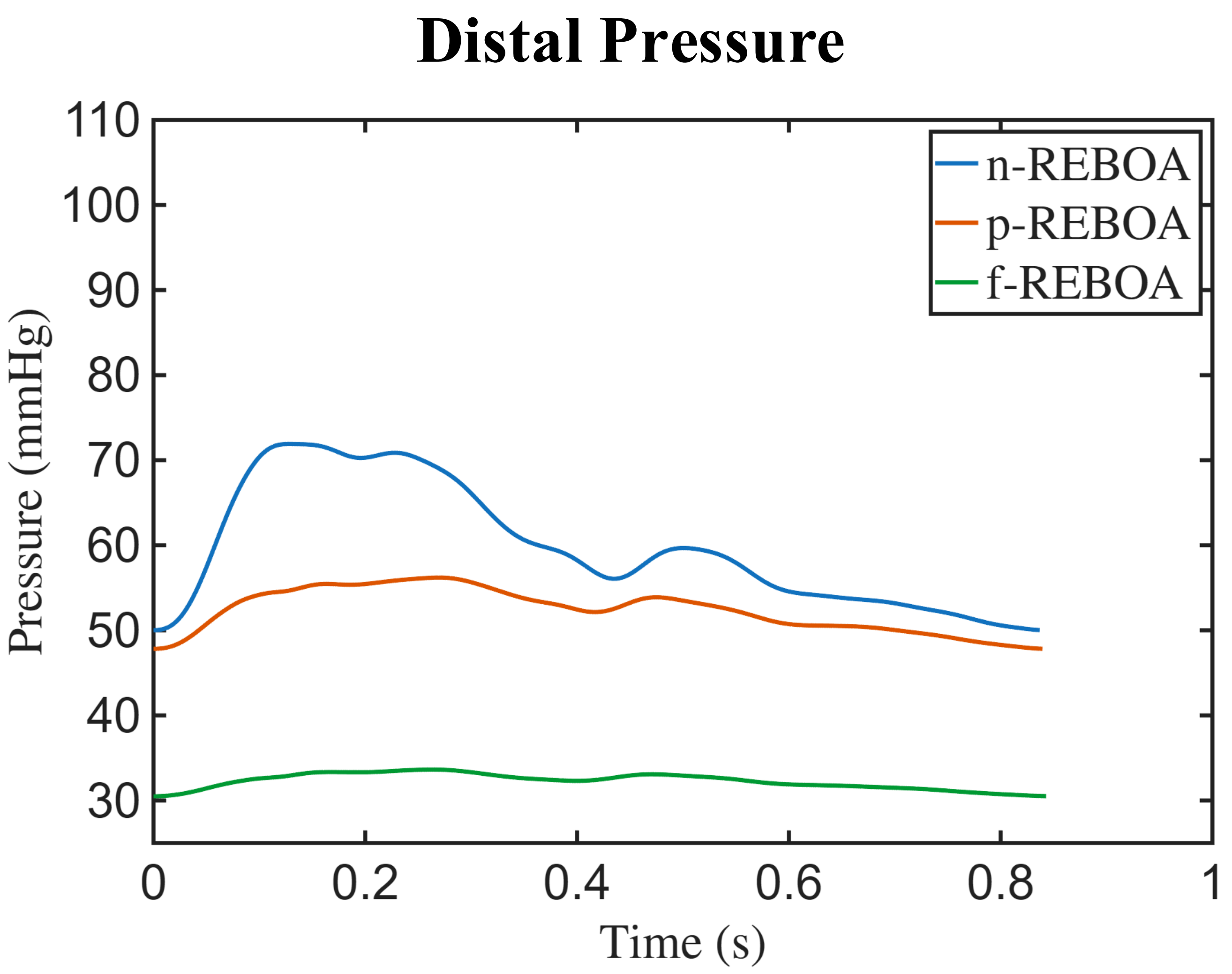




Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA)

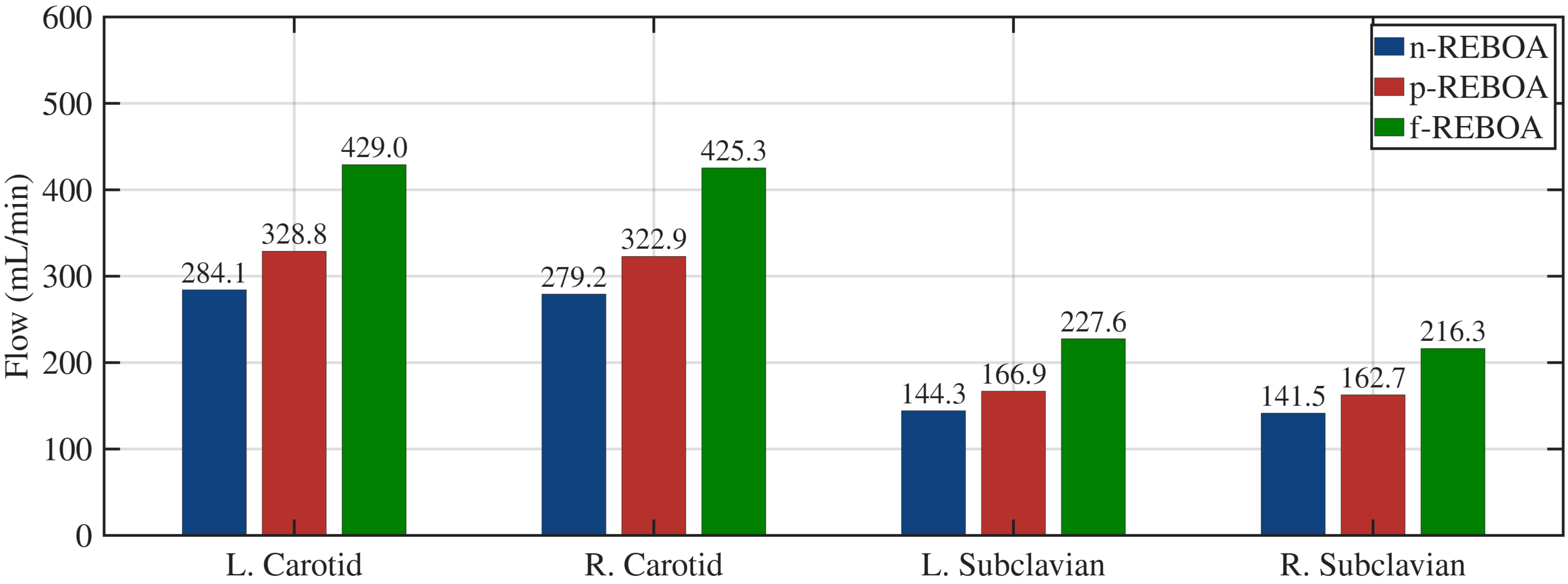


Improved the Proximal pressure



Flatlined the Distal pressure

Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA)



- Improved Carotid flowrates; supra-physiological increases at f-REBOA not observed
- Mechanical piston pump does not mimic afterload-driven supraphysiological increases in left ventricle contractility (slope of ESPVR of LV)

Limitations & Future Work

Vasospasm at the injury location enforced via external phantom compression

Need precise characterization of local vasospasm profile at injury location for fabricating customized phantoms

Currently only modeling aortic hemorrhages

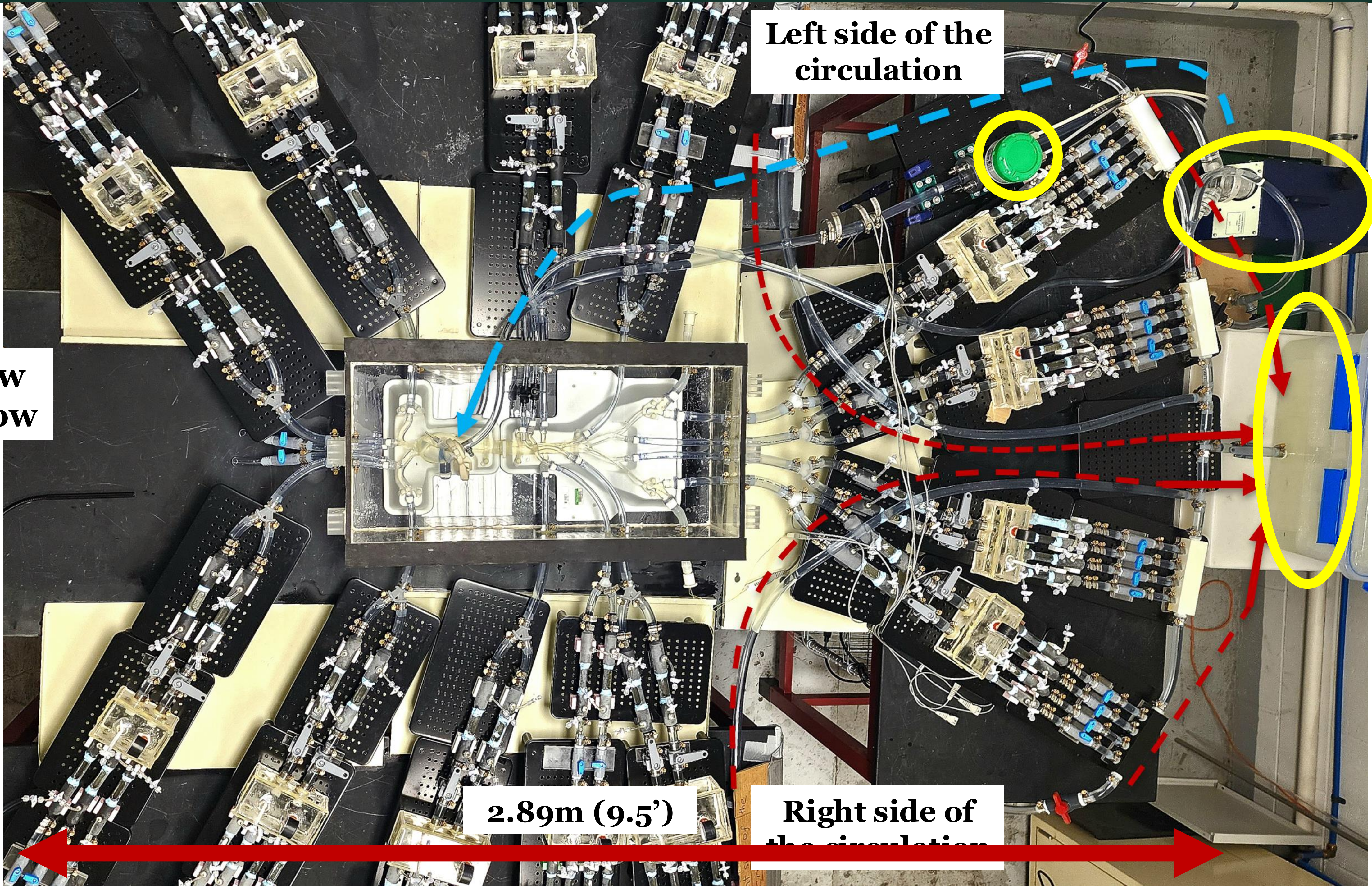
Modify the simulator to model Branched artery & Solid organ injuries

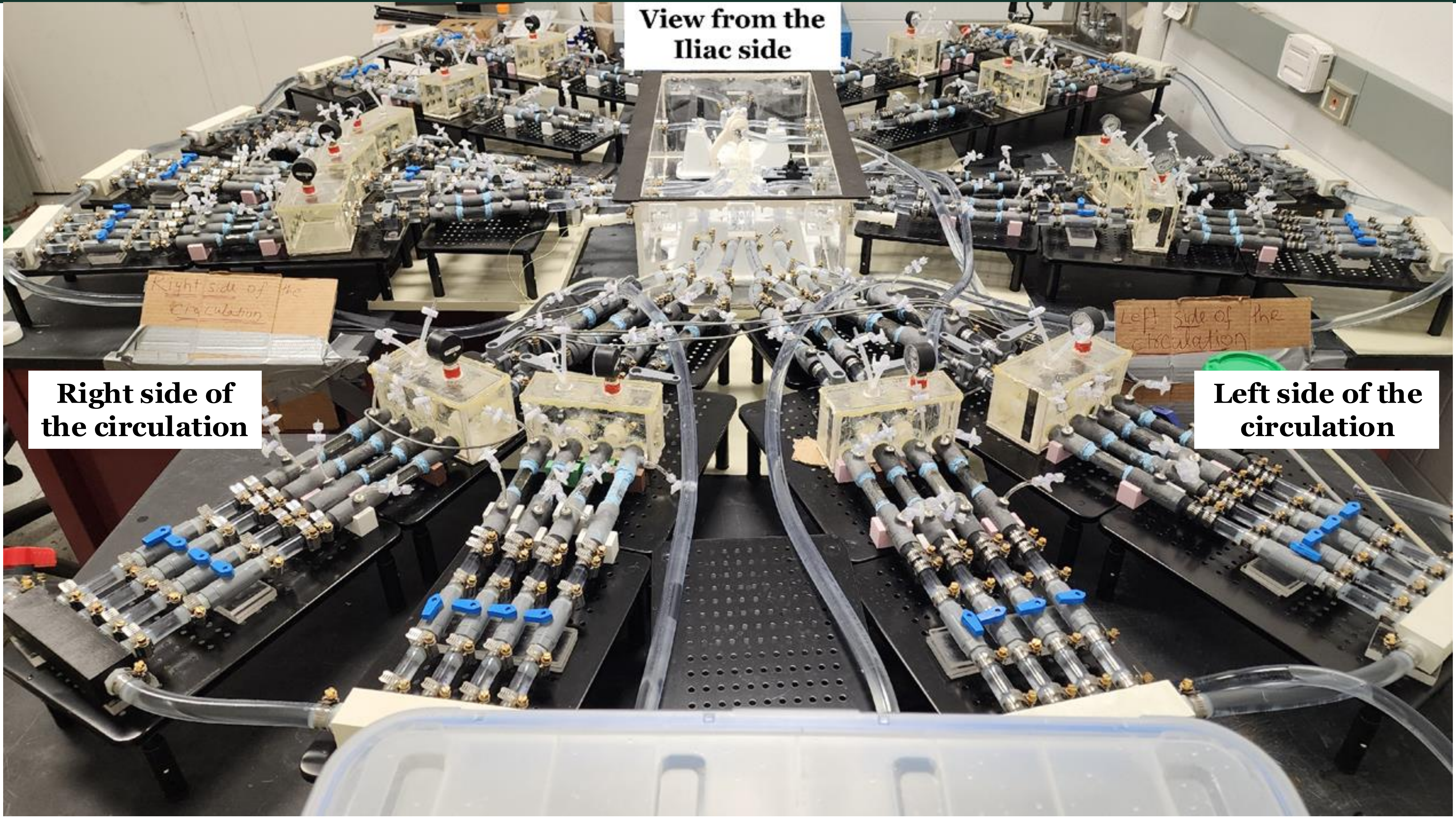
Only pressure-based endovascular hemorrhage localization investigated

Explore endovascular velocity & flow-based localization

The NCTH Simulator

Inflow
Outflow




View from the Iliac side
Right side of the circulation
Left side of the circulation
Right side of the circulation
Left side of the circulation

Acknowledgements

A huge Thank You to our collaborators:

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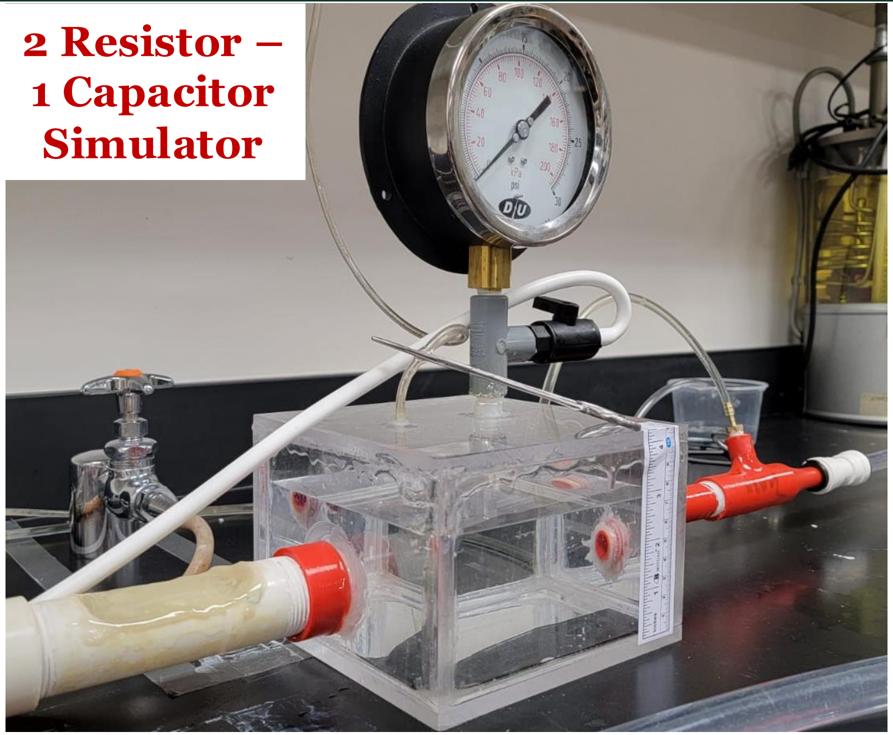
Adam Willis, MD, PhD – Department of Neurology & Rehabilitation Medicine; Uniformed Services University of Health Sciences, Bethesda, MD

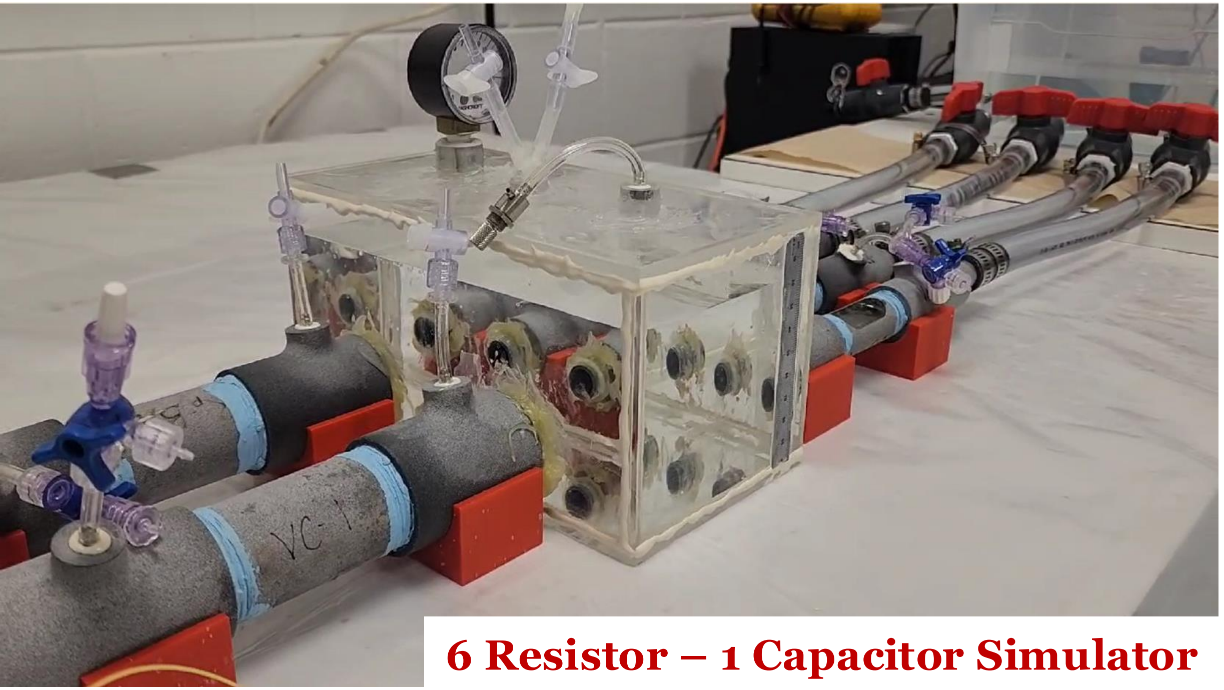
Marlin Wayne Causey, MD – Brooke Army Medical Center, Department of Surgery, San Antonio, TX

2 Resistor – 1 Capacitor Simulator



2 Resistor – 1 Capacitor Simulator

Thank You!

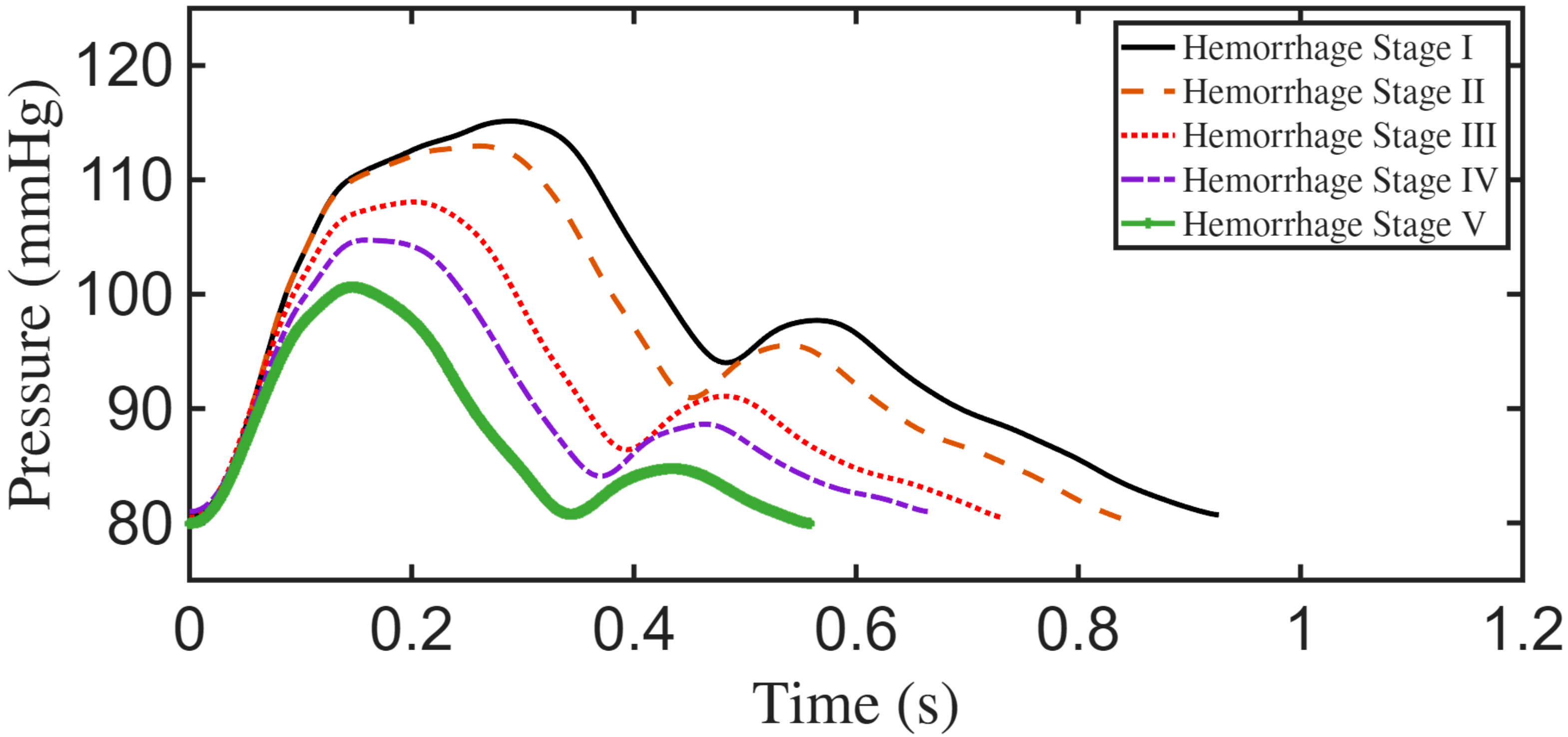


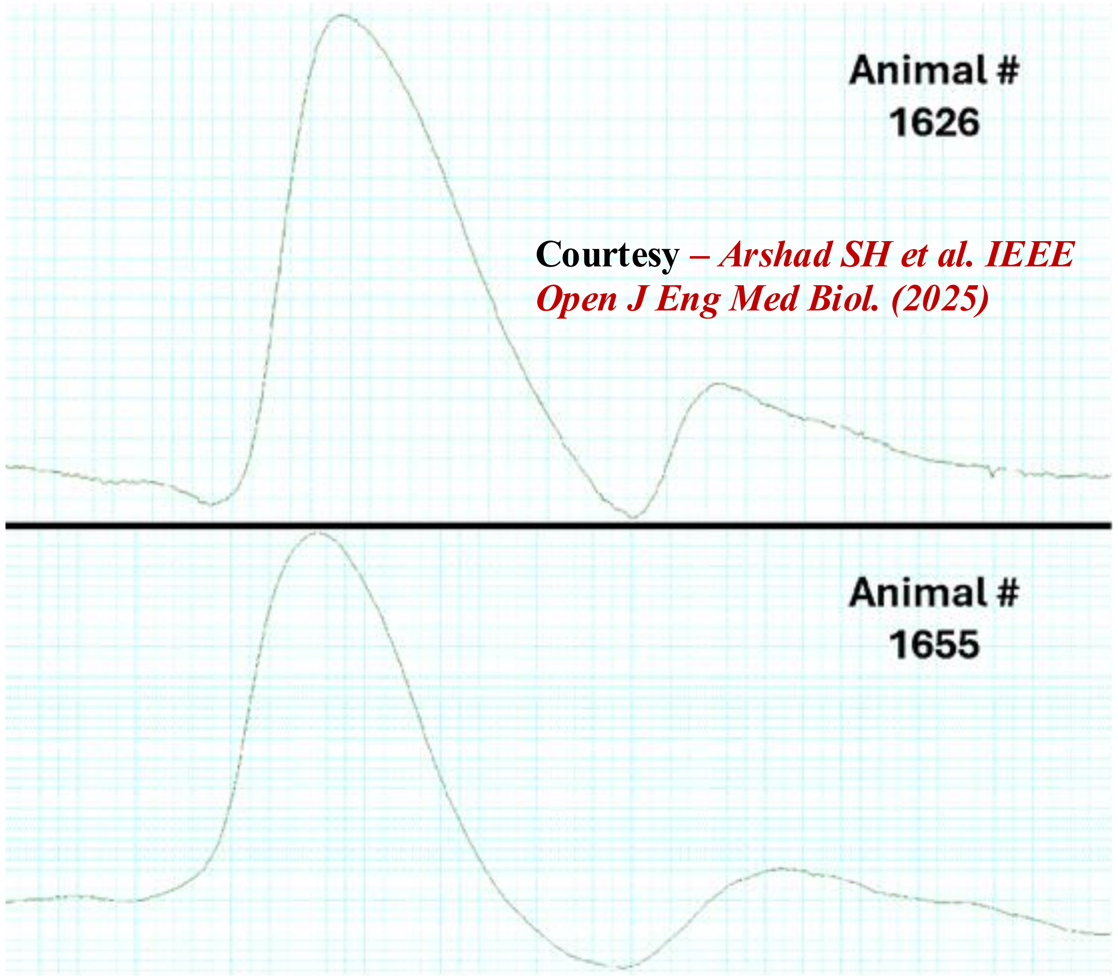
6 Resistor – 1 Capacitor Simulator

76 Resistor – 13 Capacitor Simulator

Backup Slides

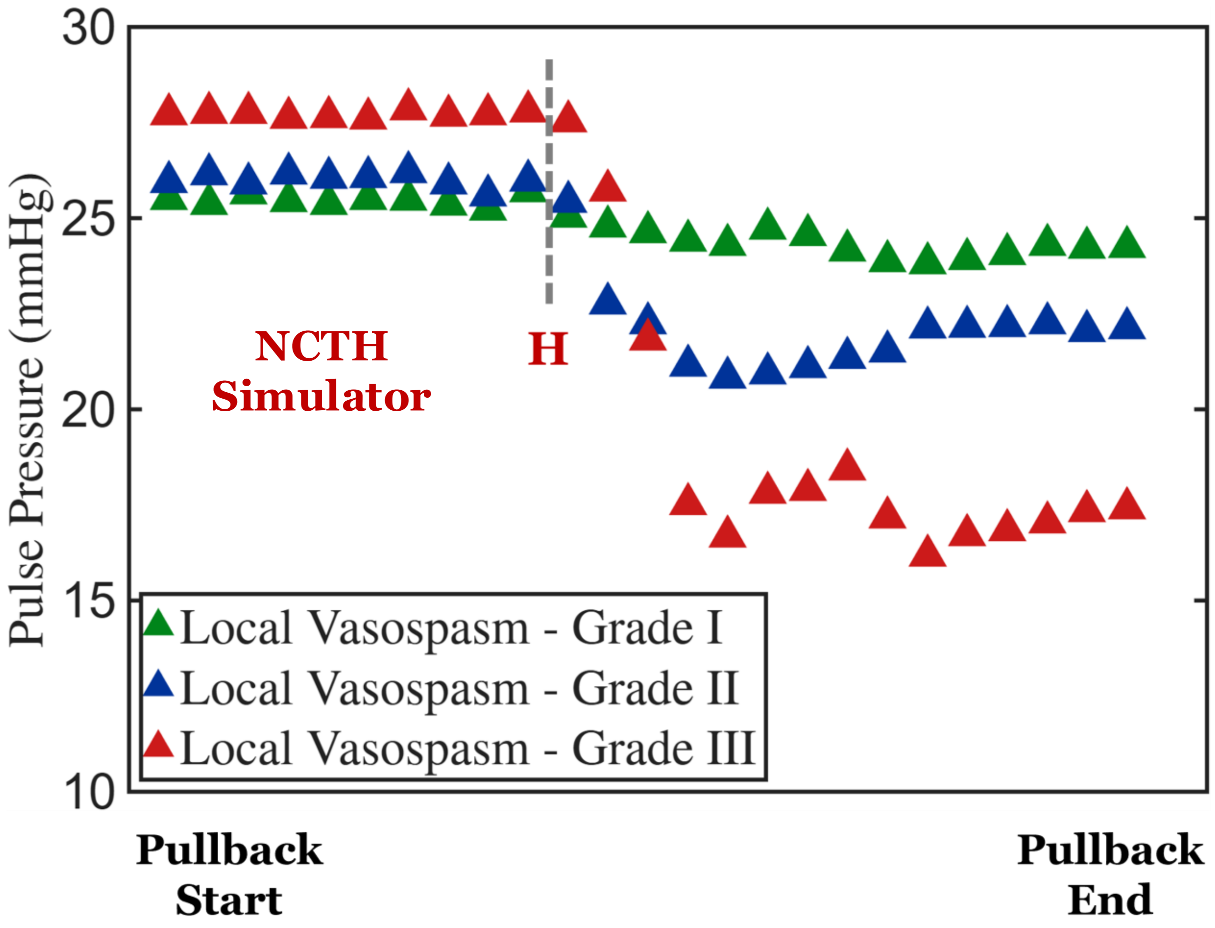
Waveform Morphology Comparison with Porcine data

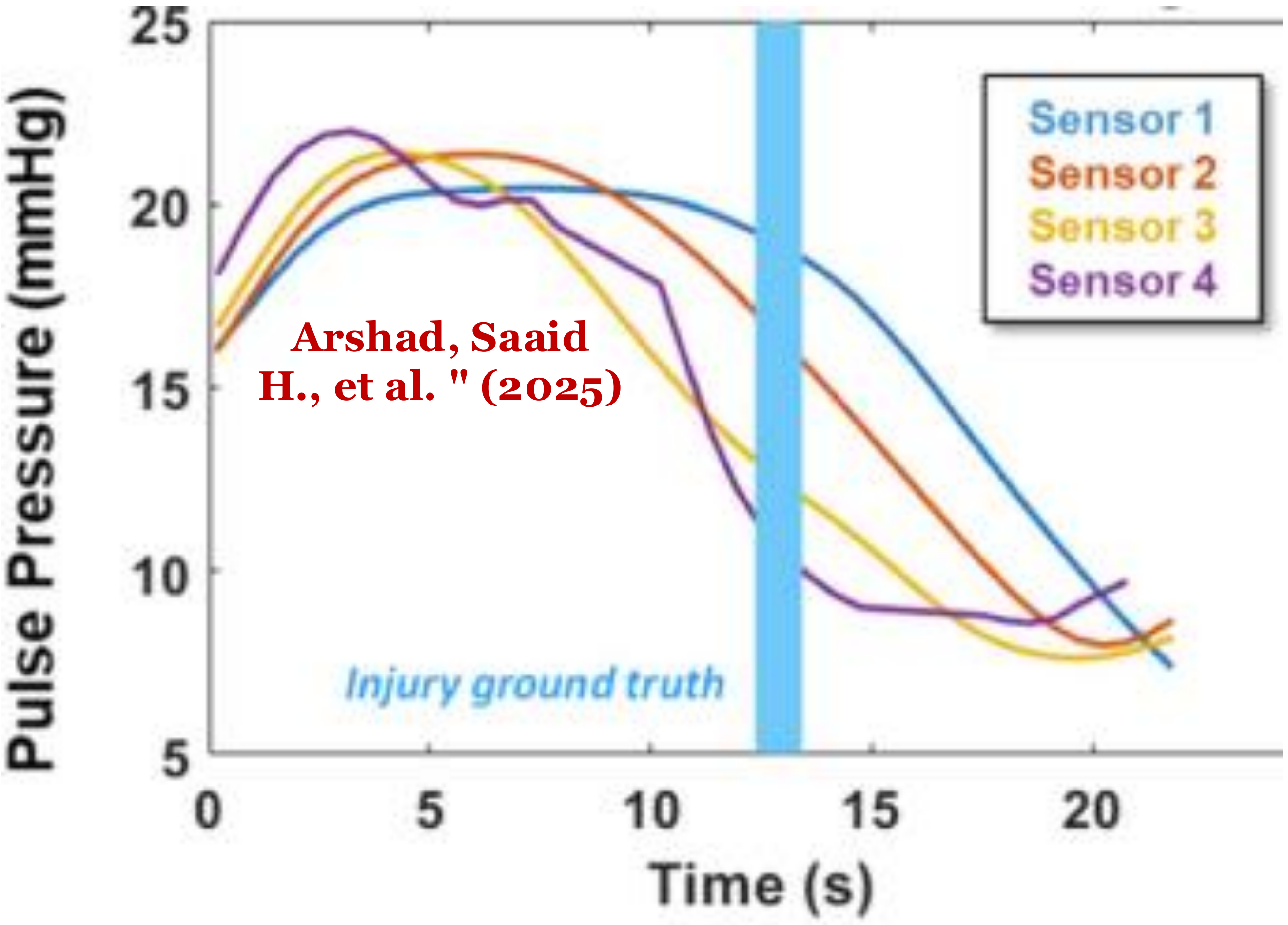




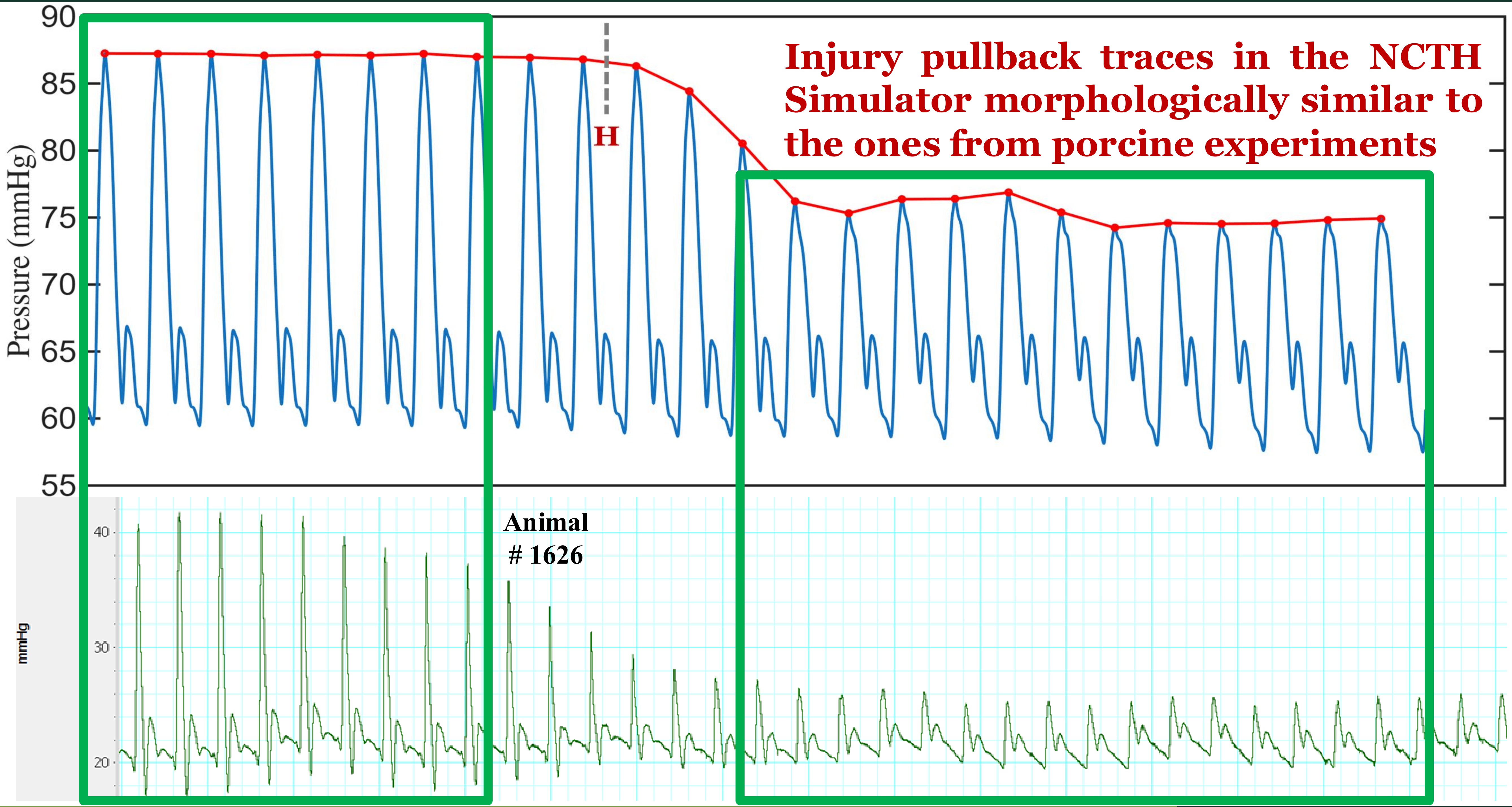
Dicrotic wave pattern attributed to a combination of High HR + Reduced PP + Increased downstream resistance

Endovascular Localization of Hemorrhage (Porcine Comparison)



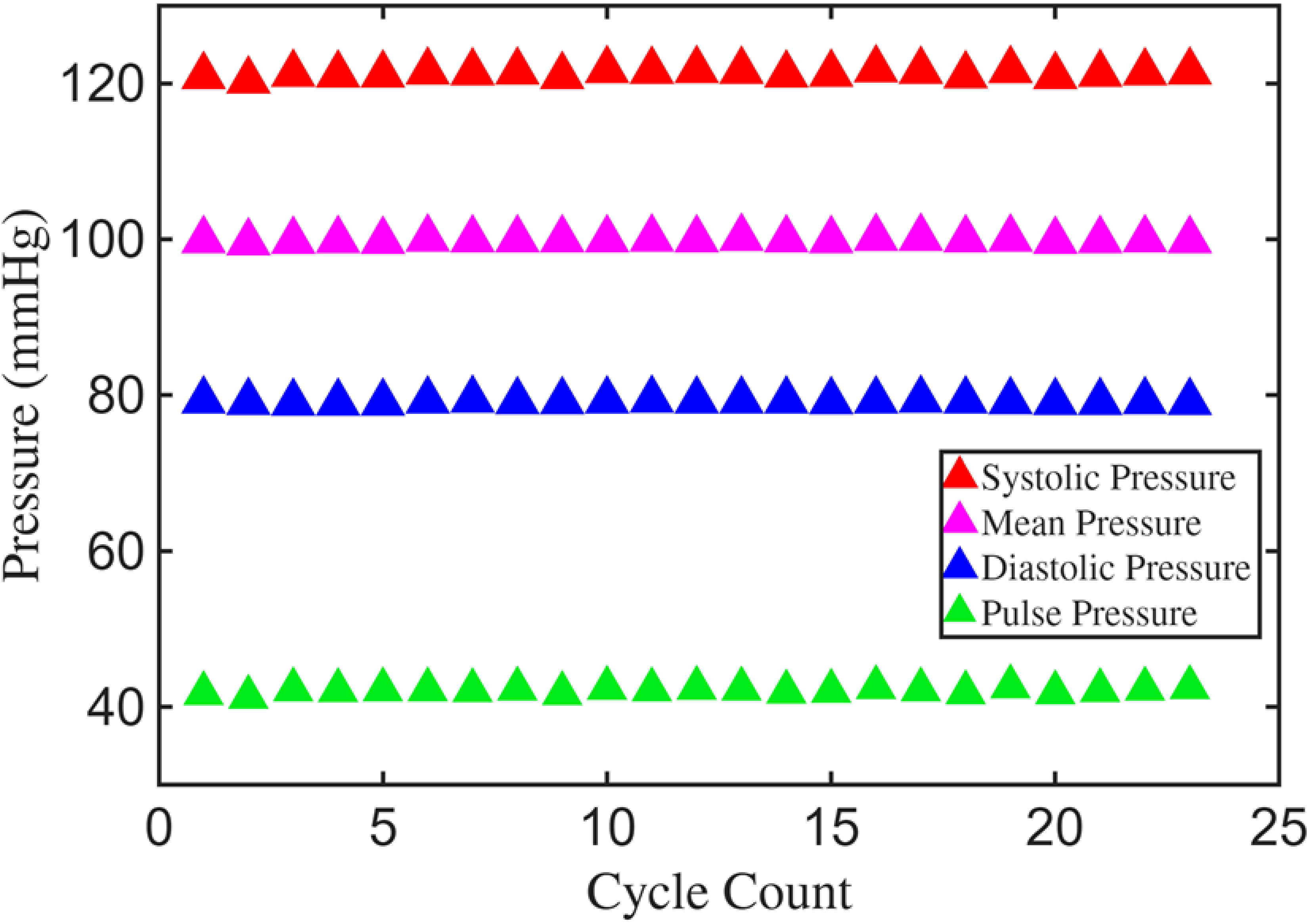


NCTH Simulator reproduced the Pulse Pressure based hemorrhage localization signature seen in the porcine experiments for a known Zone 1 aortic hemorrhage



Injury pullback traces in the NCTH Simulator morphologically similar to the ones from porcine experiments
Pressure (mmHg)
90
85
80
75
70
65
60
55
H
Animal # 1626
mmHg
40
30
20

Repeatability

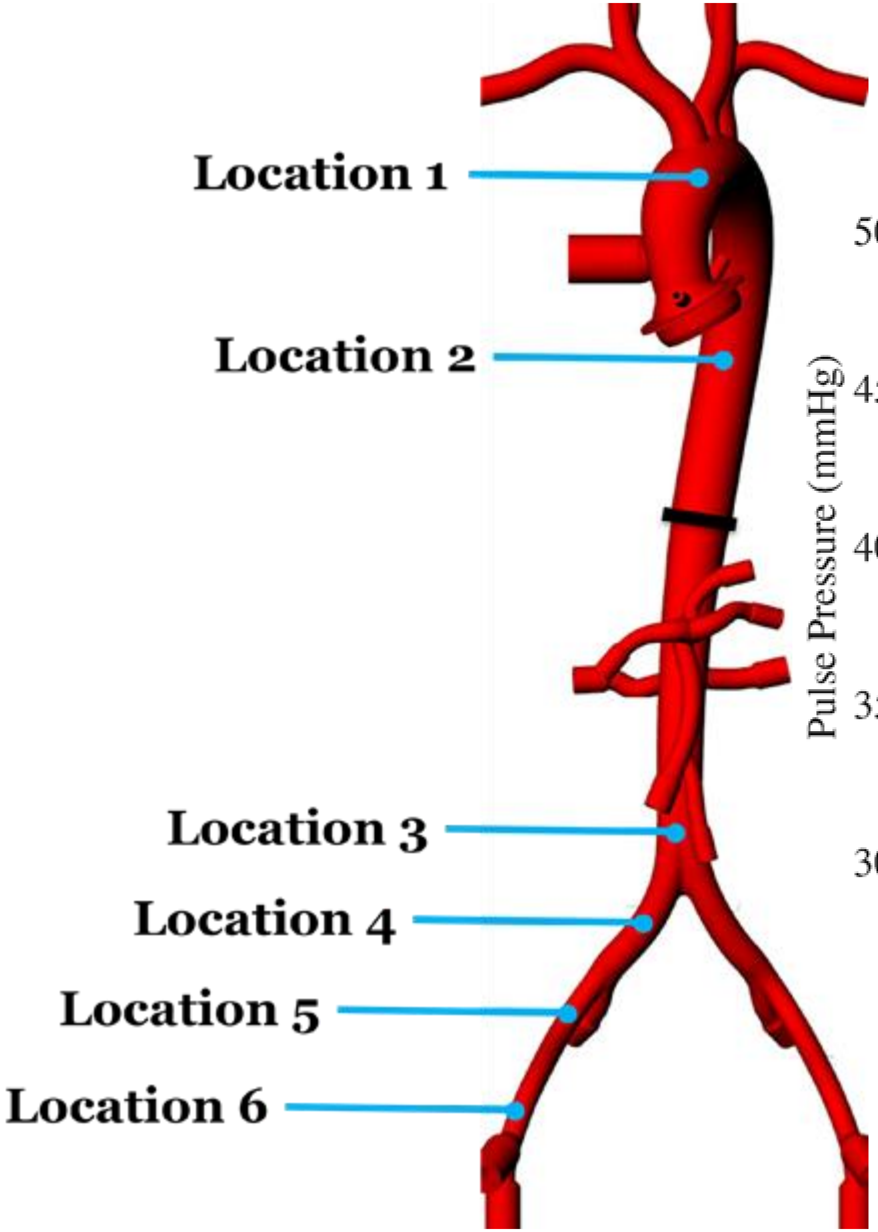


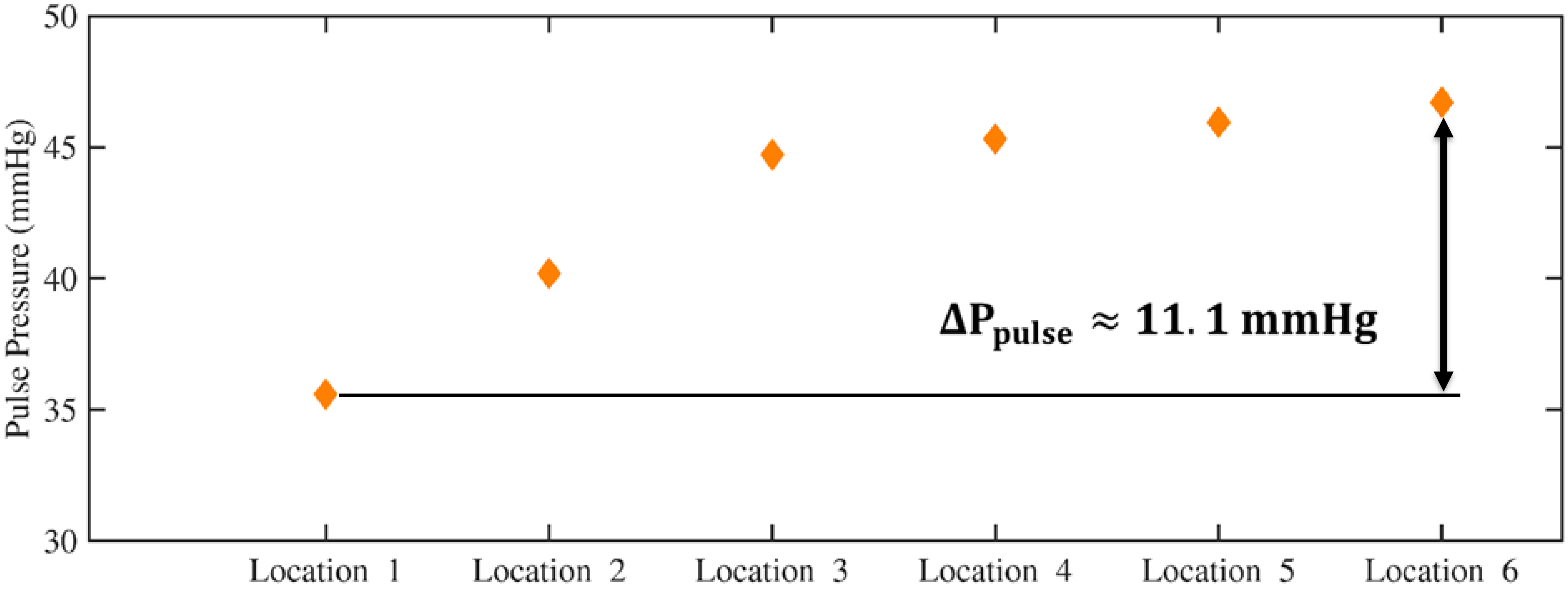
- Coefficient of Variation (CV):

$$CV = \left(\frac{\sigma}{\text{Mean}}\right) X\ 100$$

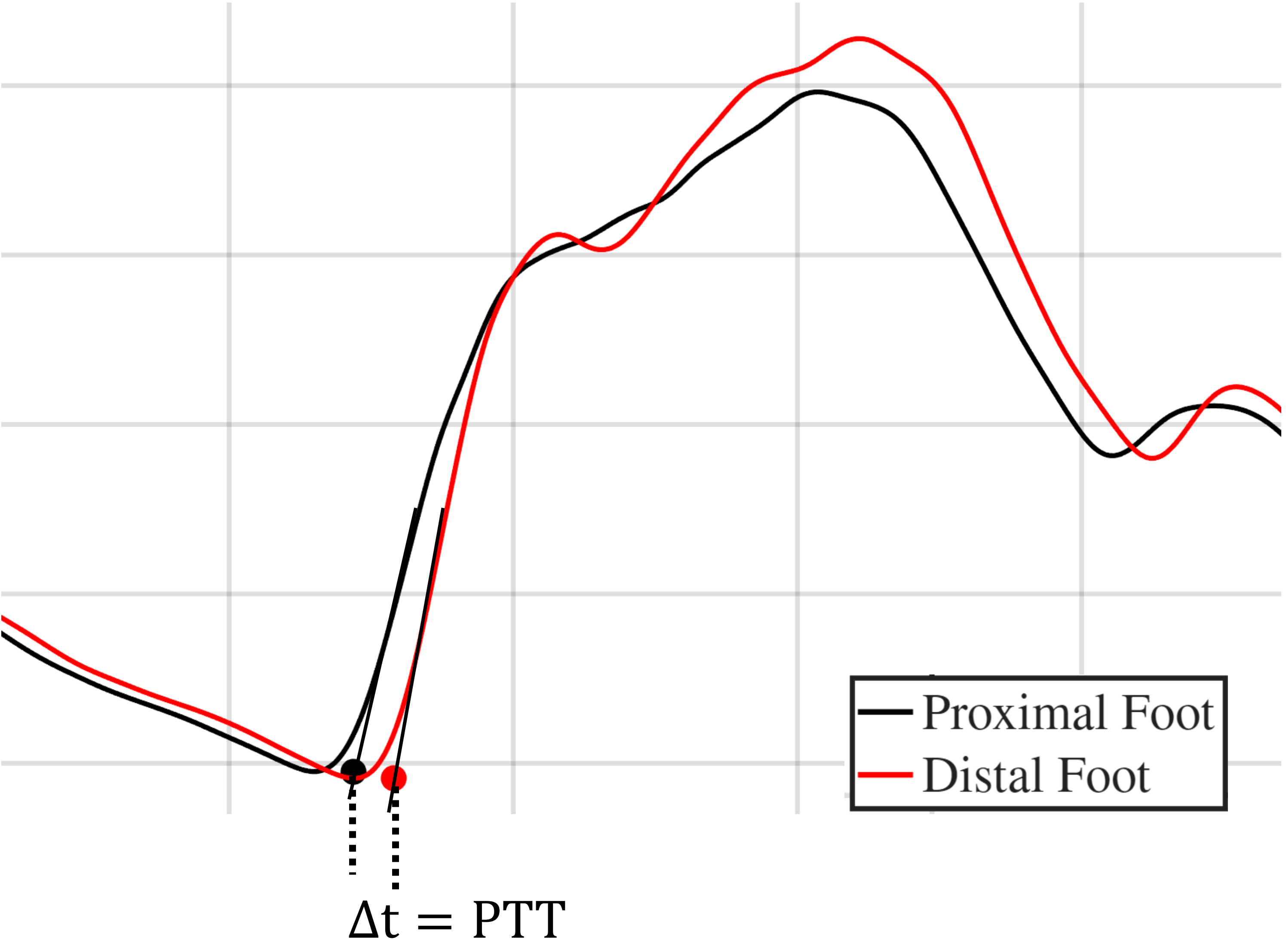
- $CV_{Systole} = 0.28\%$
- $CV_{Mean} = 0.13\%$
- $CV_{Diastole} = 0.15\%$
- $CV_{Pulse} = 0.72\%$
- High Repeatability

Pulse Pressure Augmentation





Aortic Pulse Wave Velocity



PTT determined using the intersecting tangent method

- Experimental aortic PWV (aPWV):

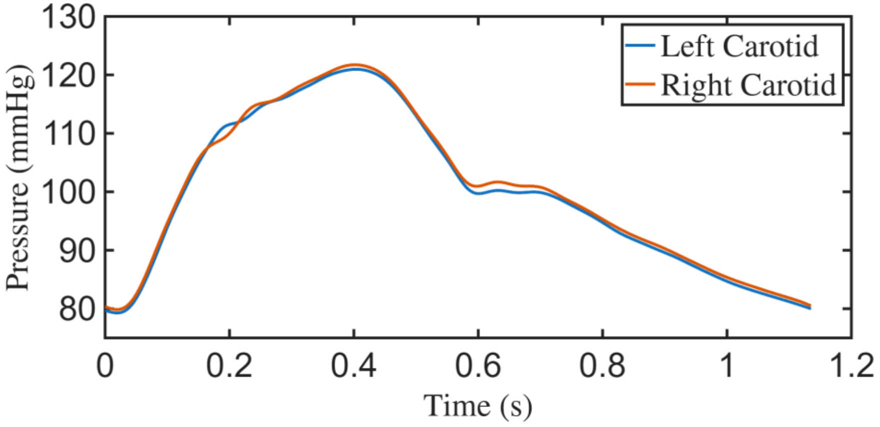
$$\overline{\text{aPWV}} = \sum_{i=1}^{23} \frac{\Delta x}{\text{PTT(i)}} = \mathbf{9.92\ m/s}$$

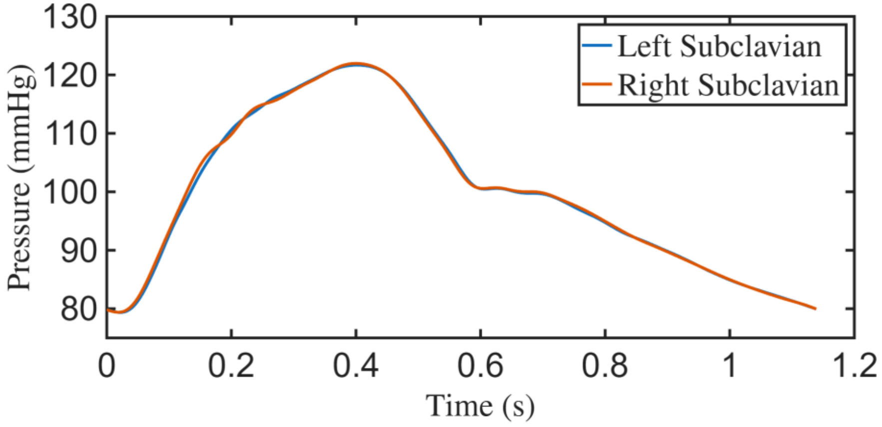
- Higher value representative of a middle-aged to an older adult aPWV
- Attributed to higher stiffness of the aortic phantom (E = 0.73 MPa)
- More compliant phantom (E ≈ 0.1 – 0.3 MPa) needed to achieve lower aPWV

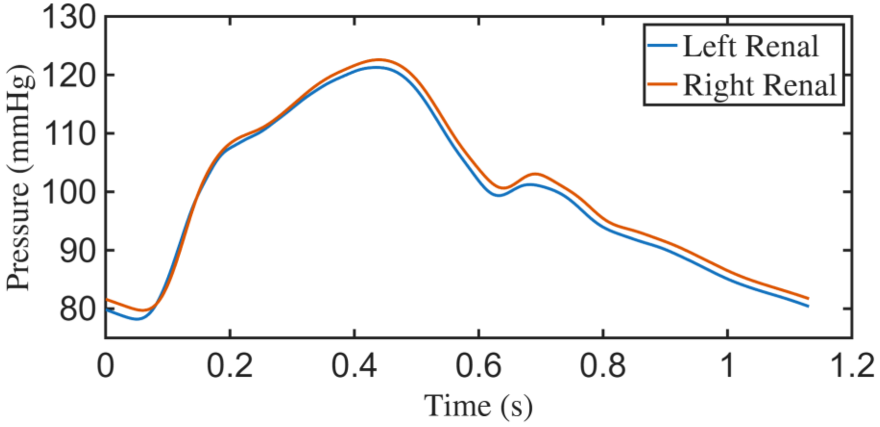
Jeong, Jae-Hak, et al. ***Scientific Reports 13.1 (2023)***

