Automated Cranial 4D Flow MRI Analysis

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Synopsis

To develop and validate a software tool for robust cerebrovascular analysis of 4D flow MRI data that includes:

- **An interactive visual interface**
- **Quick and robust automated and reproducible hemodynamic analysis**

Background

- 4D flow MRI acquires in-vivo, time-resolved, volumetric data of velocity vectors.
  - Allows for qualitative and quantitative analysis of anatomy and hemodynamics
  - Post-processing can be time consuming
- A previously-established cranial 4D flow centerline processing scheme (CPS)[1] allowed:
  - Repeatable quantitative analysis
  - Automated segmentation
  - Quick post processing times (~15 min)
  - Analysis of +1000 cranial cases
- **Purpose: Develop a quantitative velocity tool (QVT) that improves 4D flow post-processing:**
  1. Fully automated quantitative flow computations for all vessels (~3000 locations)
     - Anatomical: vessel segmentation
     - Functional: blood velocity, flow, pulsatility index, etc.
  2. Interactive 3D user interface
     - Visualization of color-coded flow parameters
     - Easy vessel selection
  3. Reduce memory requirements and post-processing times (~5 min)

Methods

- An in-vivo study was performed to assess **CPS and QVT segmentation** performances, **interobserver variabilities, vessel selection**, and **post processing times**.
- **Ten 4D flow brain scans** were acquired on healthy volunteers.
  - **PC-VIPR**[2] acquisition: field strength = 3T; volume = 22 cm^3; spatial res. = 0.69 mm^2; V_{ENC} = 80 cm/s; scan time = 7 min.; retrospective cardiac gating (20 frames).
- The QVT graphical interface (Figure 1) was developed in MATLAB18b (Mathworks, MA).

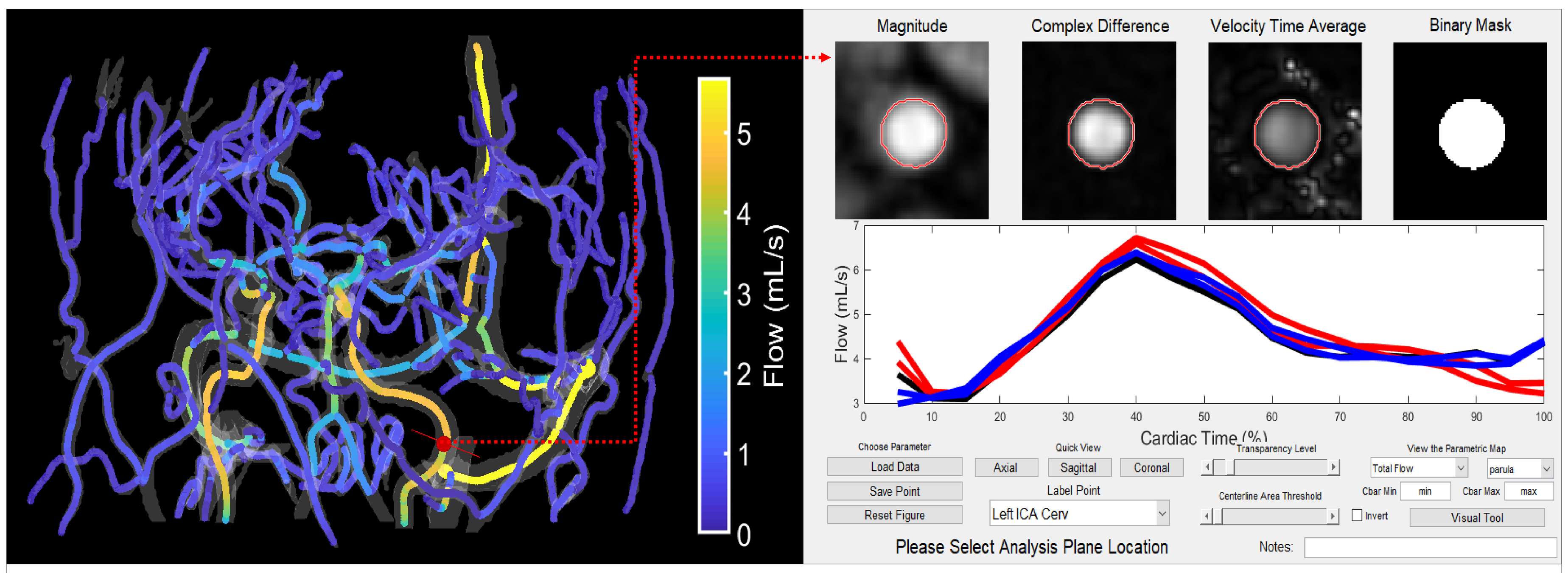

Figure 1: 4D flow post-processing tool with 3D interactive graphical user interface. As the user moves the cursor, the cross-sectional images and flow waveforms are updated in real-time.

- A **threshold-based vessel segmentation algorithm** was developed (Figure 2**).**
- Automated calculations of blood flow parameters were completed across the vascular network and color-coded in the 3D interface (Figure 3).

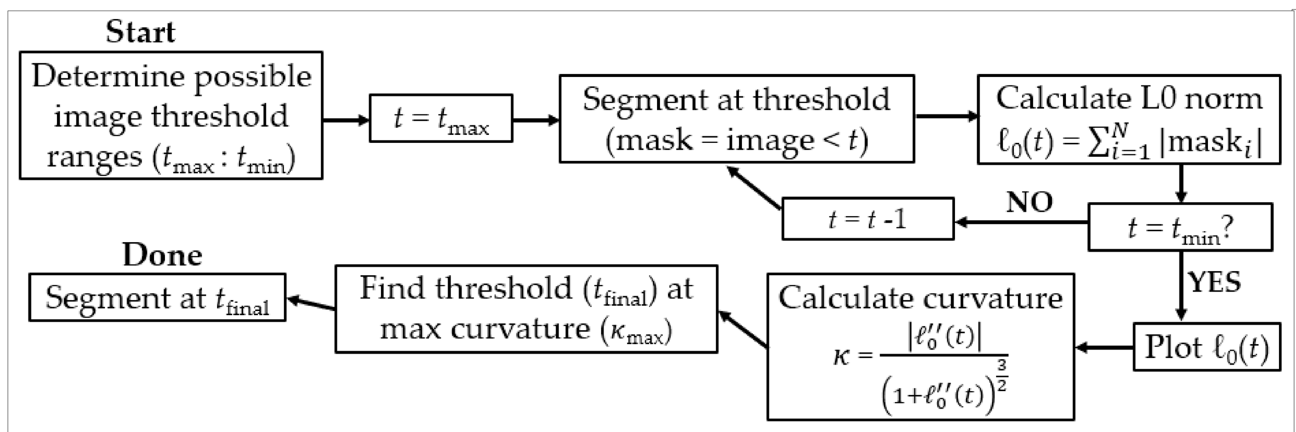

Figure 2: Flowchart for threshold-based segmentation. This algorithm iterates through all possible thresholds and calculates L0-norm. The norm is plotted as a function of threshold, and the point of maximum curvature is the final threshold used.

- **Flow analysis** was completed in **13 locations**: internal carotid arteries (**ICA**), basilar artery (**BA**), middle cerebral arteries (**MCA**), posterior cerebral arteries (**PCA**), straight sinus (**SS**), superior sagittal sinus (**SSS**), and transverse sinuses (**TS**).
- Automated vessel segmentation methods were evaluated against a manual segmentation:
  - K-means segmentation (CPS) and threshold-based segmentation (QVT)
- Number of missed (non-selectable) vessels were counted for both tools.
- **Intra-observer variability** of flow was calculated between two observers.
- **Conservation of flow** at ICA, MCA, ACA and TS, SS, SSS junctions was assessed with QVT.

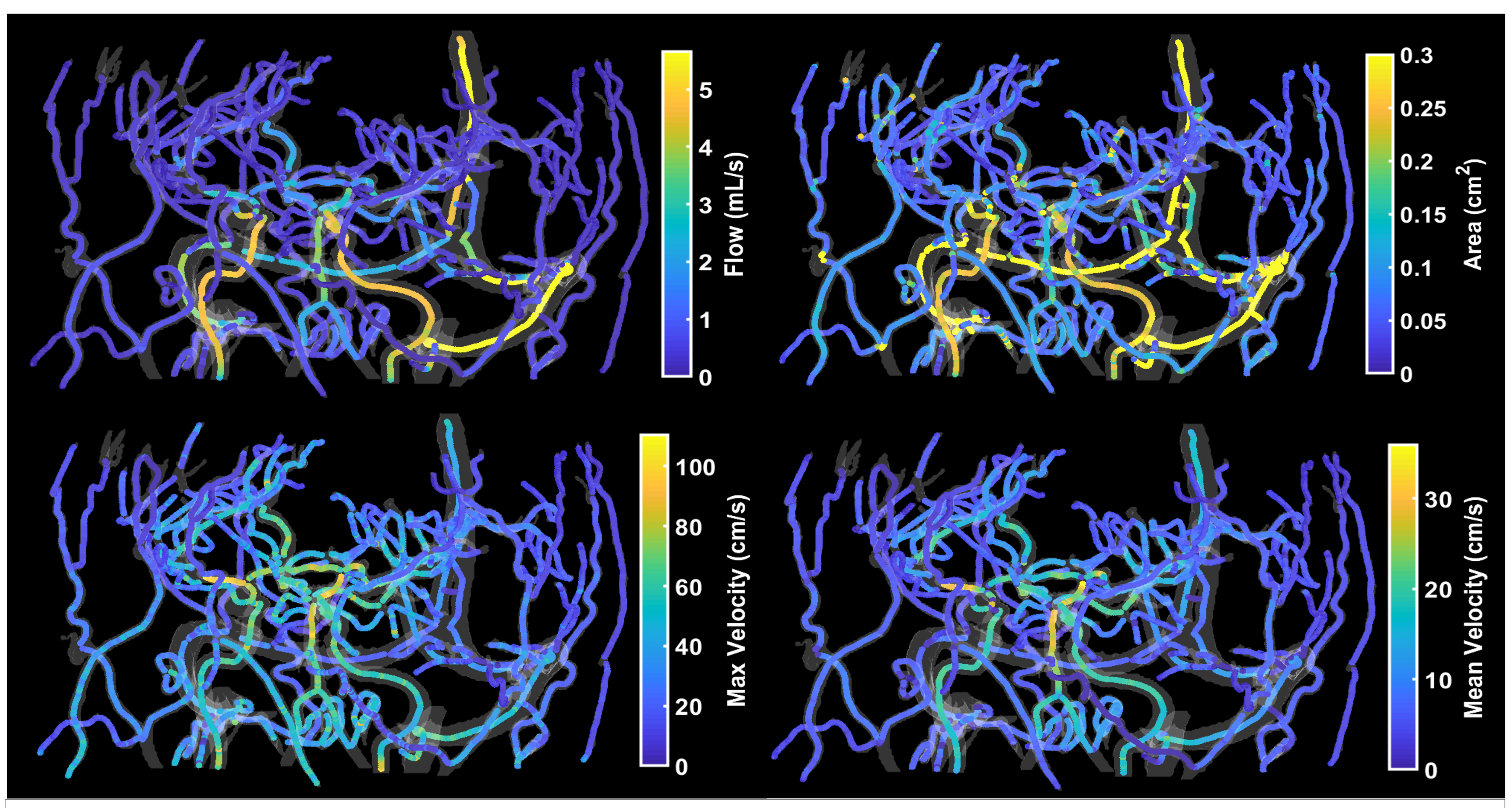

Figure 3: Quantitative parameters (area, flow, velocity) color-coded on automatically-generated centerlines.

Results

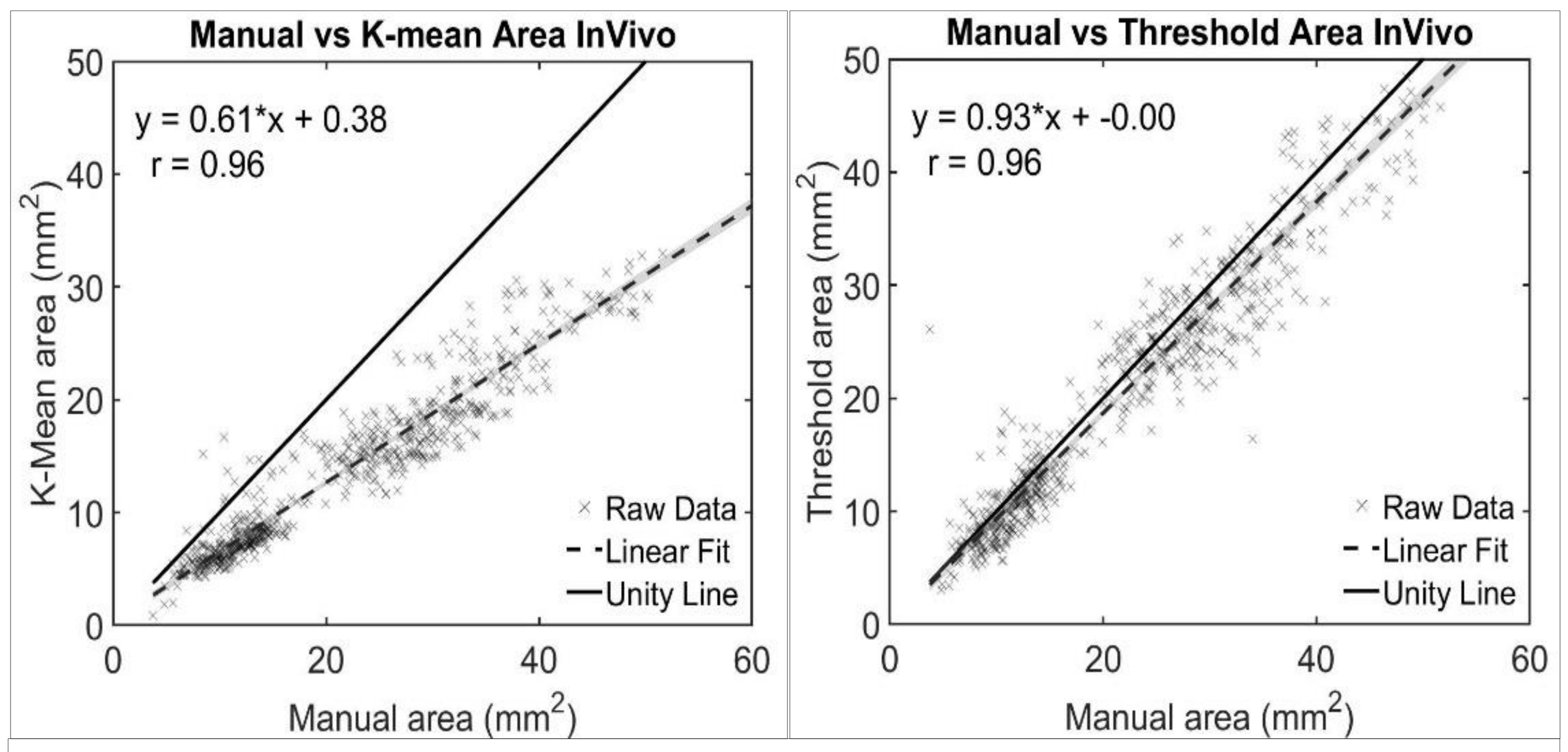

Figure 4: Linear regression (correlation) plots of k-means-derived (CPS) segmented vessel areas and iterative threshold-based (QVT) areas versus ground-truth manual segmentation.

- Regression (Figure 4) for both segmentation methods showed high correlation (R=0.96).
- Threshold-based segmentation was more accurate compared to manual segmentation (slope=0.93) than k-means segmentation (slope=0.61).

- Examples of segmentation improvements are shown in Figure 5.
- Number of missed vessels reduced from 16.2% to 3.8% when analyzed in QVT.
  - MCA, PCA, and TS accounted for 25/26 missed vessels.
  - Average variance of flow along vessel segments was similar for CPS (2.8±2.6%) and QVT (2.9±2.2%).

