Novel Non-invasive Estimation of Coronary Blood Flow using Contrast Advection in Computed Tomography Angiography

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Background

Coronary computed tomography angiography (CTA) is a promising tool for assessment of coronary stenosis and plaque burden. