MR Image-Based Hydrodynamics in Type I Chiari Malformation

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Acknowledgements

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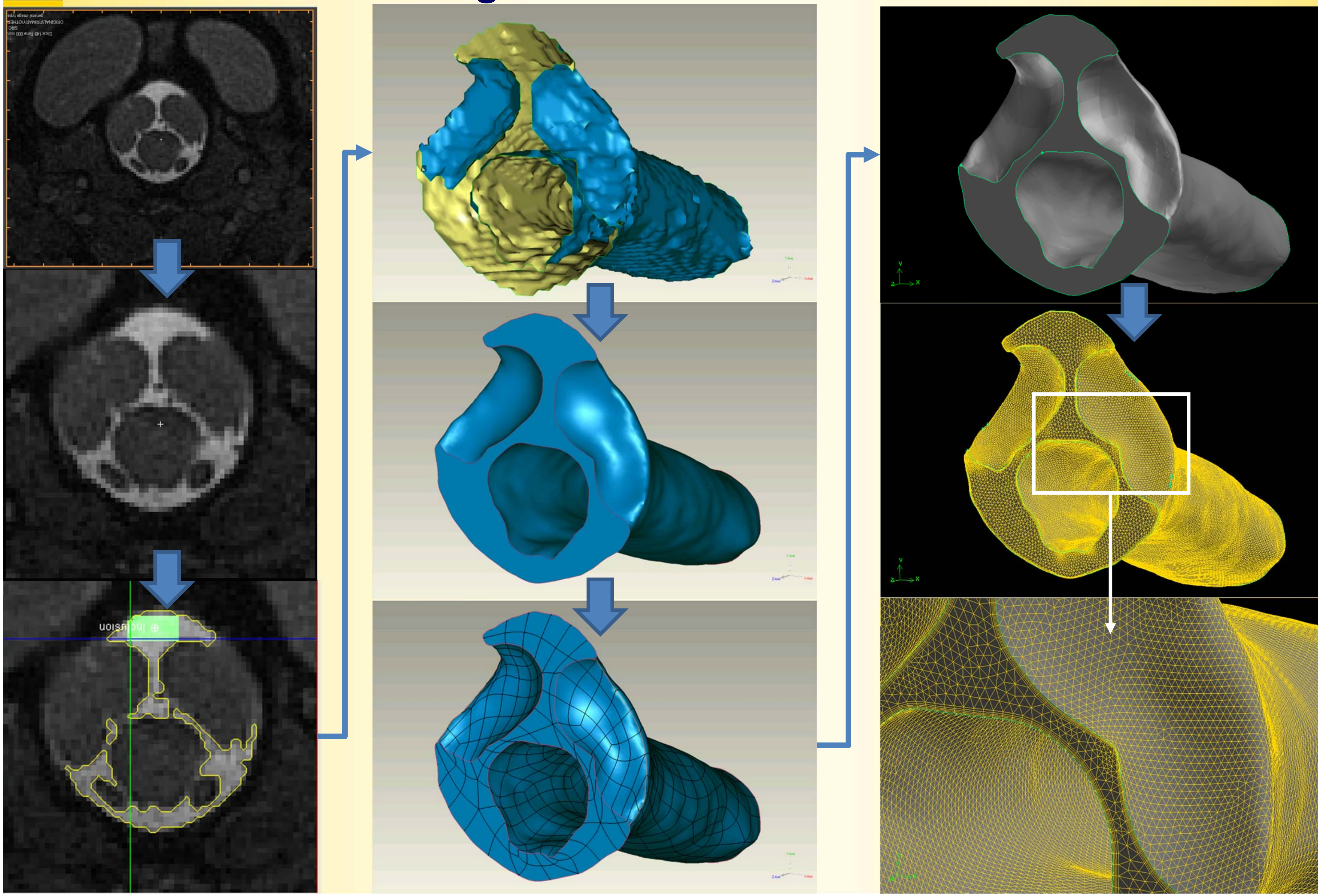
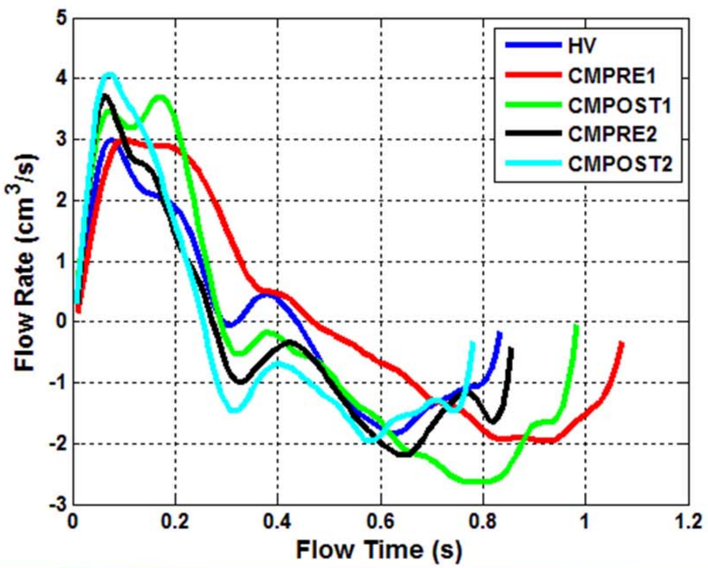
Outline

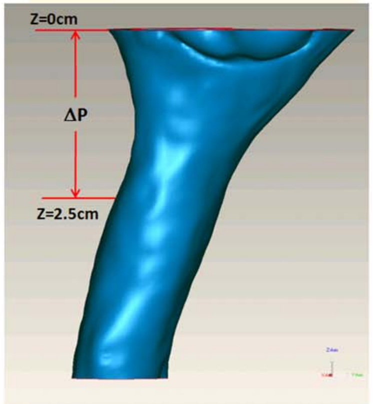
- Geometry of the cervical spinal SAS
  - Modeling SAS geometry
  - Boundary condition analysis
  - Integrated longitudinal impedance analysis
- CSF volume flow rate
  - C2 vs. C6 vs. T2
  - Analysis of percent volumetric expansion (compliance)
- CSF pulse wave velocity

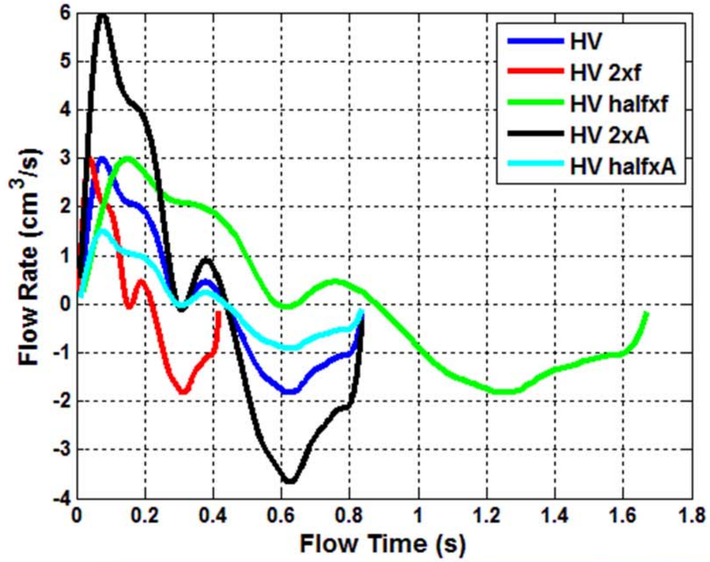
SAS Geometry Reconstruction + Finite Volume Meshing



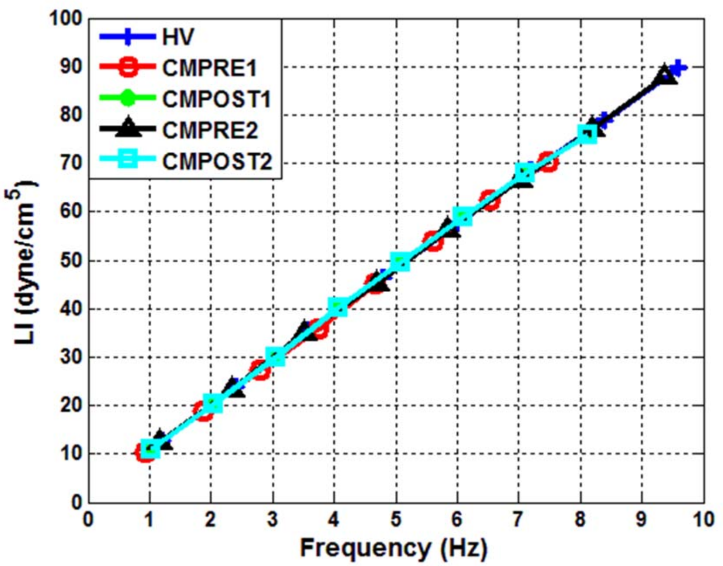
Boundary Conditions: Volume Flow Waveform

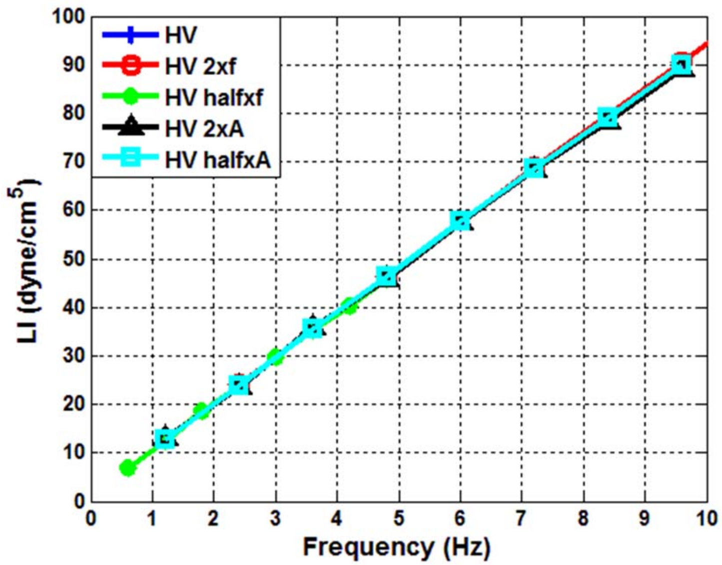






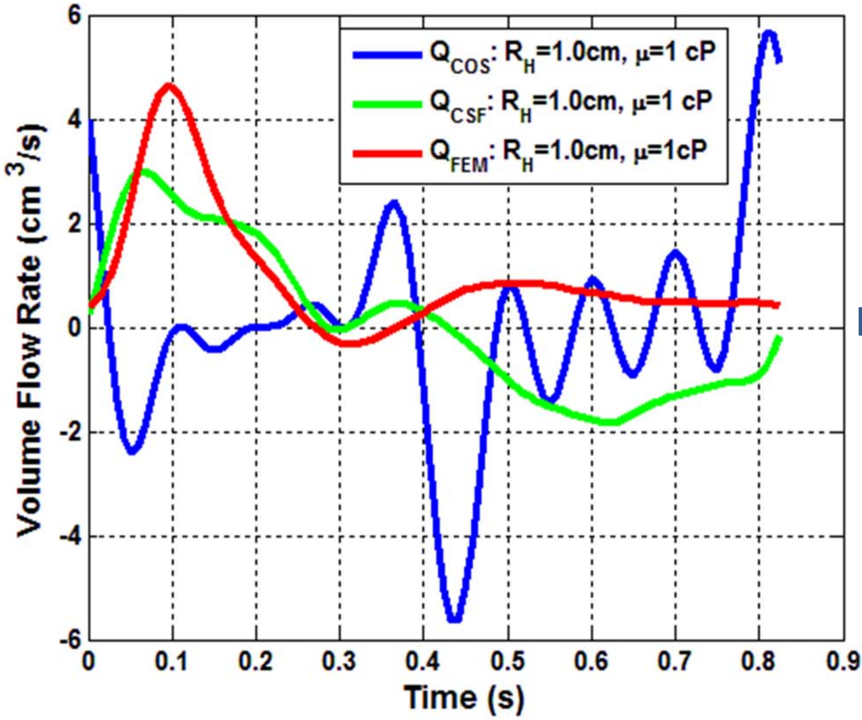
Maximum and minimum integrated LI vary from mean by 1.3% and 0.7%, respectively.