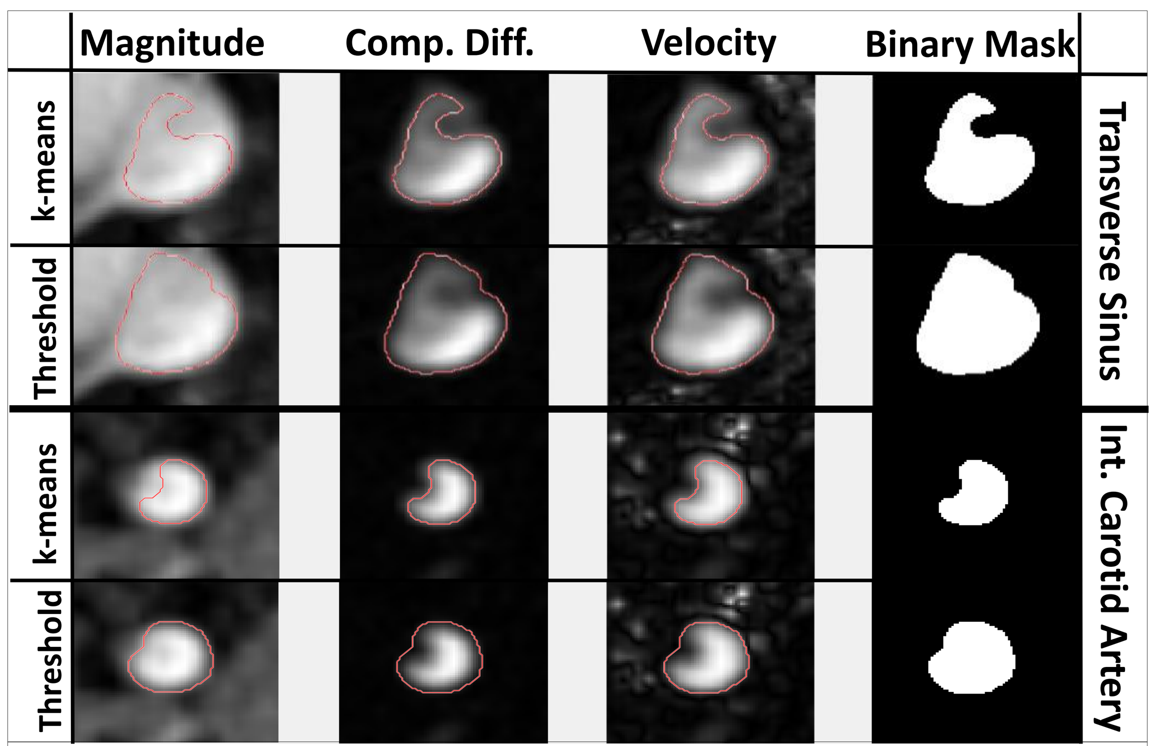

Figure 5: Old k-means segmentation and new threshold segmentation in transverse sinus (top) and internal carotid artery (bottom).

- Bland-Altman analysis of flow quantification between users showed a mean difference and 95% CIs of 0.042 [-0.37, 0.45] ml/s with the QVT (Figure 6).
- Bias and CIs are reduced when compared to old CPS -0.1 [-1.88,1.68] ml/s.
- Internal consistency of flow was observed at vessel junctions for the QVT (Figure 7).

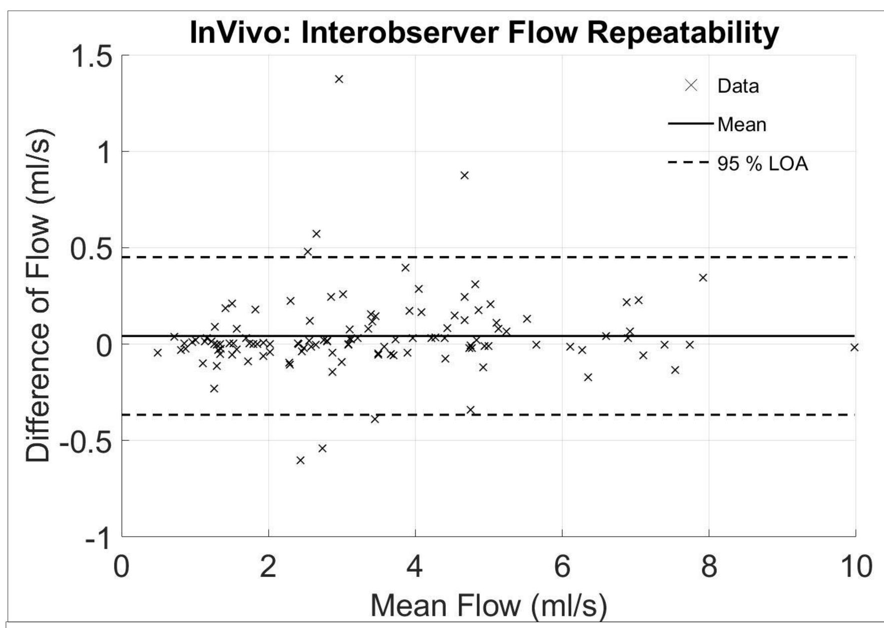

Figure 6: Bland-Altman plot of inter-observer repeatability for QVT.