- Strong agreement **(2.1%)** with Womersley model derived theoretical aPWV

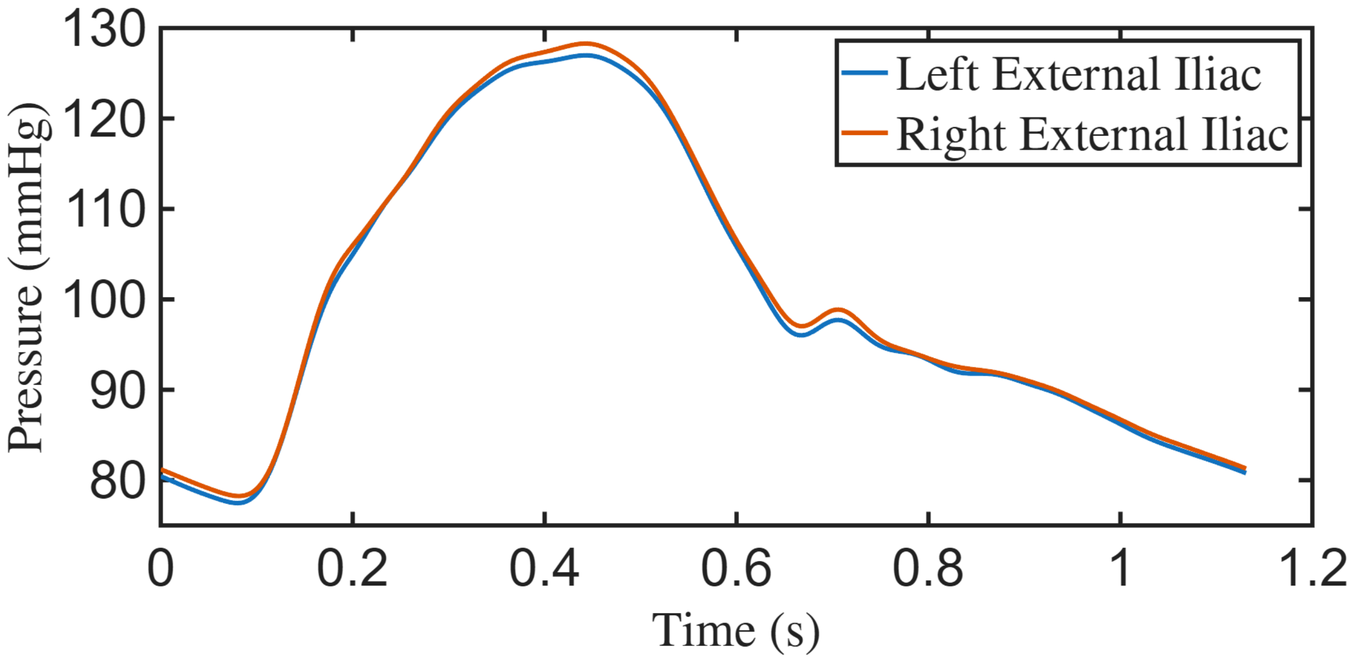
Bilateral Hemodynamic Symmetry

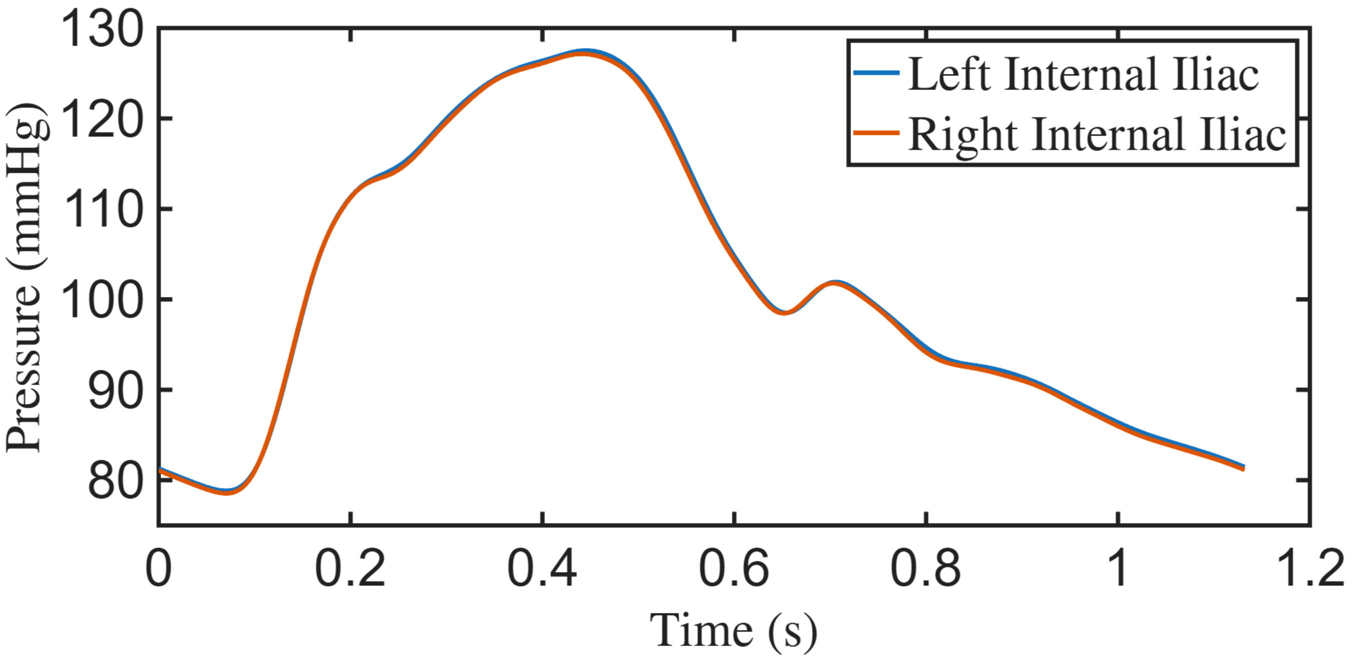




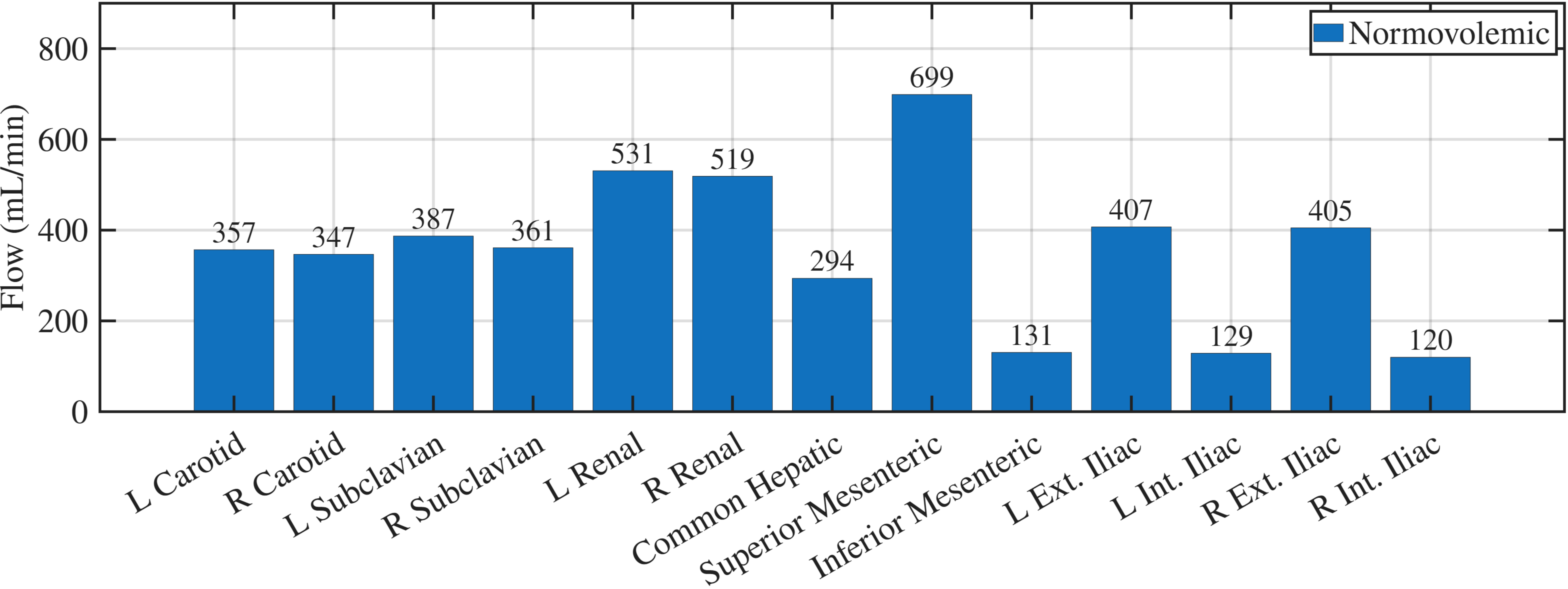


Reproducible Impedance Modules



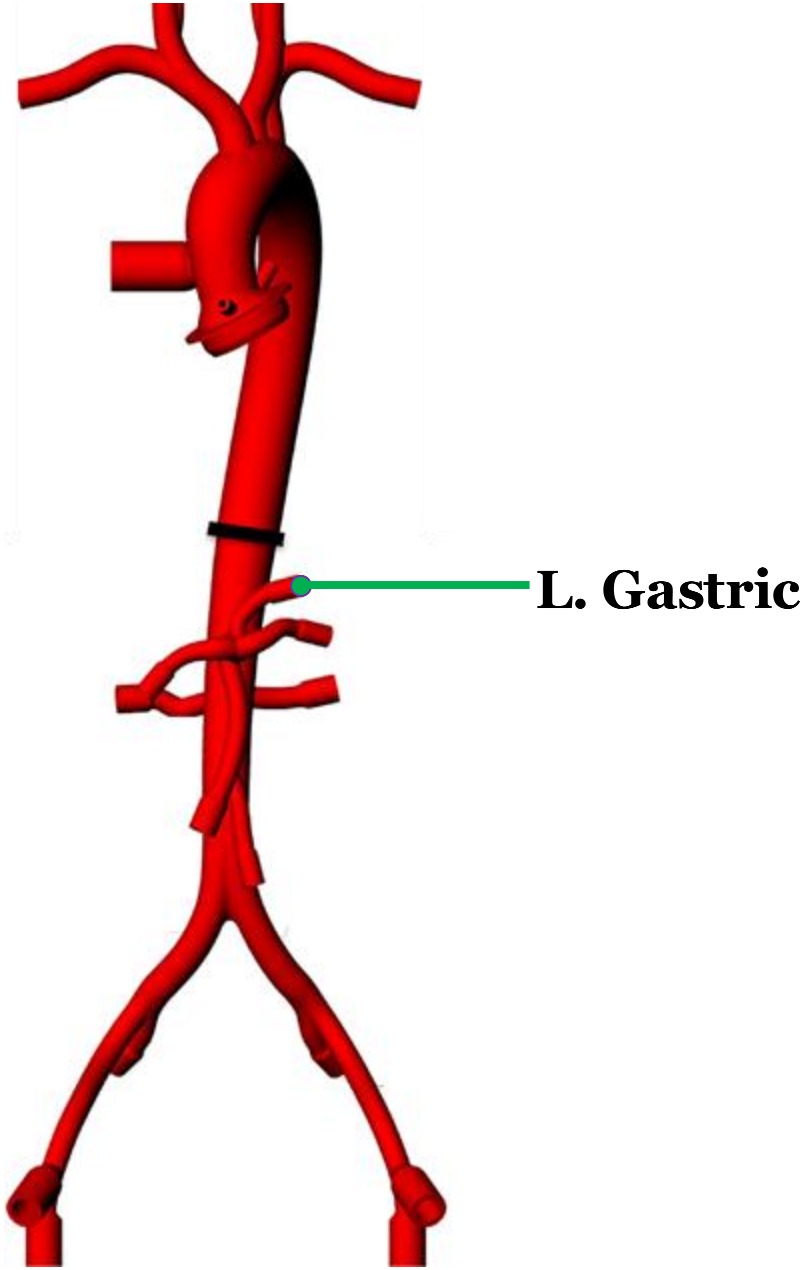


Normovolemic Branch Mean Flowrates



Highest flowrates carried by Superior Mesenteric and the Renals

Non-Compressible Torso Hemorrhage – Systemic Level

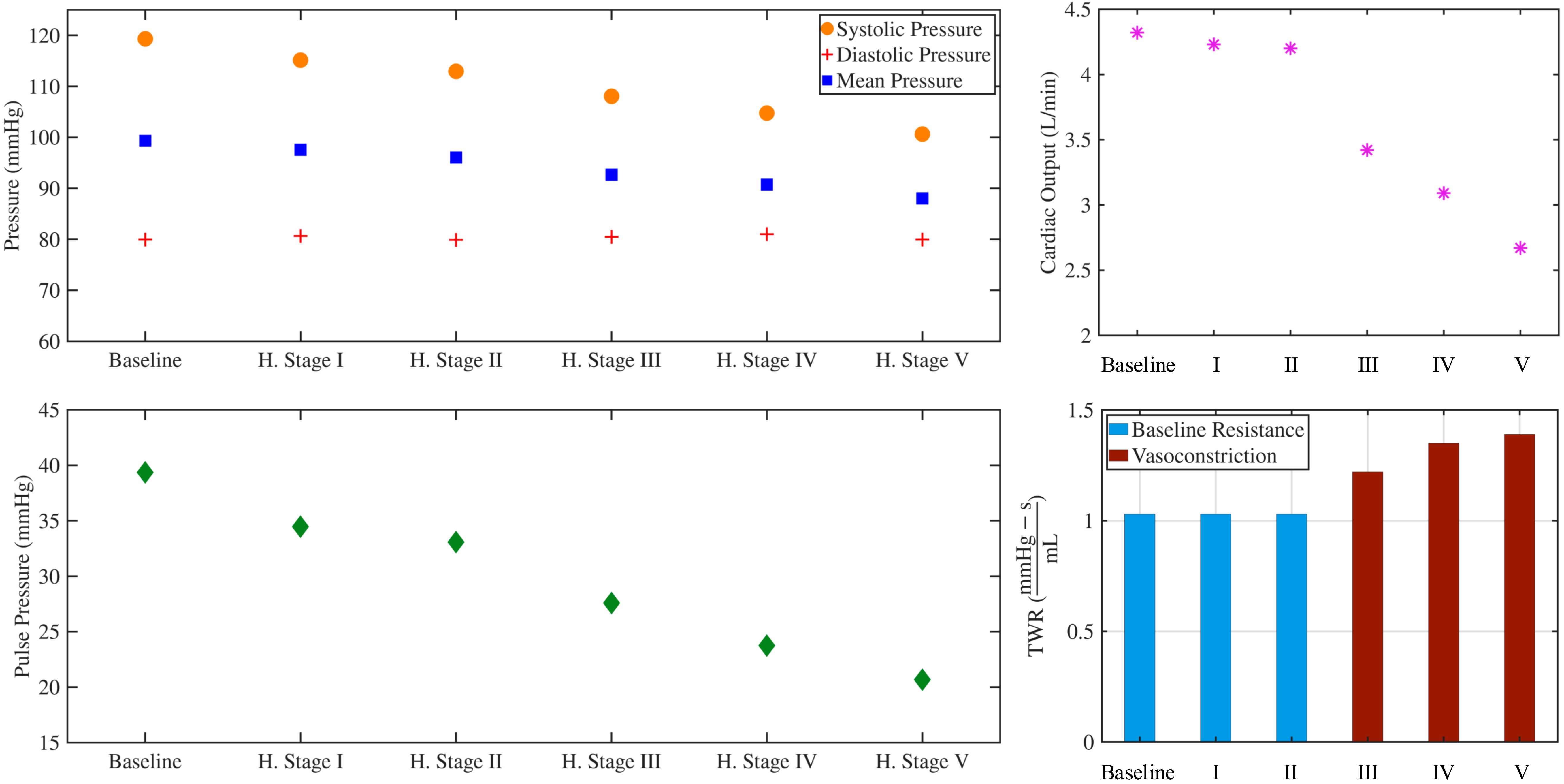


A Zone 1 aortic hemorrhage mimicked via a bleed from **left gastric artery** at ≈ **1.1 mL/sec**

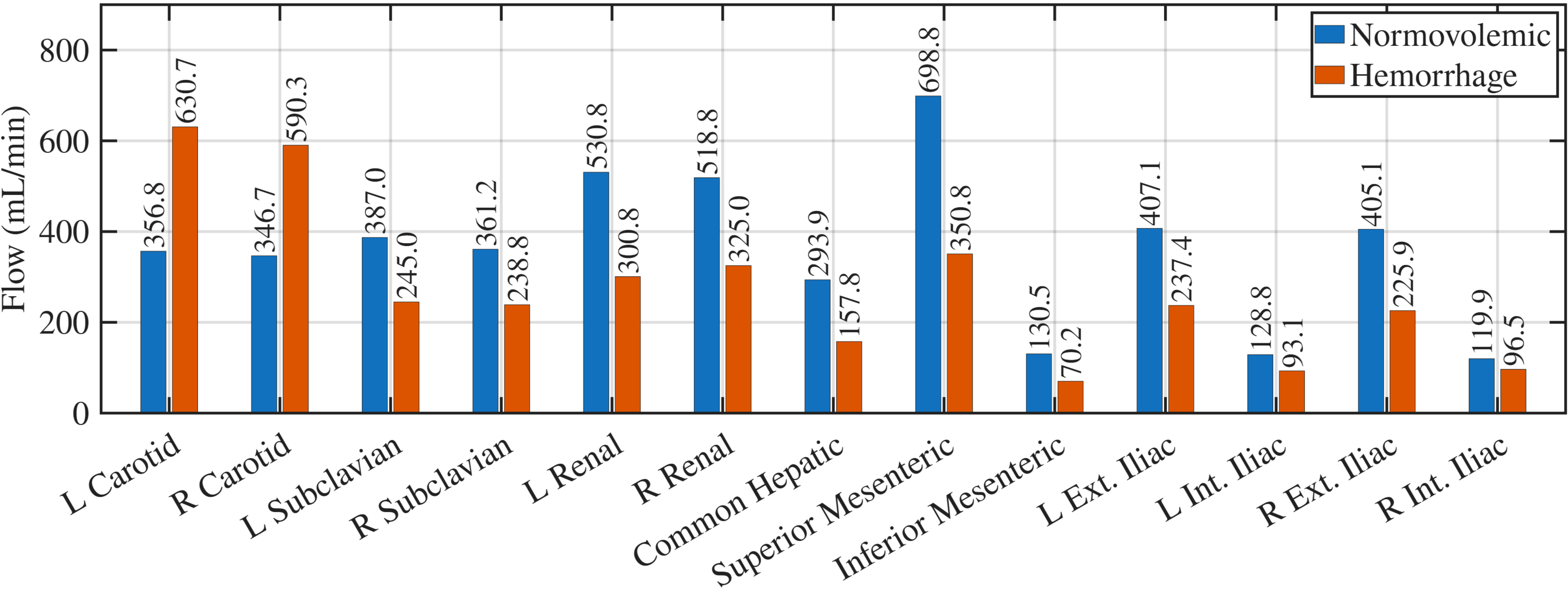
Volume loss mimicked by a **reduced SV**

Compensatory response introduced in two phases:
1. Tachycardia **(Increased pump stroke rate)**

2. Tachycardia + Peripheral Vasoconstriction **(Increased Total Windkessel Resistance)**


Systolic Pressure
Diastolic Pressure
Mean Pressure
Pressure (mmHg)
120
110
100
90
80
70
60
Baseline
H. Stage I
H. Stage II
H. Stage III
H. Stage IV
H. Stage V
Cardiac Output (L/min)
4.5
4
3.5
3
2.5
2
Baseline
I
II
III
IV
V
Pulse Pressure (mmHg)
45
40
35
30
25
20
15
Baseline
H. Stage I
H. Stage II
H. Stage III
H. Stage IV
H. Stage V
Baseline Resistance
Vasoconstriction
TWR (mmHg − s / mL)
1.5
1
0.5
0
Baseline
I
II
III
IV
V