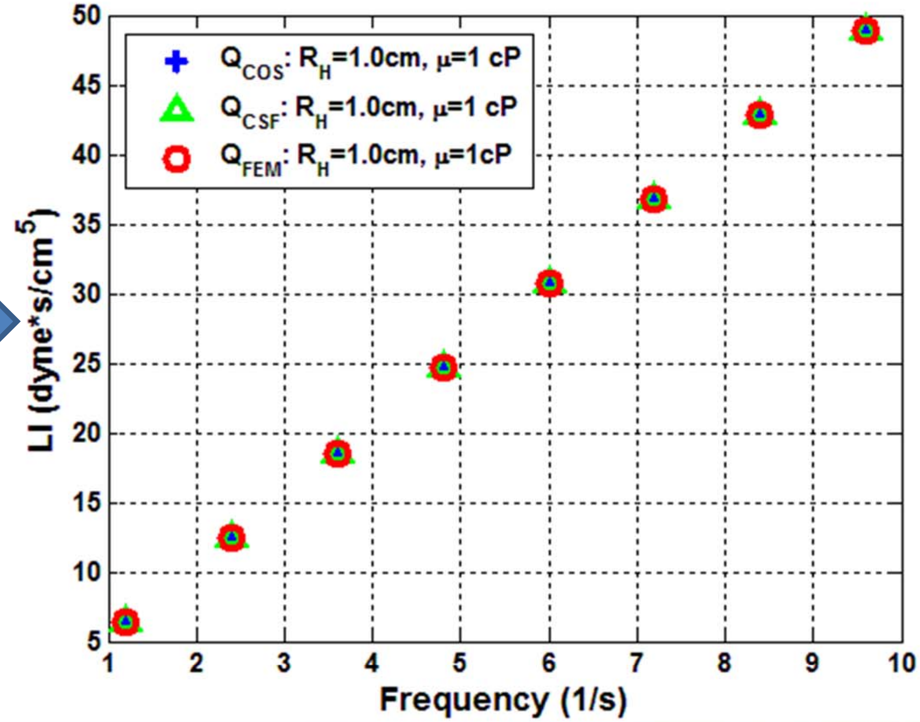




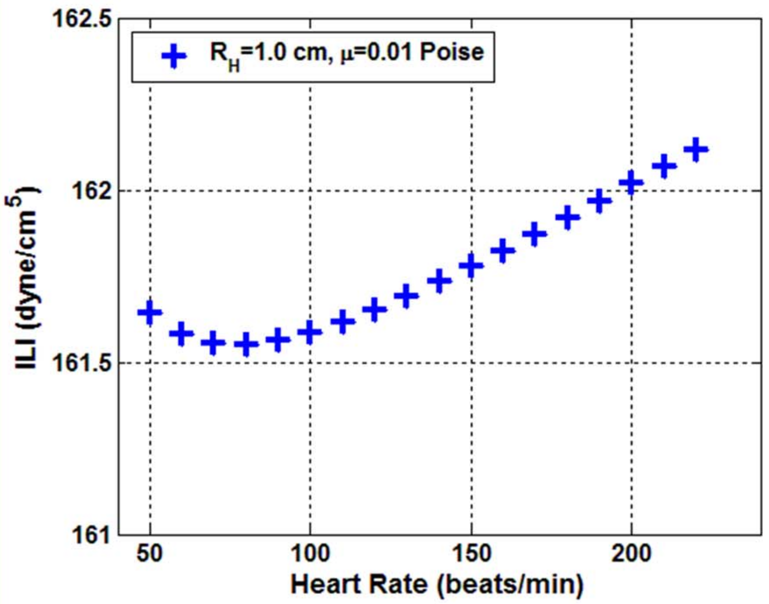
Longitudinal Impedance in a Straight Tube: Womersley Flow

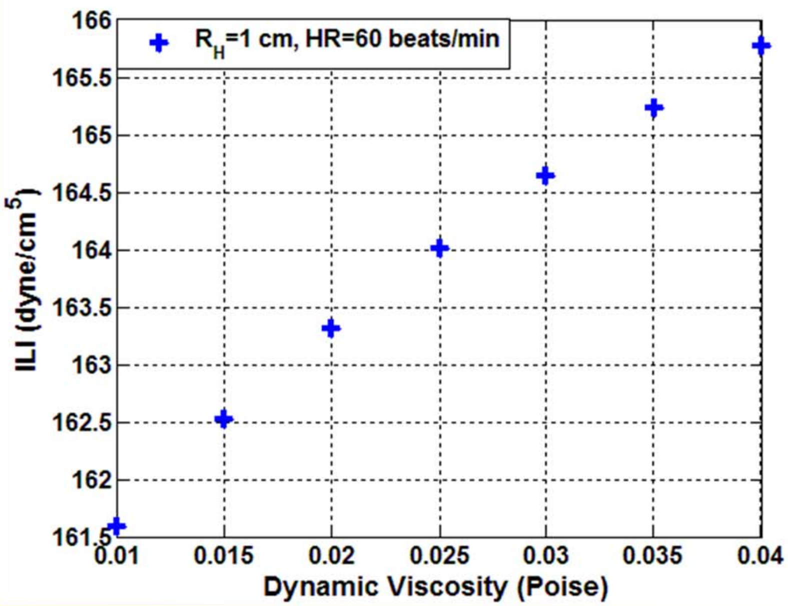
$$\left|\frac{\Delta P}{Q}\right| = \left|\frac{i\mu\alpha^{2}L}{\pi R_{H}^{4}}\left[1-\frac{2J_{1}\left(i^{3/2}\alpha\right)}{i^{3/2}\alpha J_{0}\left(i^{3/2}\alpha\right)}\right]^{-1}\right| = f\left(HR,\mu,\frac{1}{R_{H}^{2}}\right)$$

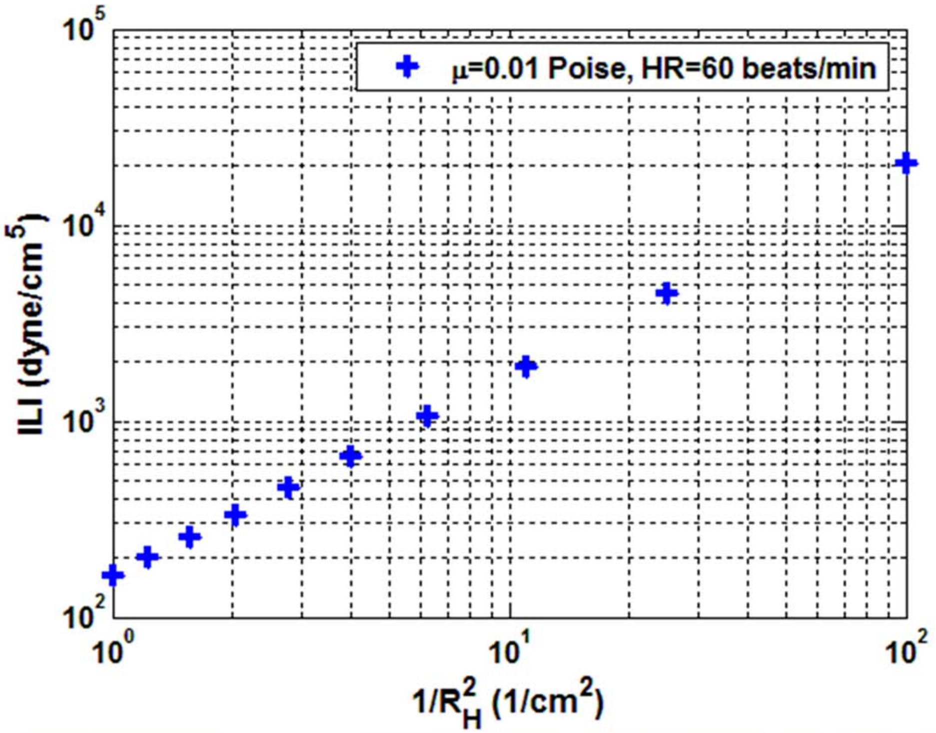




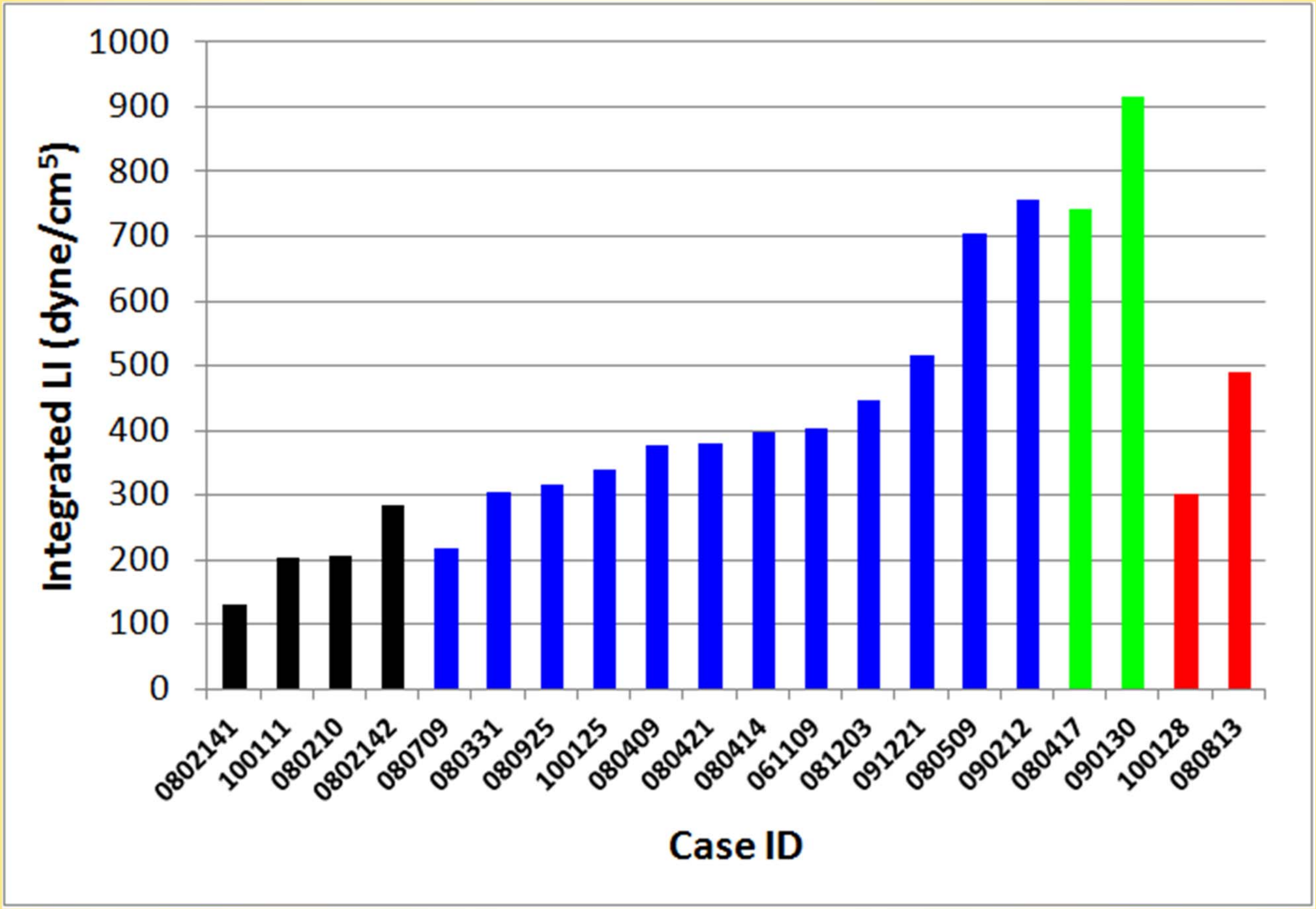
Longitudinal Impedance in a Straight Tube: Womersley Flow