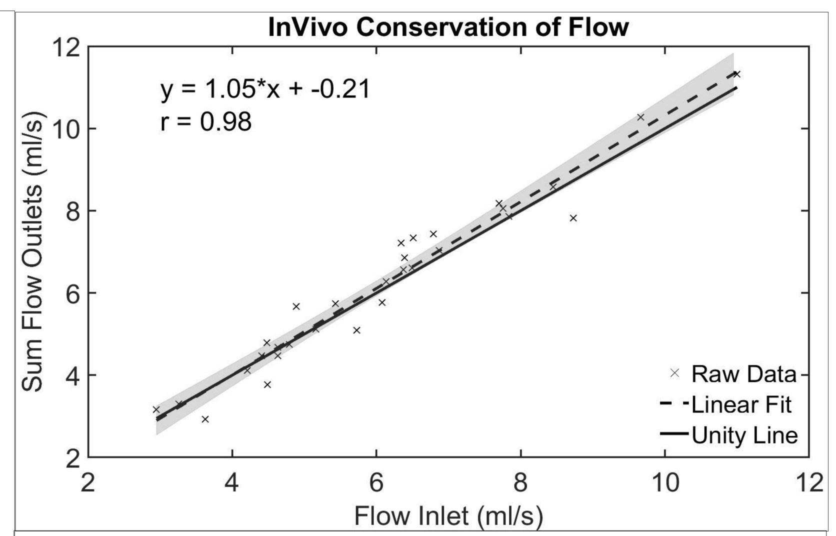

Figure 7: Linear regression plot of inlet and outlet flow at vessel junctions (ICA, ACA, MCA and SSS, SS, TS junctions). High correlation reflects good internal flow consistency with the QVT.

- Angiogram and centerline generation times decreased from 48.6 s to 13.2 s.
- Automated data loading and processing increased from 3.4 min to 6 min
- Processing times (vessel selection and flow validation) decreased from 15.2 min to 5.0 min (1.17 min and 0.38 min per plane).
- Memory requirements were reduced from ~6GB to ~1GB

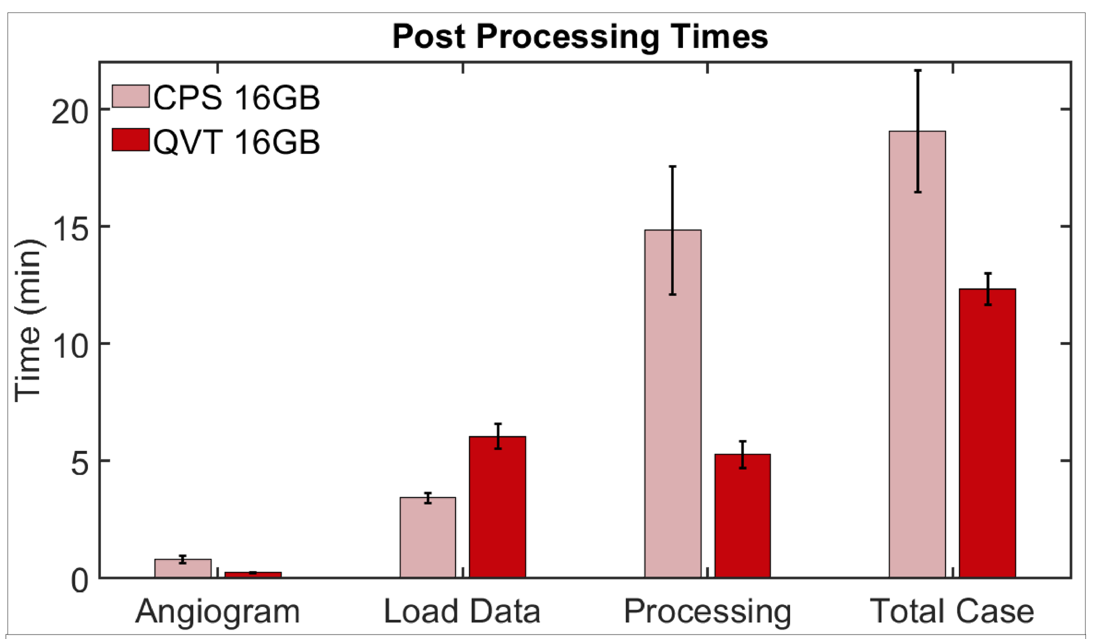

Figure 8: Processing times for new and old tool with 16 GB machine.

Discussion

- Robust analysis tools with high repeatability are extremely desirable for high-volume, long-term 4D flow studies.
- **Both tools showed high user repeatability, small local flow measurement variations (<3%), and quick processing times.**
- **However, we confirmed that the QVT provided improved angiograms, quicker vessel selection, easier visualization, reduced computer memory requirements, and faster processing times.**
  - **Due to these improvements, we suggest utilizing the QVT moving forward.**
- To further verify these findings, more extensive repeatability and flow consistency testing should be performed.

References

[1] Schrauben, E. et al. JMRI 2015; 42:1458-64. [2] Gu, T. et al. AJNR 2008; 26:743-749