Normovolemic and Hemorrhagic Mean Flowrates

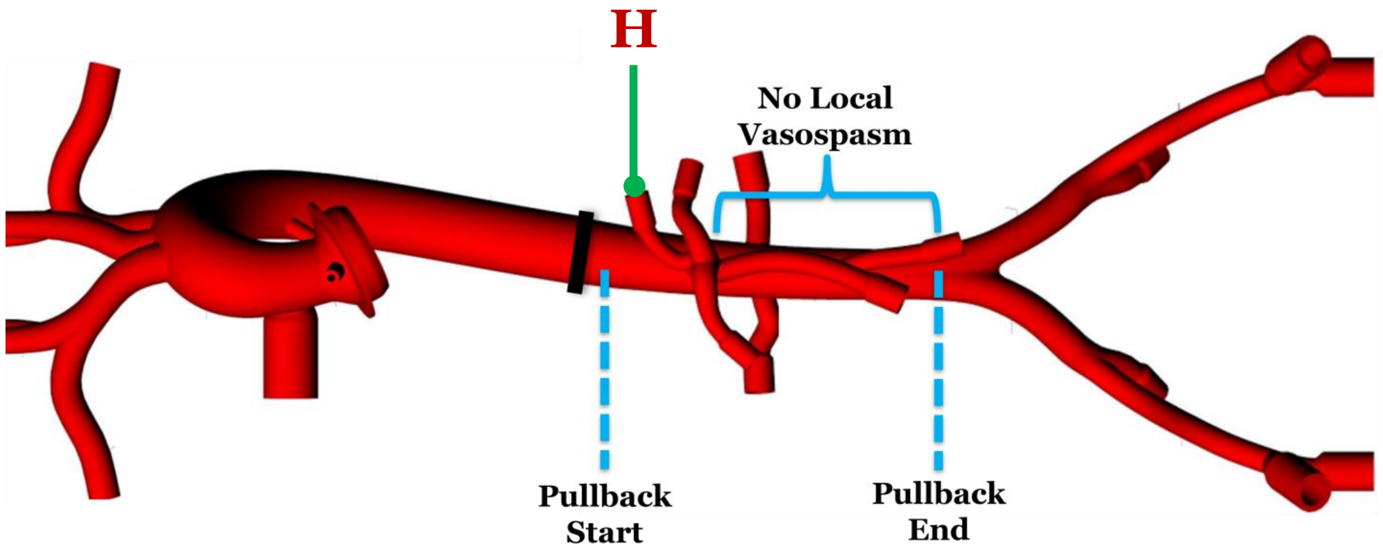


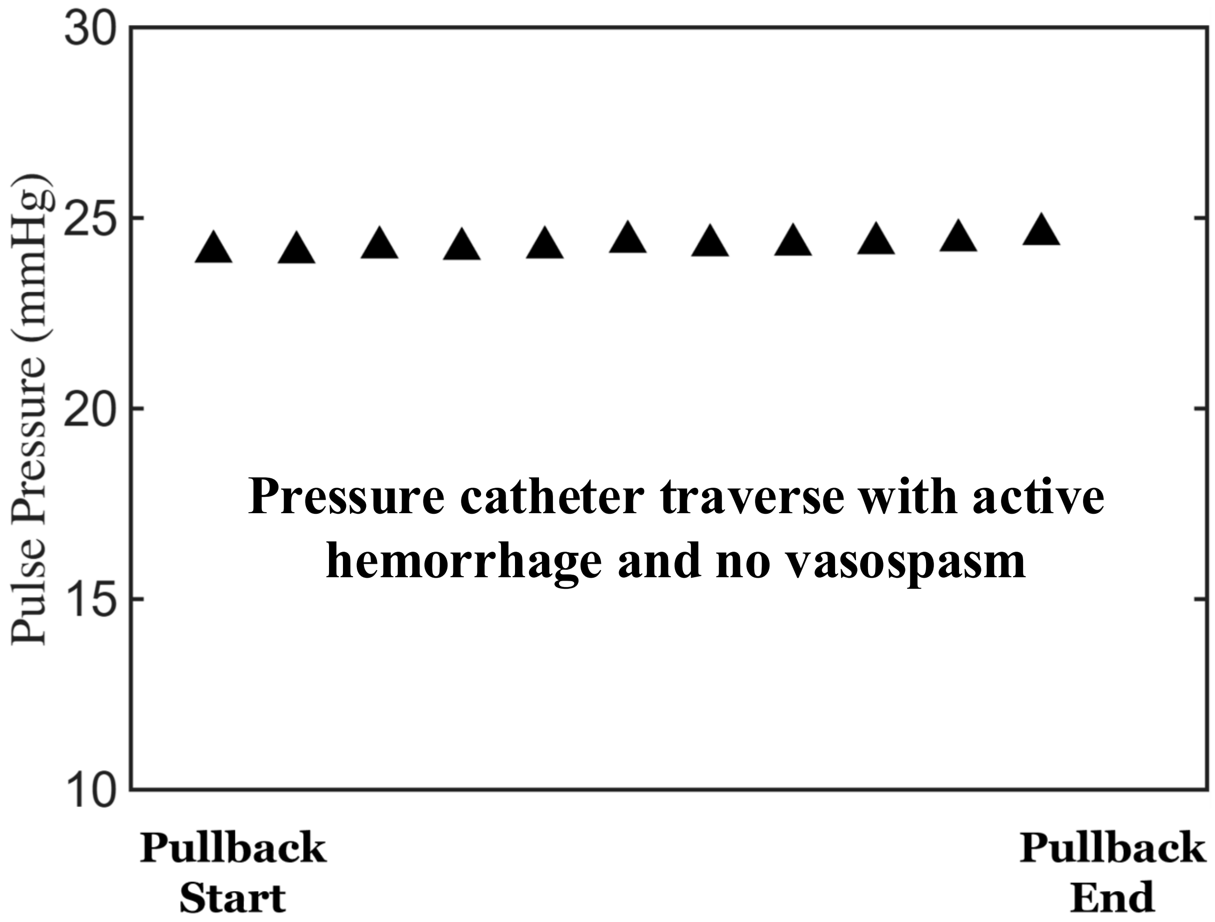
Higher than expected Carotid flowrate (H)

Operated Carotids close to Level II vasodilation

Fix: Operate Carotids at lower vasodilation or baseline level

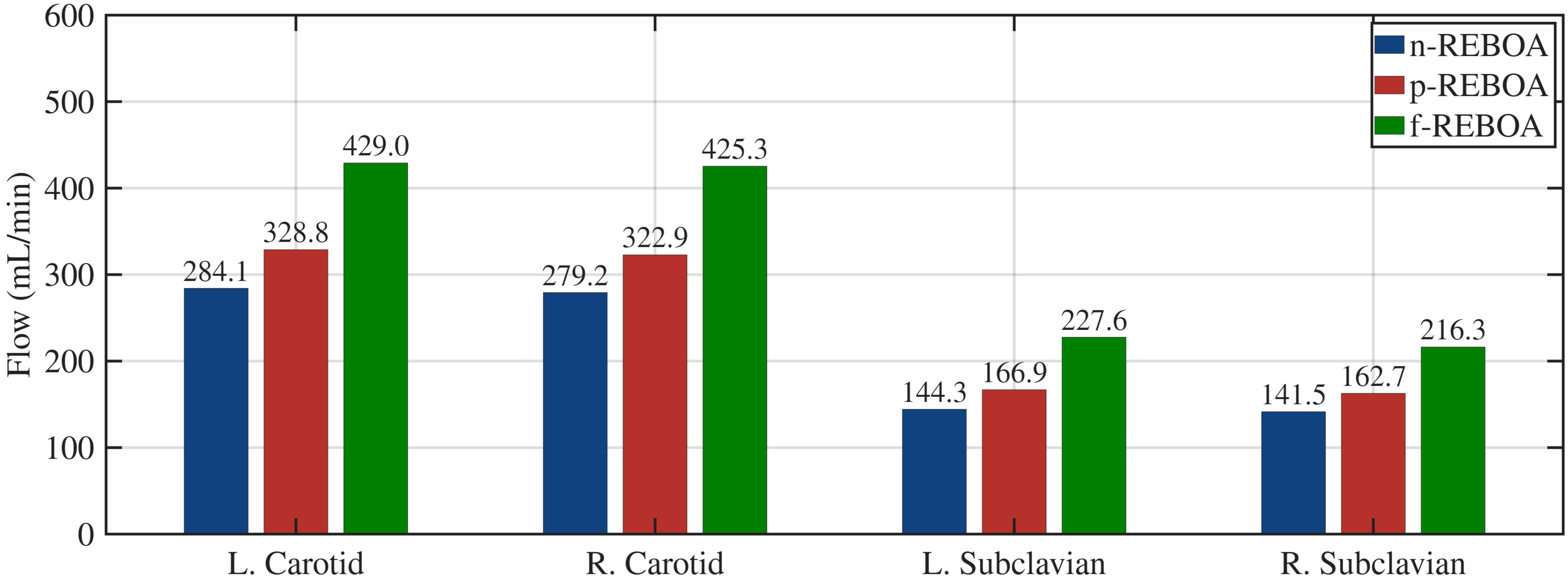
Endovascular Localization of Hemorrhage (Pulse Pressure based)





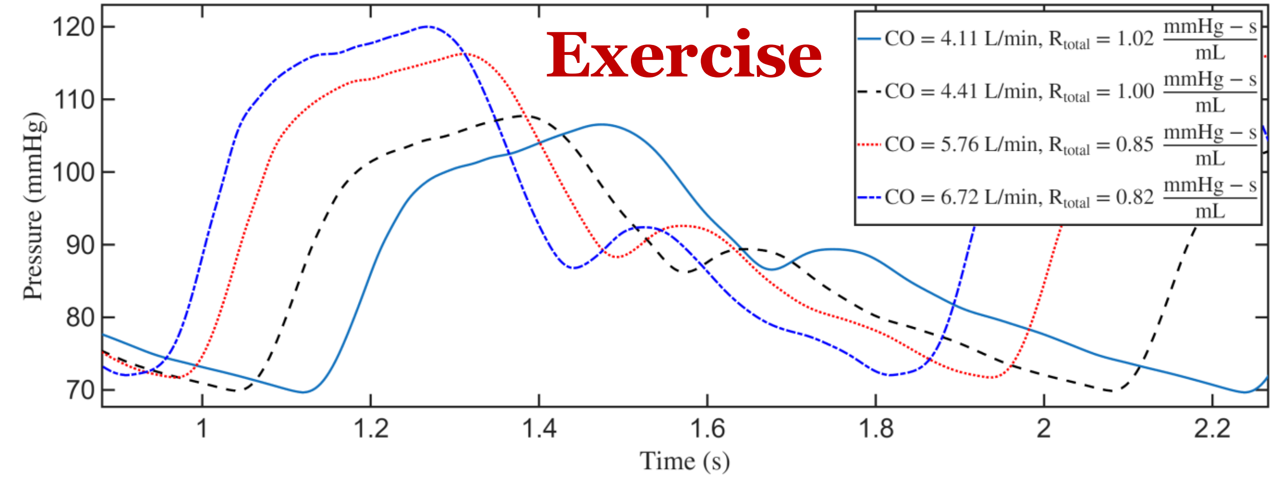
- Pulse Pressure based aortic hemorrhage localization study under hypovolemic conditions
- Control case – Hypovolemic catheter pullback with no vasospasm at injury location

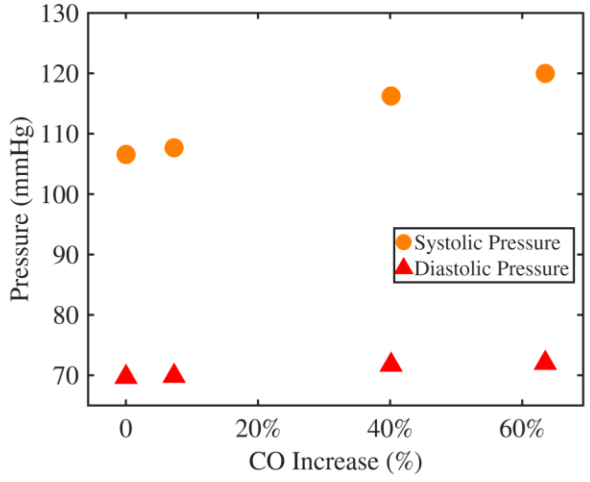
Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA)