Integrated LI:
Volunteer vs. Asymptomatic CMI vs. Symptomatic CMI



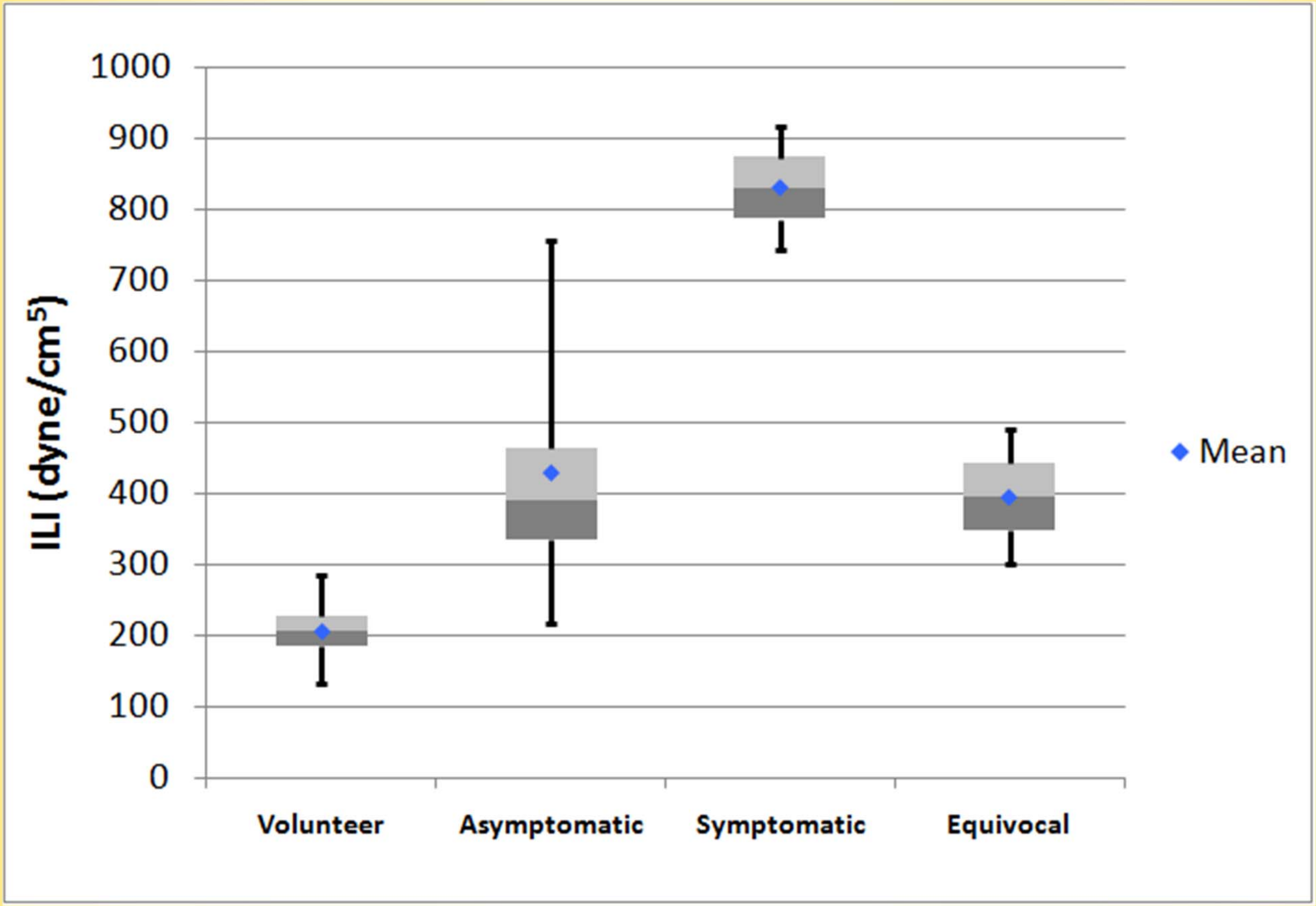
Black = Volunteers; Blue = Asymptomatic; Green = Symptomatic; Red = Equivocal/Indeterminate

Statistical Analysis

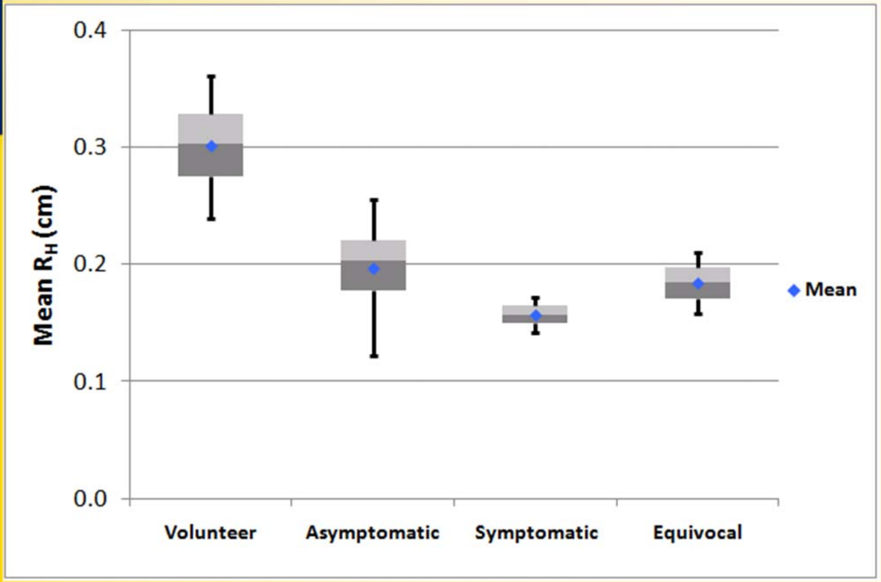
- Compare hydrodynamic parameters between groups using one-way analysis of variance by ranks (Kruskal-Wallis Test) with $\alpha = 0.05$.

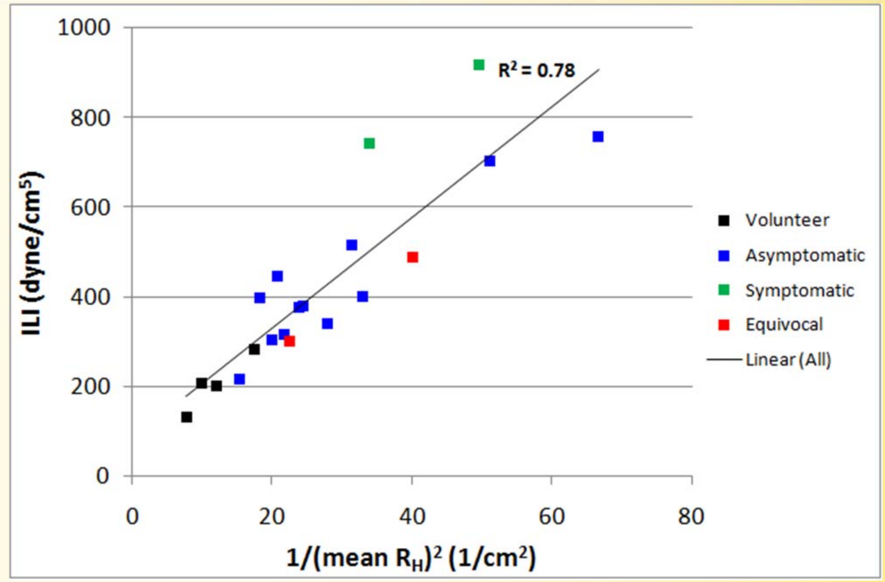
- Generic Statistical Hypothesis:
  - H_0: Distribution of values for (*Hydrodynamic Parameter*) is the same for all groups
  - H_A: Median value of (*Hydrodynamic Parameter*) is not the same for all groups

Integrated LI:
Volunteer vs. Asymptomatic CMI vs. Symptomatic CMI

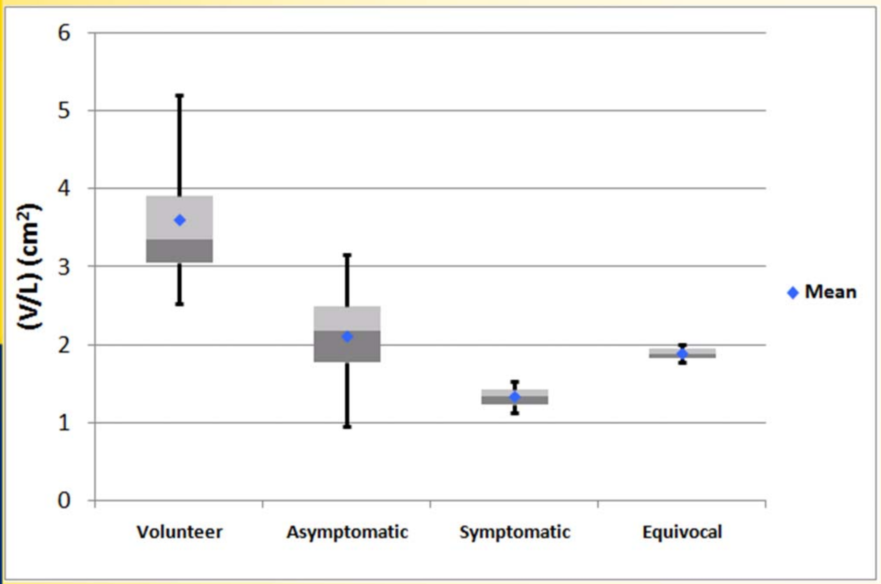


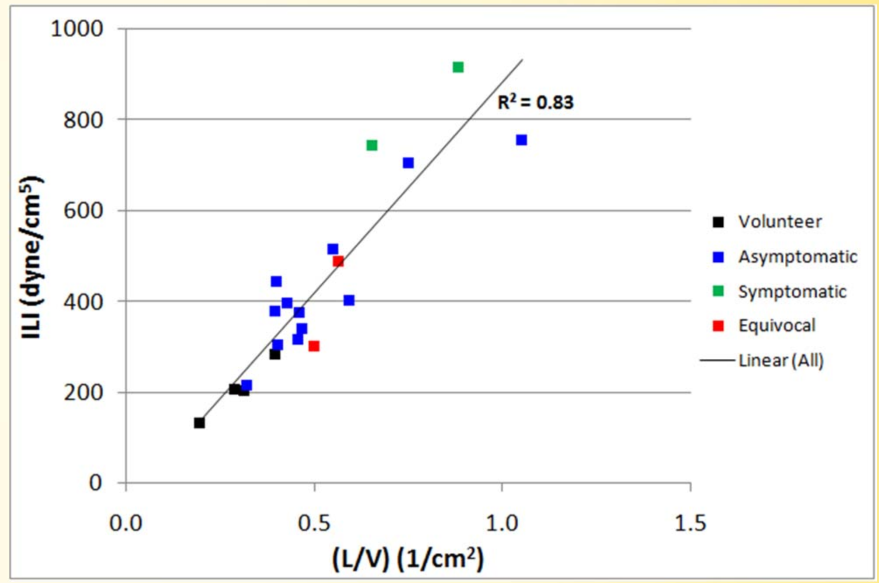
***Median integrated LI in each group is NOT the same (p<0.01)**





- **Median Mean R_H in each group is NOT the same (p=0.015)**

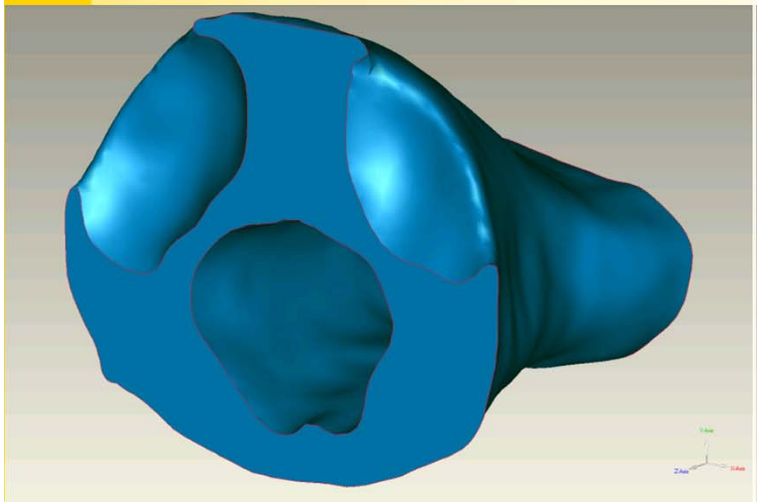


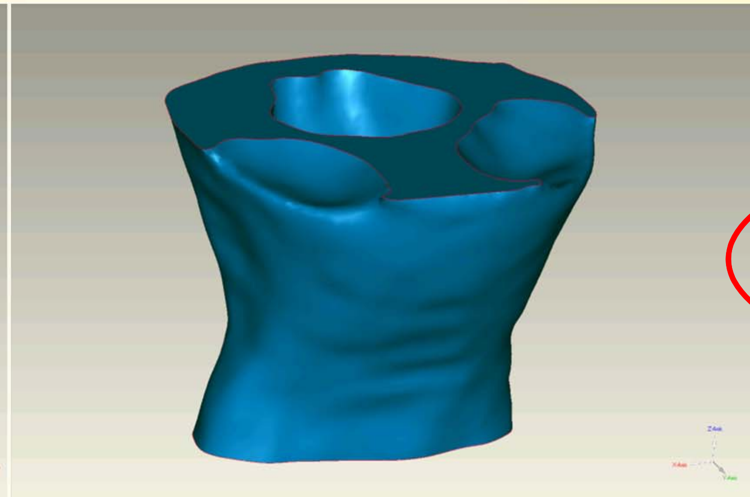


- **Median (V/L) in each group is NOT the same (p=0.017)**

*For oscillatory flow in a straight tube, $LI = \frac{\Delta p}{Q} \propto \frac{1}{R_H^2} \propto \frac{1}{A_{CS}} \propto \left(\frac{L}{V}\right)$

Integrated LI vs. Geometric Measurements : Volunteer-Asymptomatic

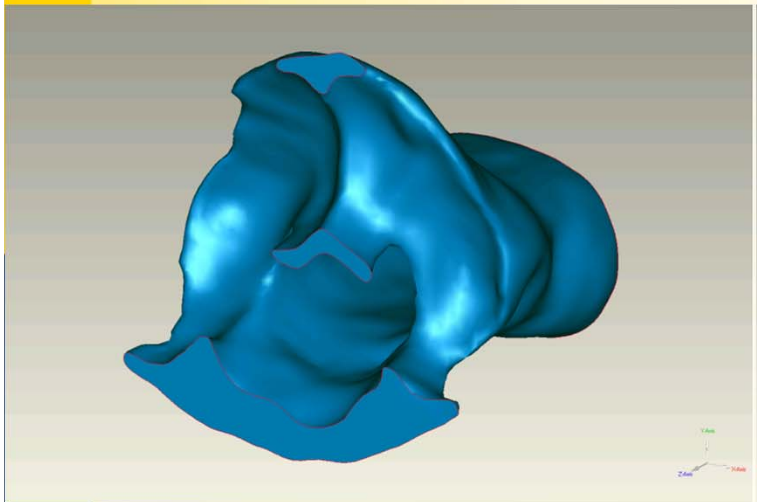


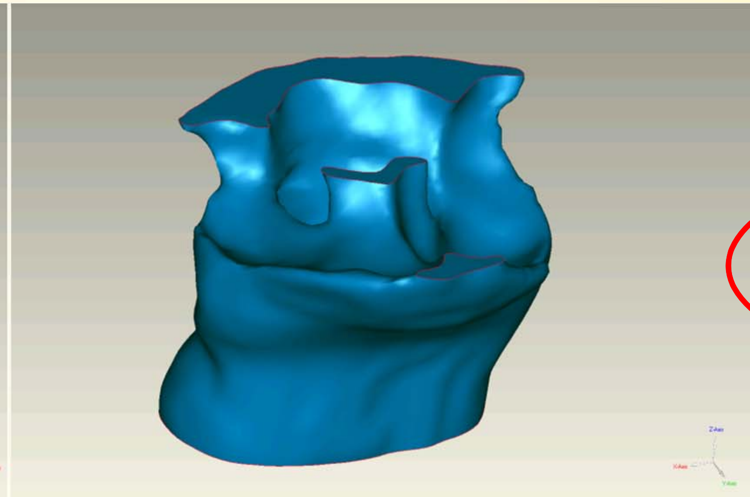


Case ID: 0802142
Group: Volunteer

V_{CSAS} : 6.32 cm^3
Mean R_H: 0.239 cm

LI: 284 $dyne/cm^5$



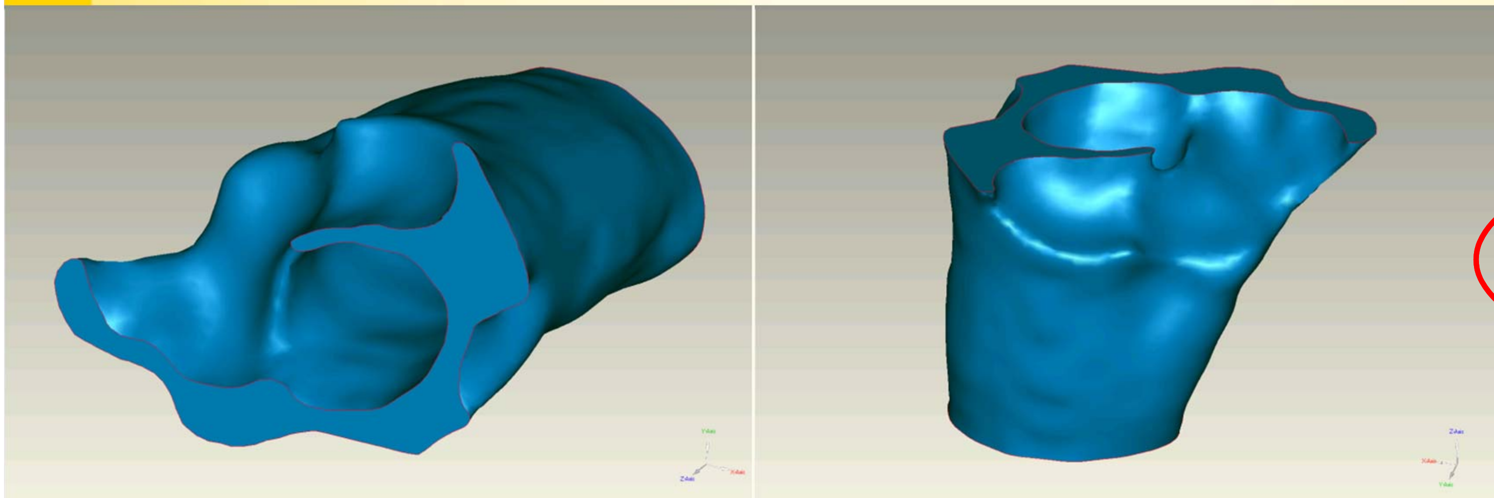


Case ID: 080421
Group: Asymptomatic

V_{CSAS} : 6.35 cm^3
Mean R_H: 0.202 cm

LI: 380 $dyne/cm^5$

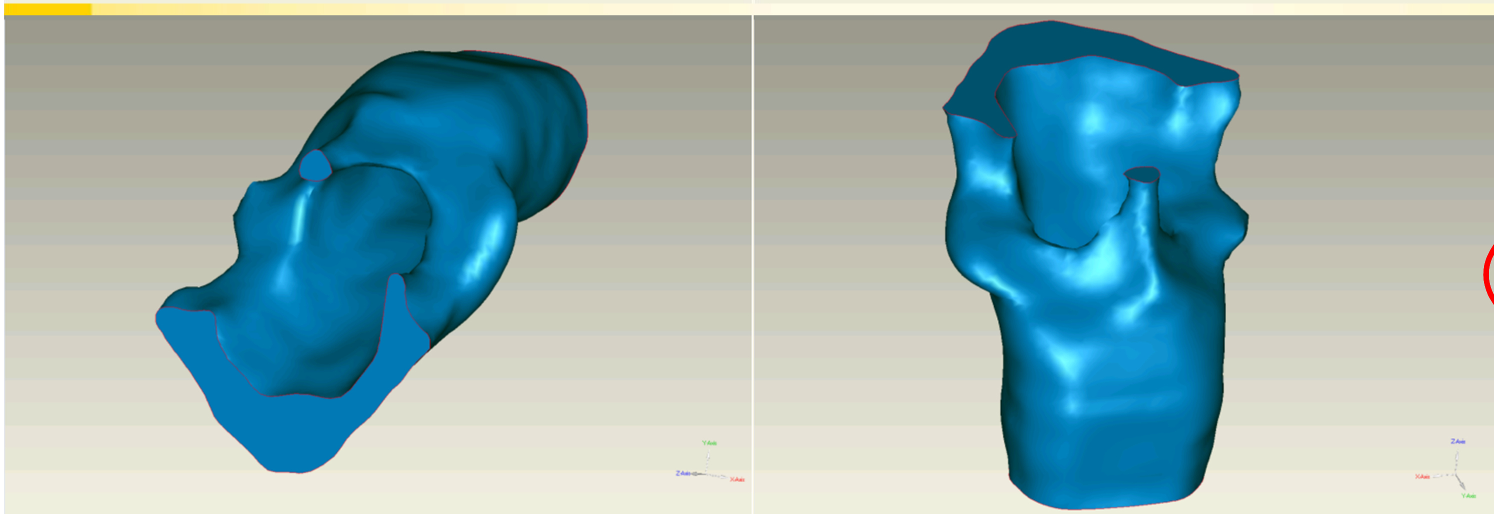
Integrated LI vs. Geometric Measurements: Symptomatic-Asymptomatic