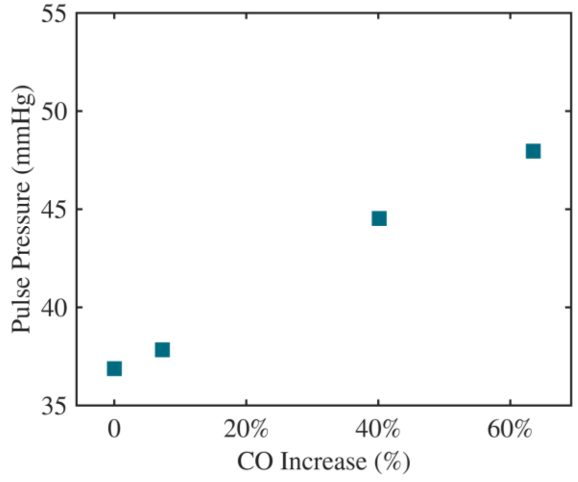


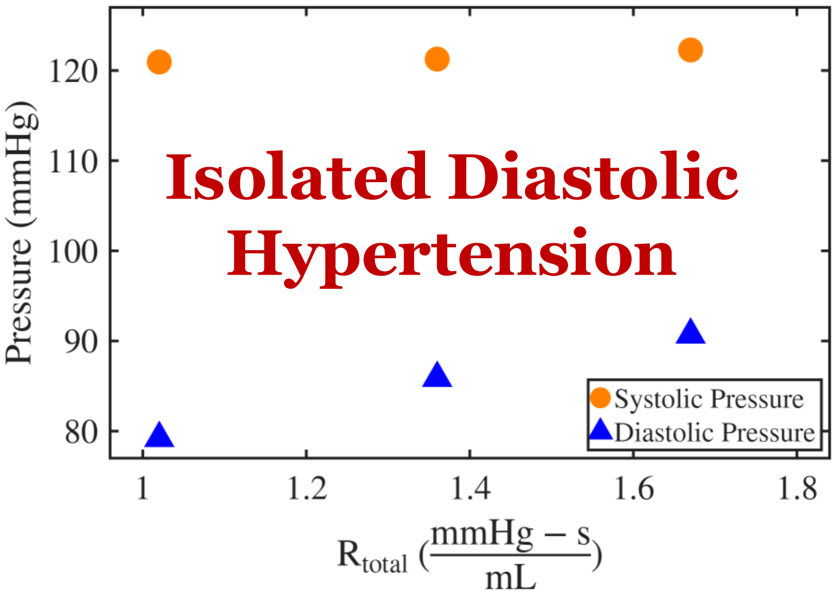
- Did not observe the supraphysiological increases in carotid flow observed in vivo
- **Dynamic cardiac feedback missing from the purely mechanical Pulsatile Pump**
- Supraphysiological increases attributed to afterload-driven supraphysiological increases in left ventricle contractility; **Stonko DP et al.** ***Frontiers in Physiology (2022)***
- **Avoided raising the pump SV to preserve phantom structural integrity**

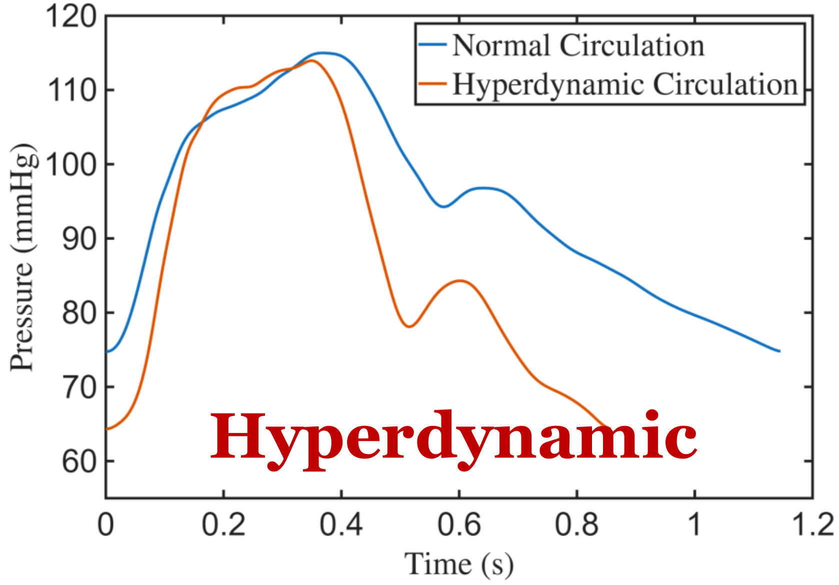
Additional Physiologies Simulated

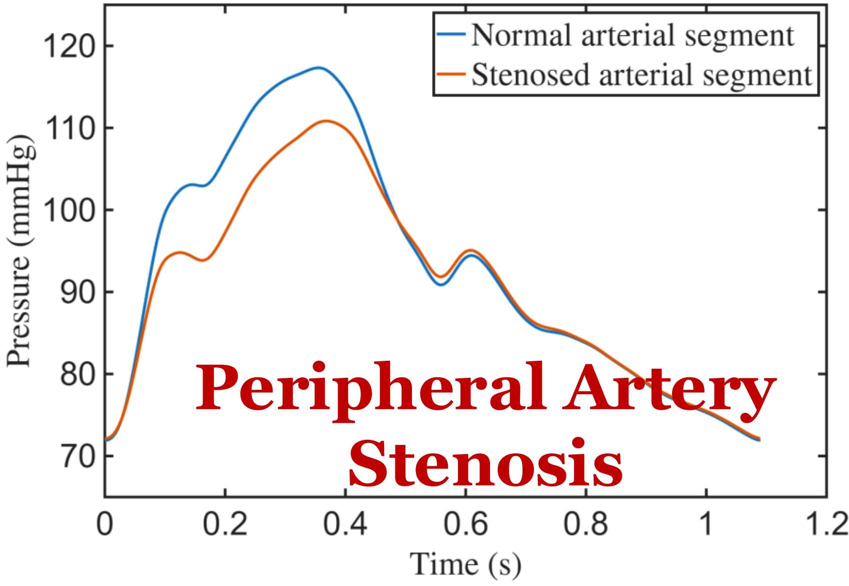




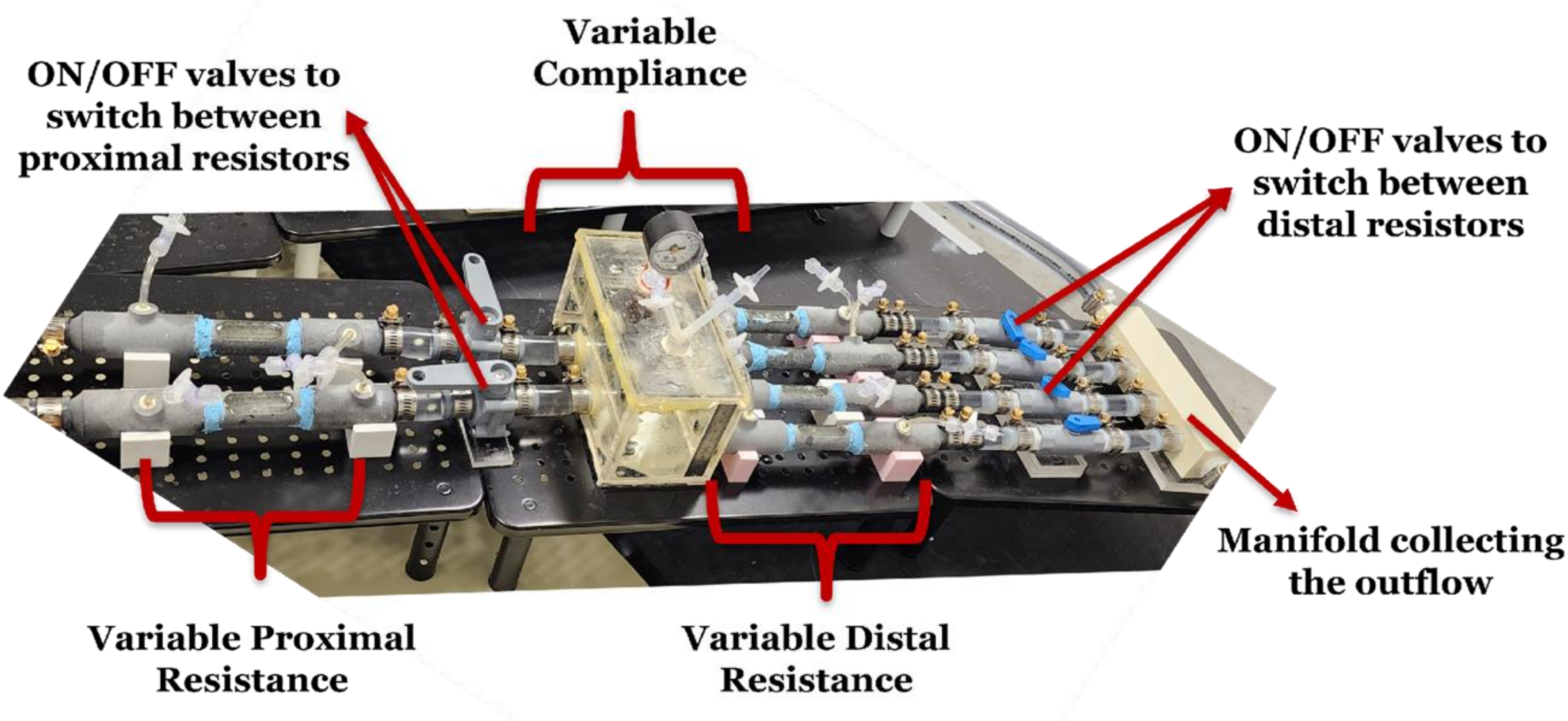




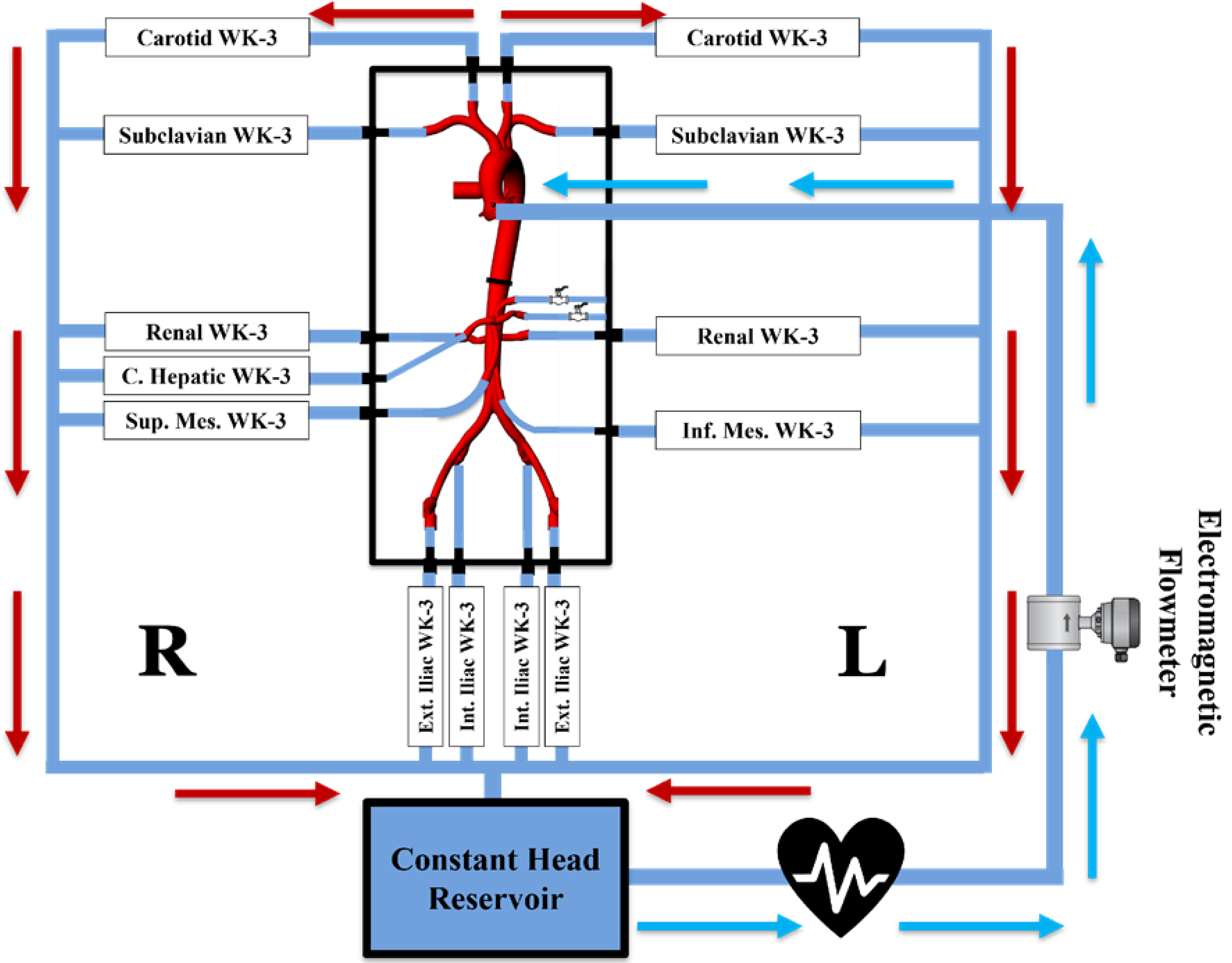




Assembled Windkessel Module



The NCTH Simulator



Limitations & Future Work

Vasospasm at the injury location enforced via external phantom compression	**Need precise characterization of local vasospasm profile at injury location for fabricating customized phantoms**
Cerebral autoregulation hemorrhage response of vasoconstriction & vasodilation not modeled	**Should replace the higher distal vasodilation resistor with a medium distal vasoconstriction resistor**
Currently only modeling aortic hemorrhages	**Modify the simulator to model Branched artery & Solid organ injuries**
Only pressure-based endovascular hemorrhage localization investigated	**Explore endovascular velocity & flow-based localization**