Case ID: 061109
Group: Asymptomatic

V_{CSAS}: 4.22 cm^3
Mean R_H: 0.174 cm

LI: 402 $dyne/cm^5$

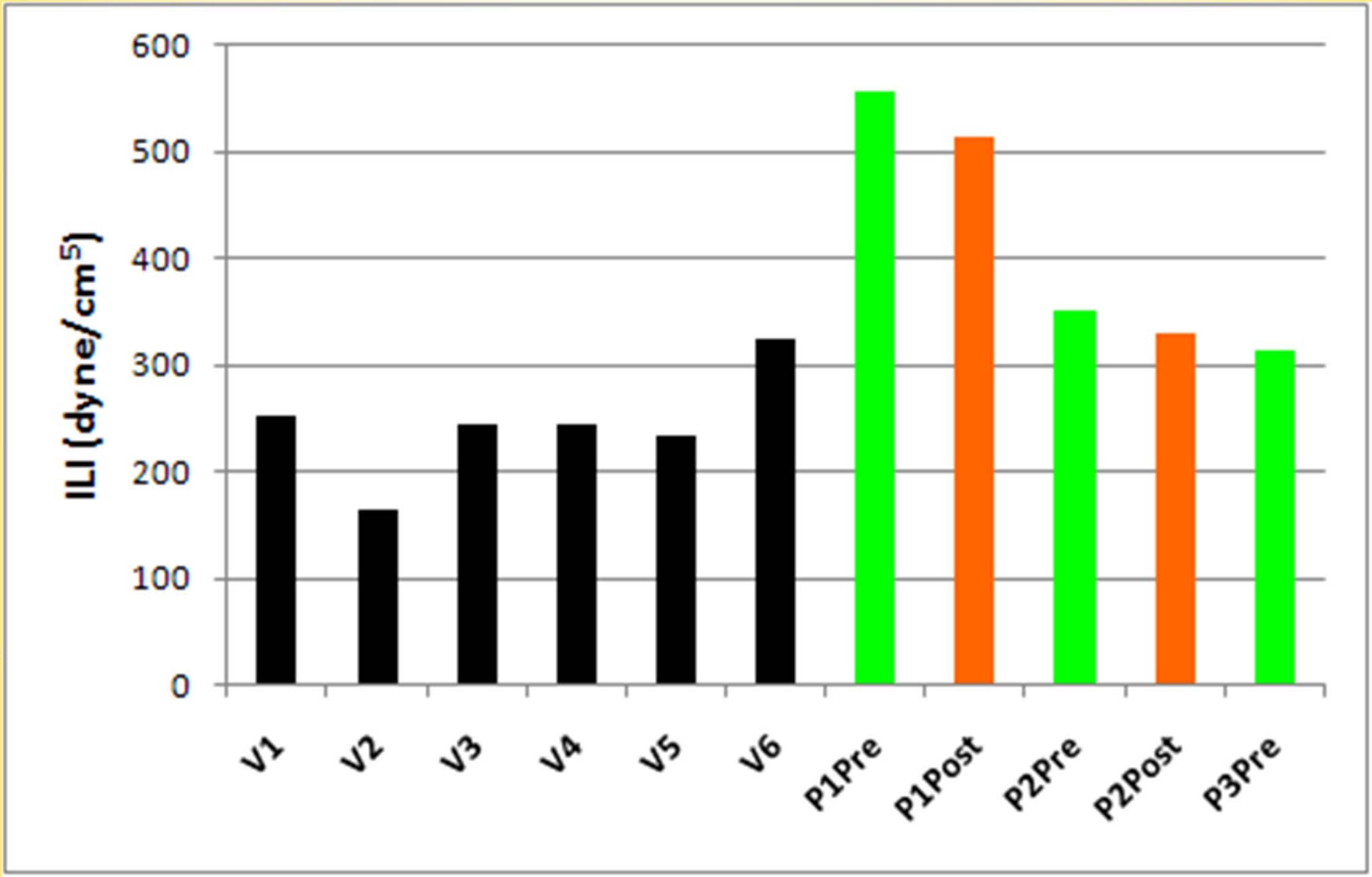


Case ID: 080417
Group: Symptomatic

V_{CSAS}: 3.84 cm^3
Mean R_H: 0.172 cm

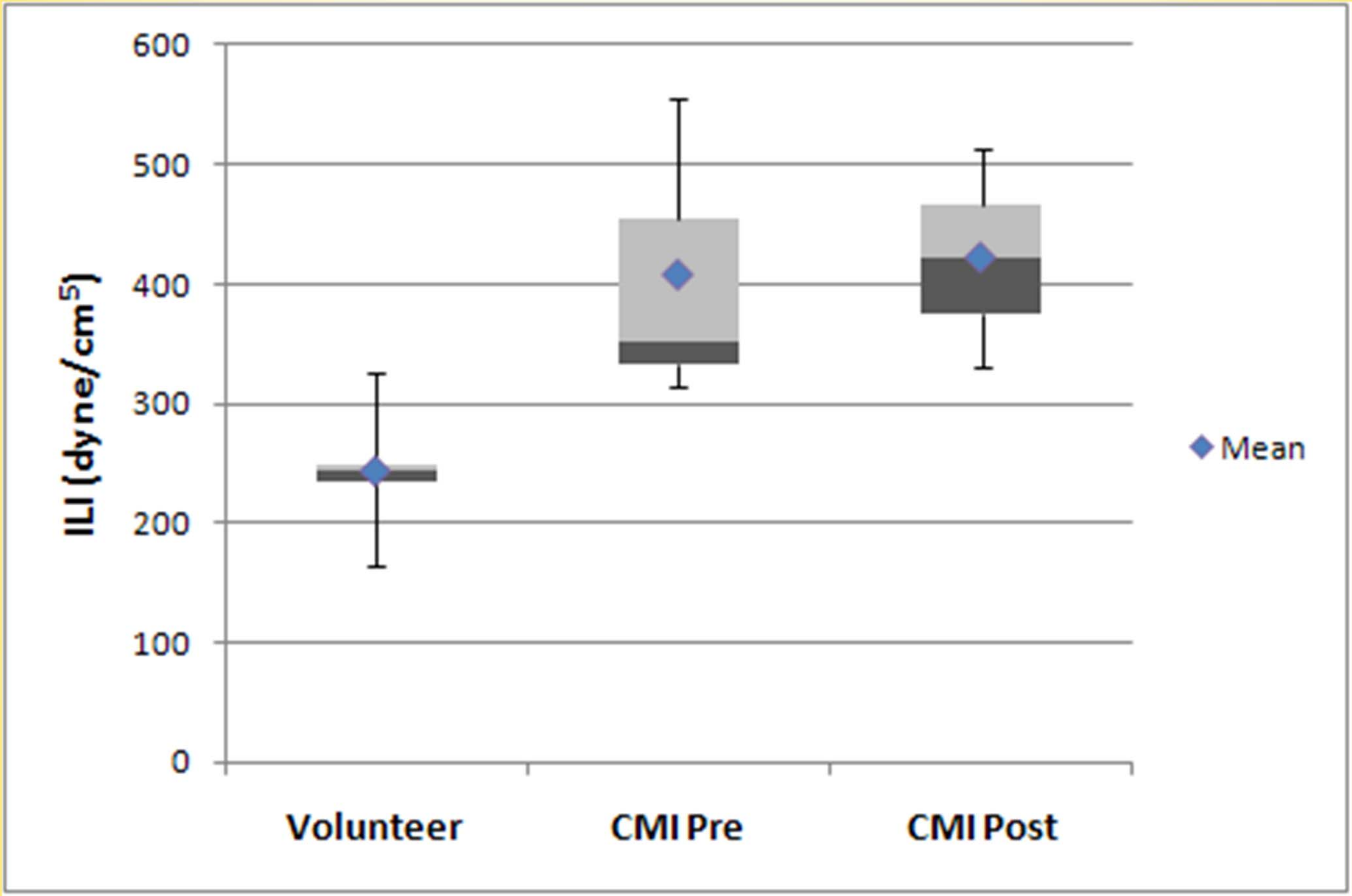
LI: 743 $dyne/cm^5$

Integrated LI: Volunteer vs. Pre-Surgery vs. Post-Surgery

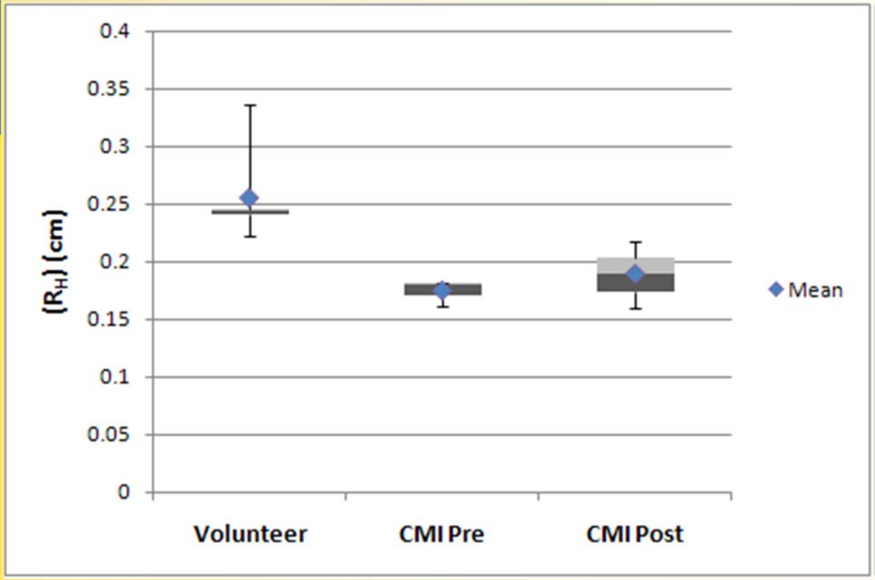


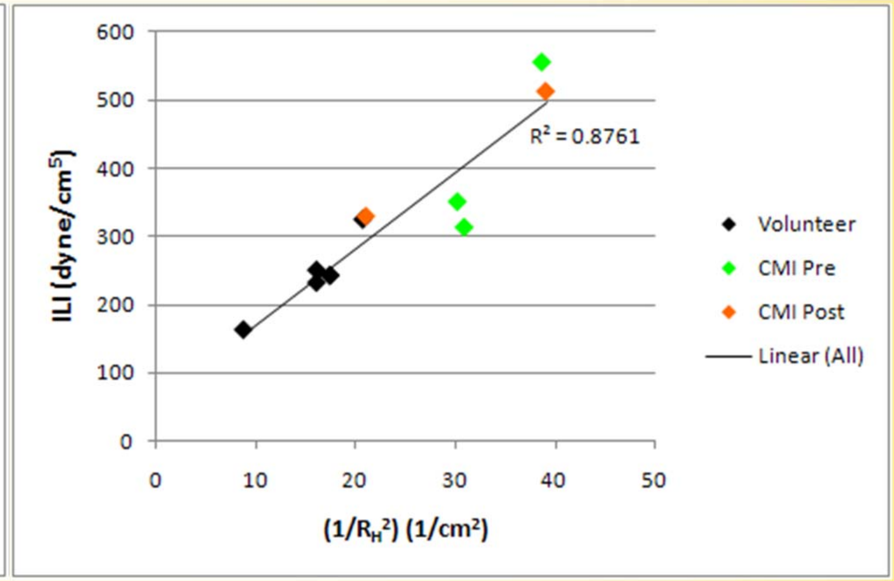
Black = Volunteers; Green = CMI Patient Pre-Surgery; Orange = CMI Patient Post-Surgery

Integrated LI: Volunteer vs. Pre-Surgery vs. Post-Surgery

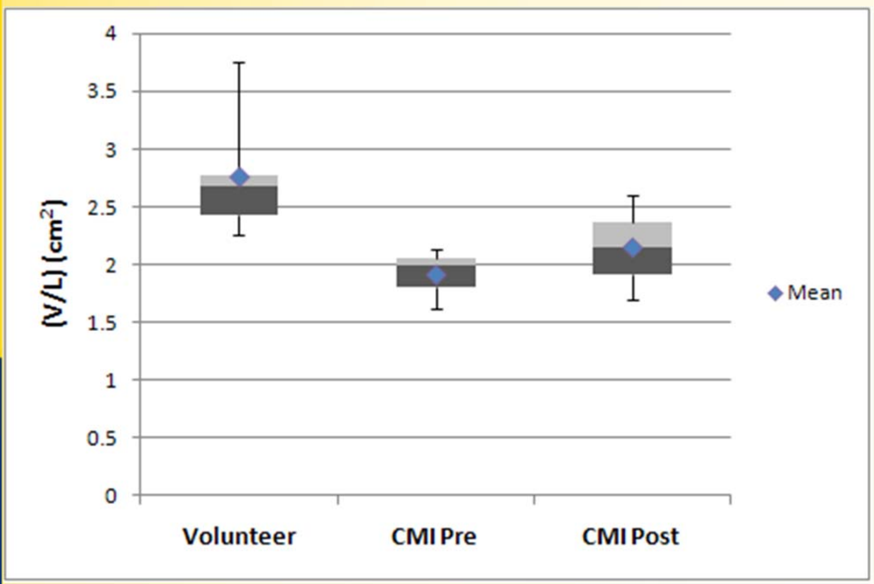


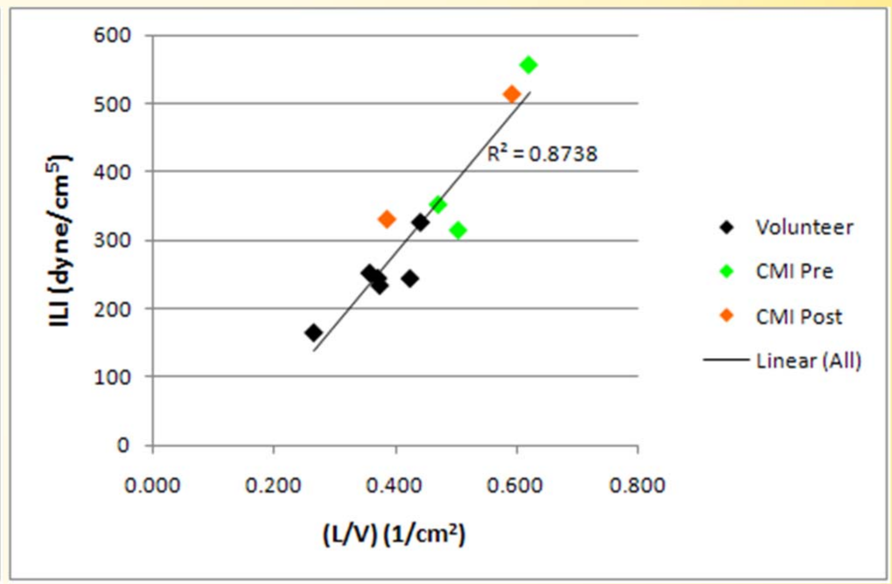
* Distribution of integrated LI for each group is the same (p=0.77)





- Distribution of Mean R_H in each group is the same ($p=0.68$)

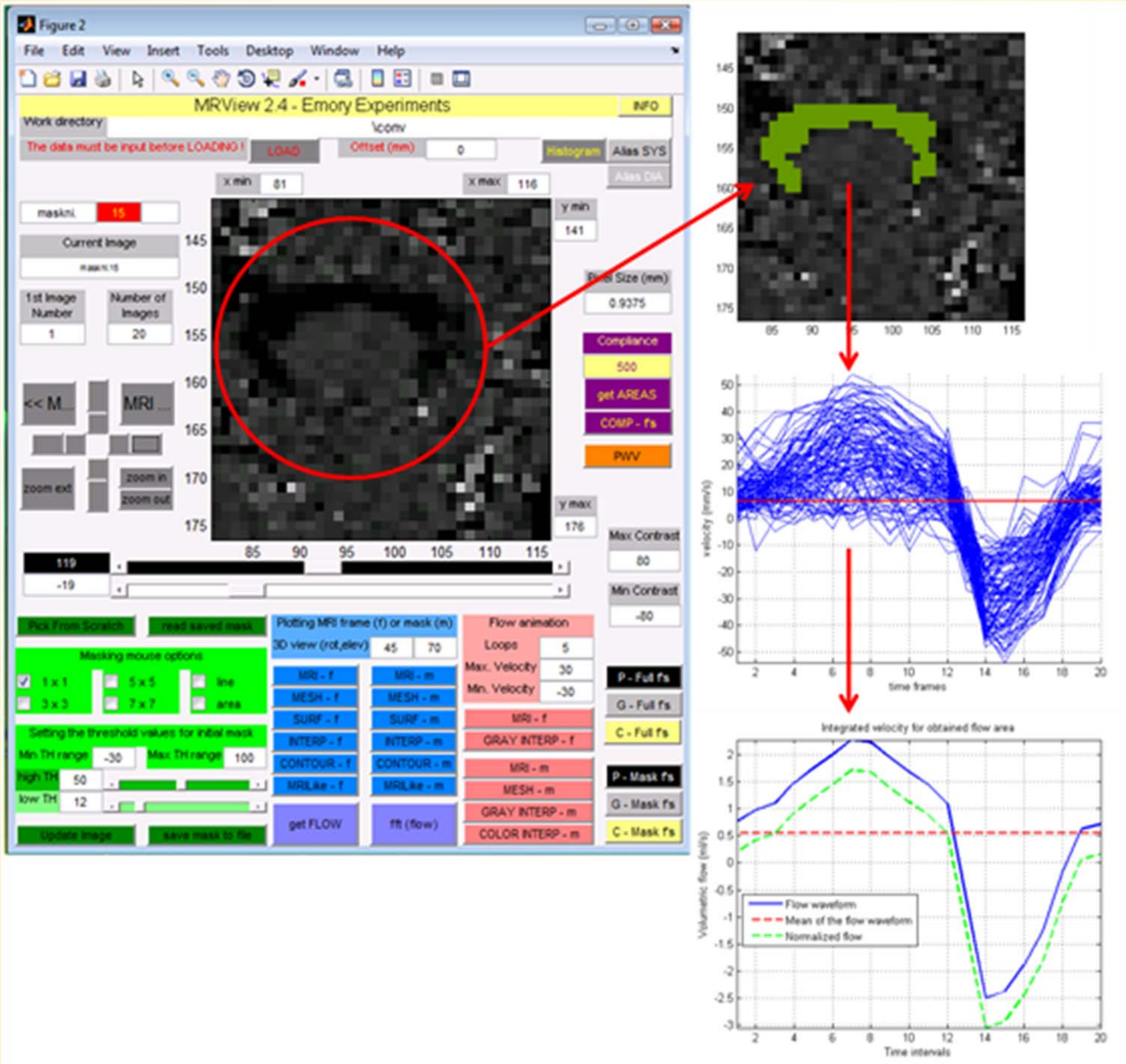




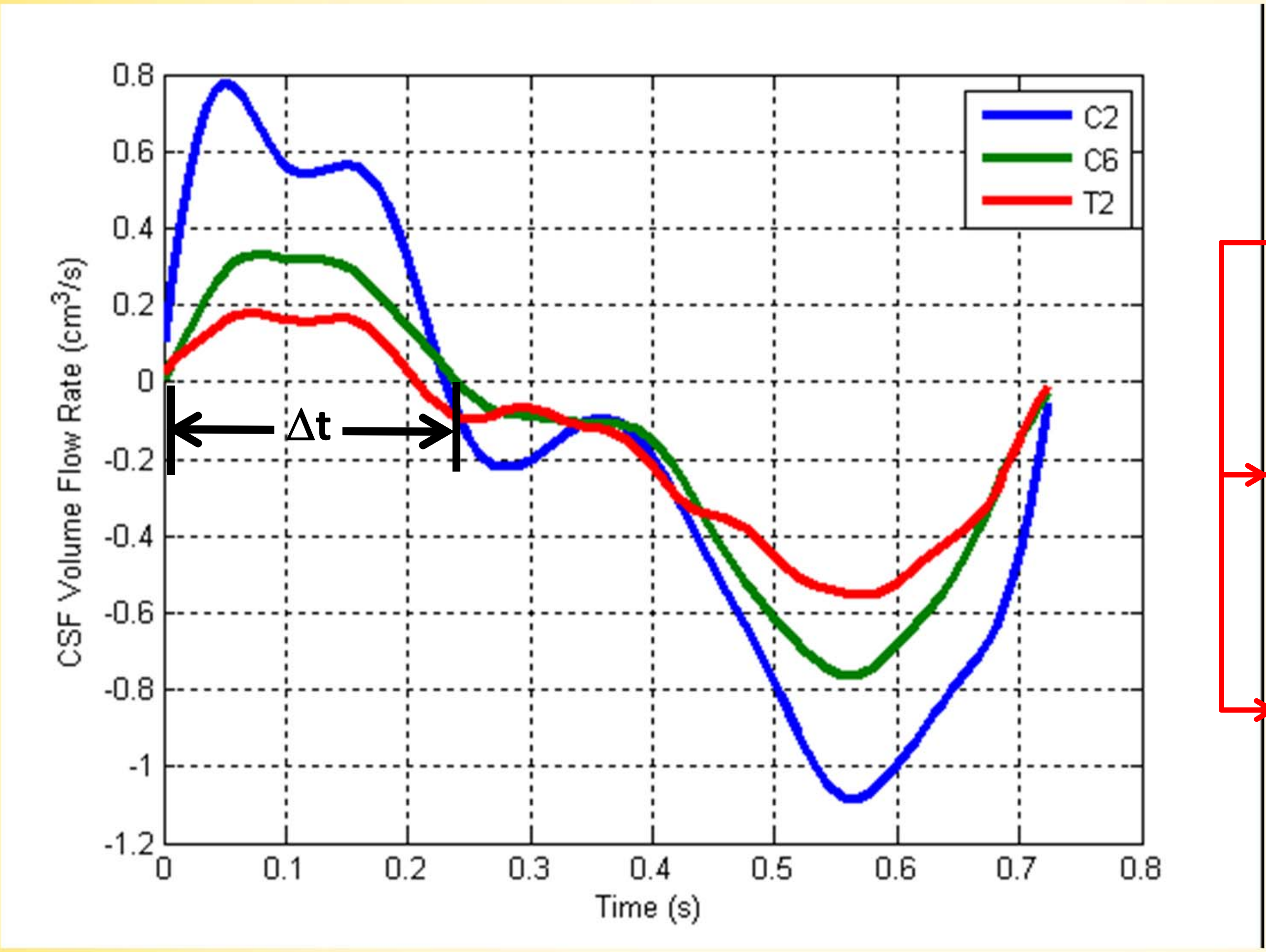
- Distribution of (V/L) in each group is the same ($p=0.82$)

*For oscillatory flow in a straight tube, $LI = \frac{\Delta p}{Q} \propto \frac{1}{R_H^2} \propto \frac{1}{A_{CS}} \propto \left(\frac{L}{V}\right)$

Volumetric Expansion Image Analysis



Volumetric Expansion Waveform Analysis

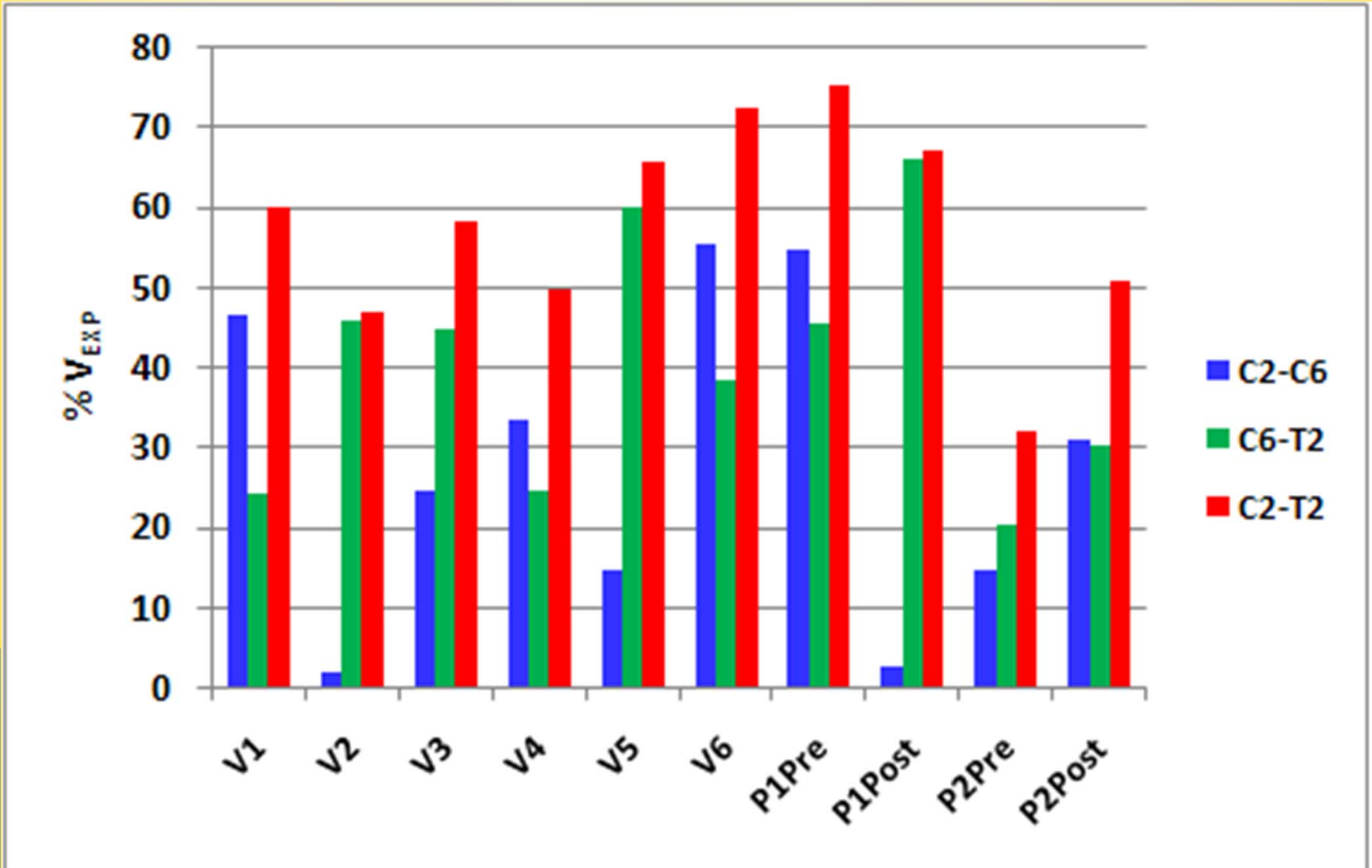


$$V_{in} = V_{C2} = \int_{t=0}^{t=0.25s} Q_{C2}(t)dt$$

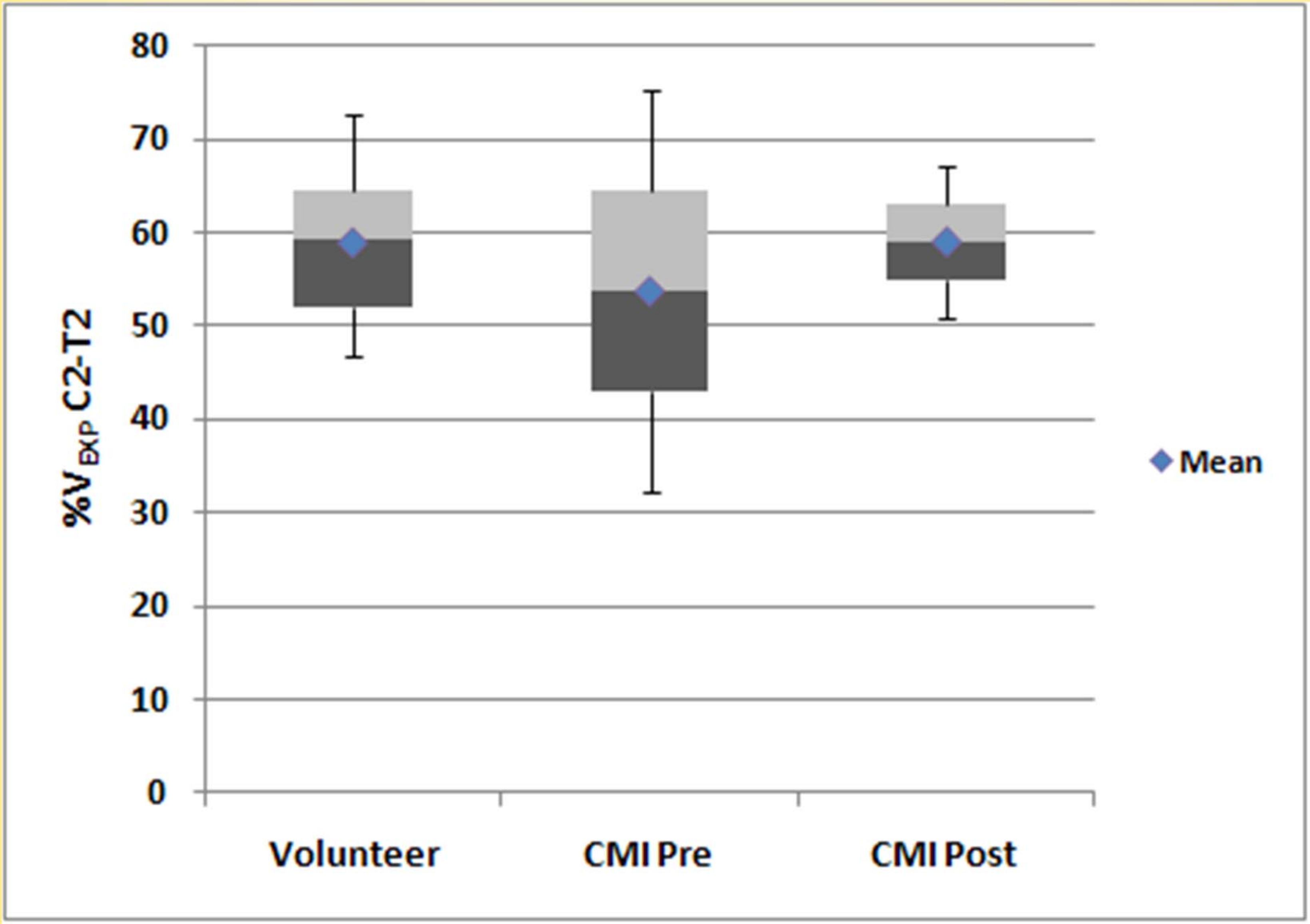
$$V_{out} = V_{T2} = \int_{t=0}^{t=0.25s} Q_{T2}(t)dt$$

$$\%V_{EXP} = \frac{V_{in} - V_{out}}{V_{in}} * 100\%$$

Volumetric Expansion
Pre-Surgery vs. Post-Surgery vs. Volunteer

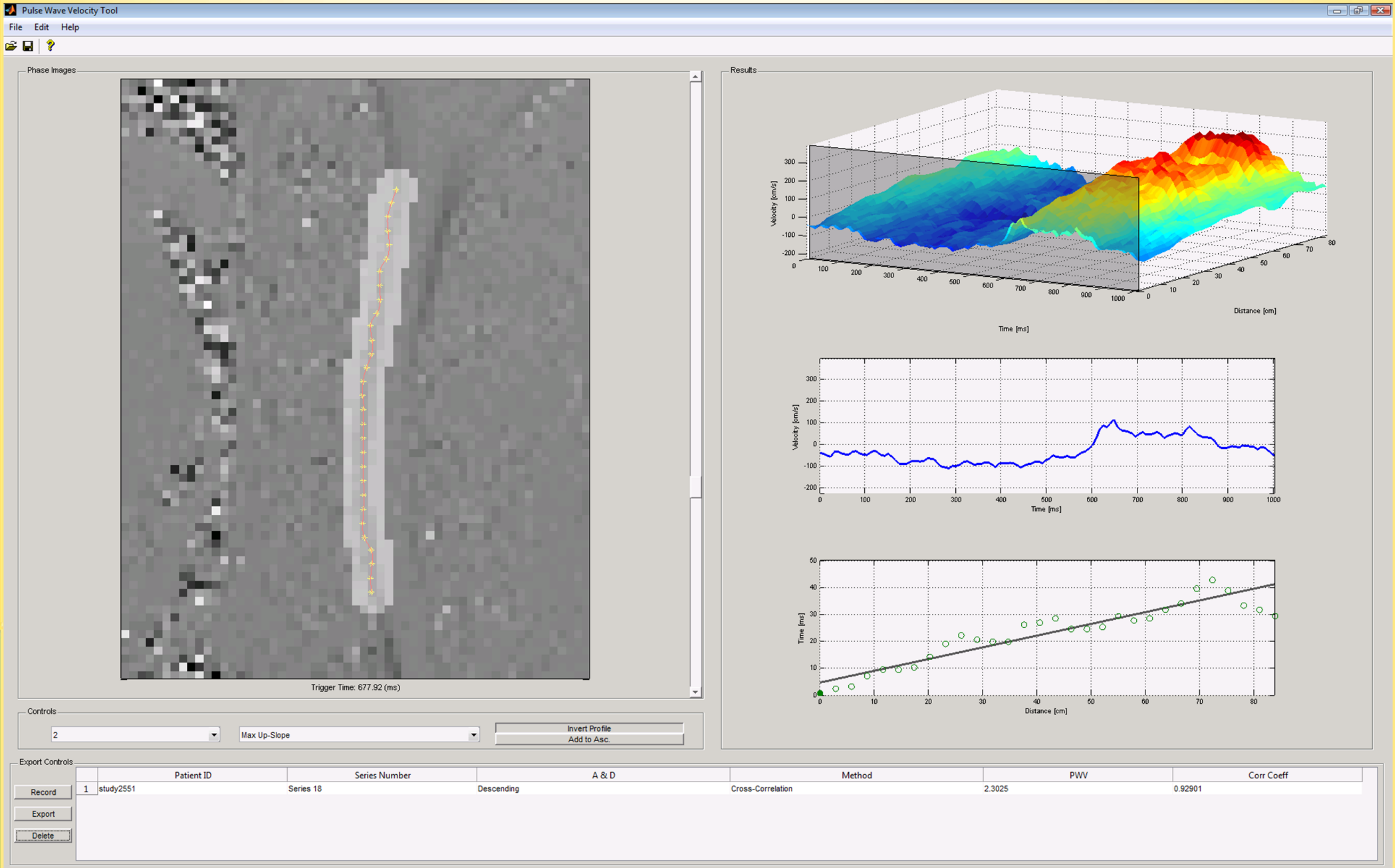


Volumetric Expansion
Volunteer vs. Pre-Surgery vs. Post-Surgery

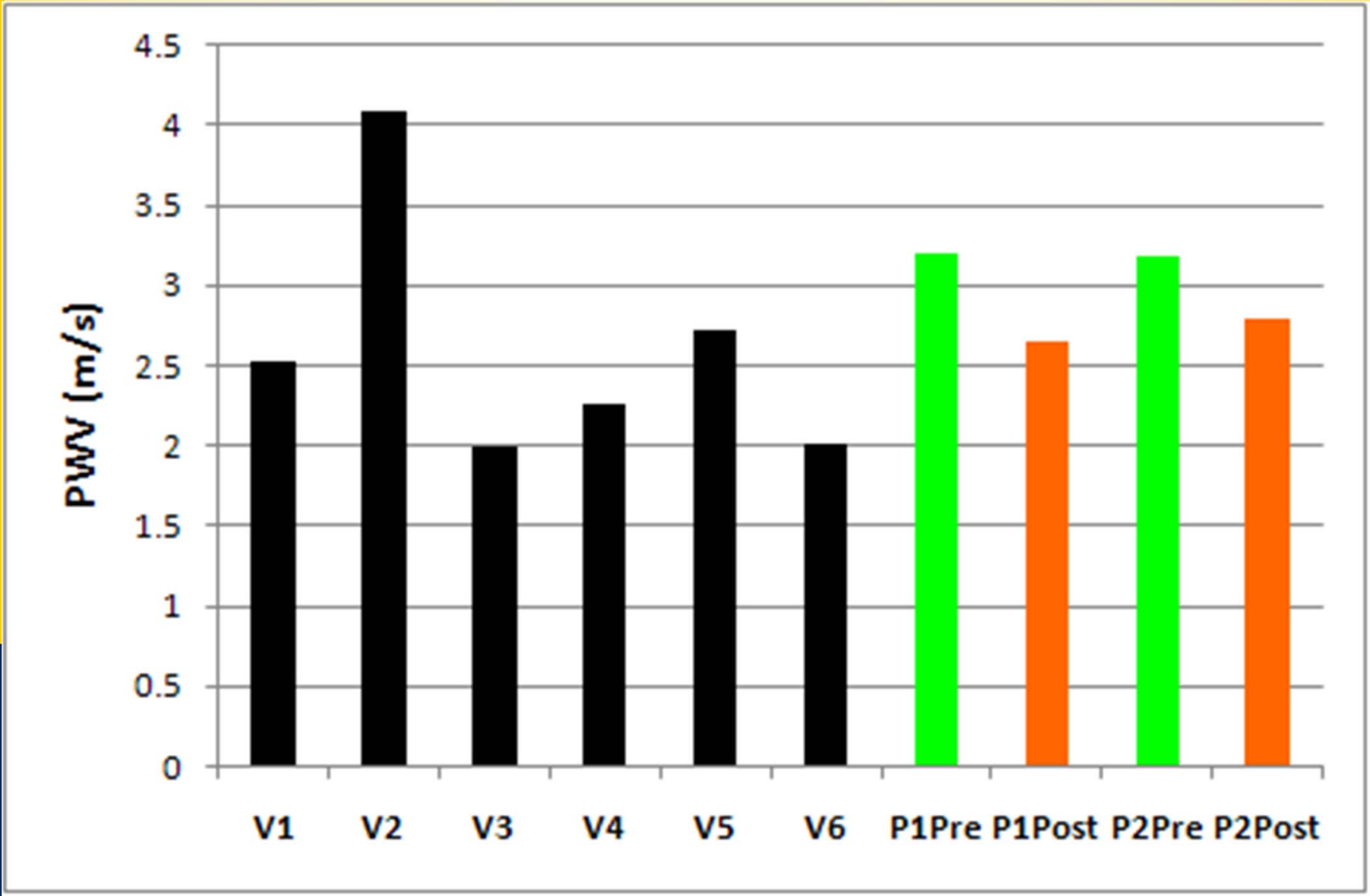


*** Distribution of %V_{EXP} C2-T2 for each group is the same (p=1)**
Note: Distributions for C2-C6 and C6-T2 are similar

Pulse Wave Velocity Image Analysis

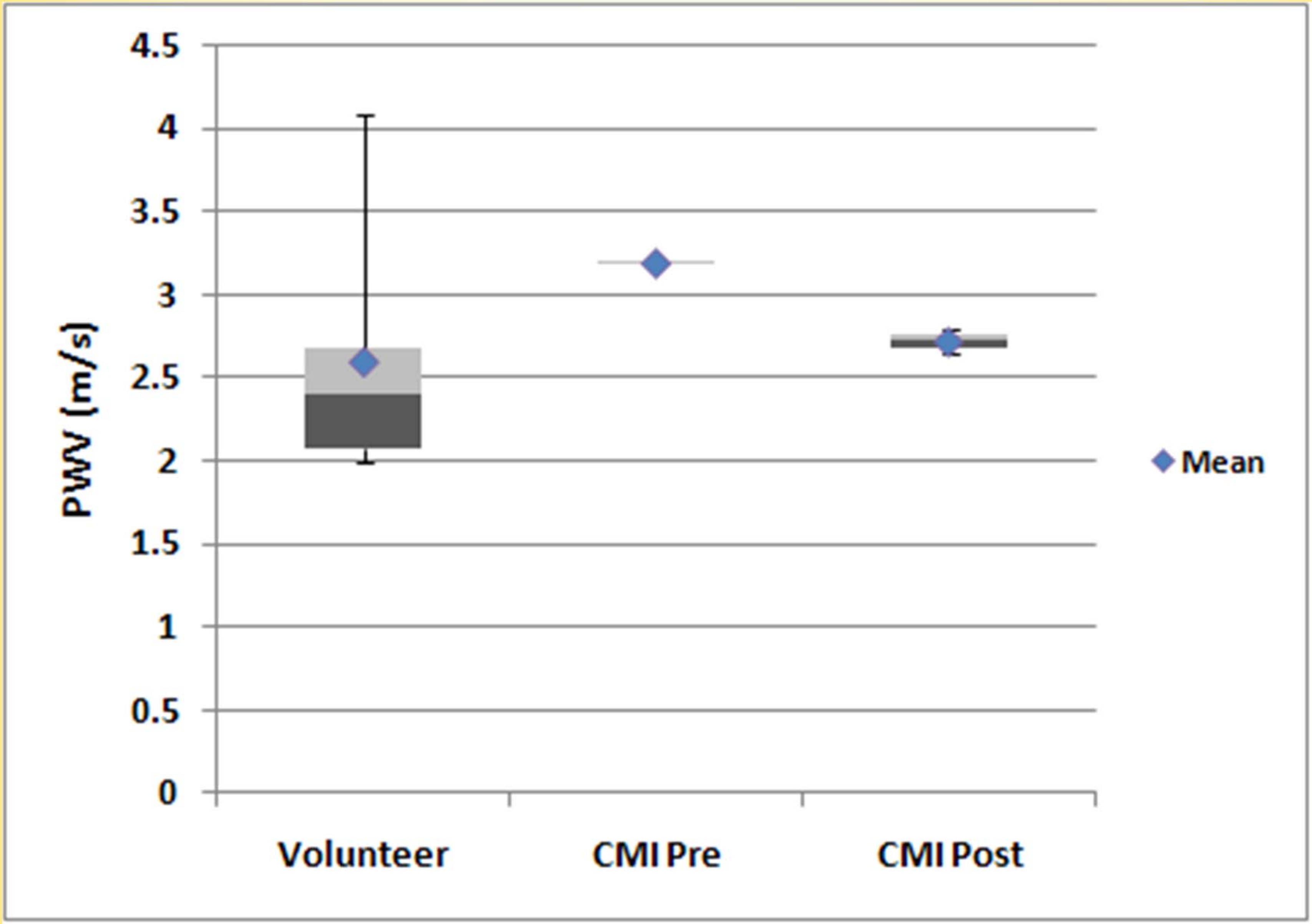


Pulse Wave Velocity
Volunteer vs. Pre-Surgery vs. Post-Surgery



*** Distribution of PWV for each group is the same (p=0.98)**

Pulse Wave Velocity
Volunteer vs. Pre-Surgery vs. Post-Surgery



* Distribution of PWV for each group is the same (p=0.98)

Summary

Integrated LI

– Independent of the shape of the volume flow waveform.

– Appears to increase with symptom severity in some cases.
  - Only mild cerebellar herniation in pre-surgery cases thus far.

– Decreases post-surgery.
  - Differences are numerical, not statistical.

– Magnitude correlates linearly to some extent with geometric characteristics of the cervical spinal canal
  - Average hydraulic radius and SAS volume.

However…

– Magnitude appears to be dominated by the geometric complexity of the cervical SAS.
  - ***MUCH SMALLER*** than that in a pipe of similar average hydraulic radius.

Summary

Volumetric Expansion

- No statistical difference between volunteers and CMI patients
- Can be dominated by C2-C6 or C6-T2 segment.
- May increase or decrease post-surgery.

Pulse Wave Velocity

- Appears to be generally higher in CMI patients when calculated by the maximum slope-linear fit method
- Decreases post-surgery
  - Differences are numerical, not statistical.

Questions?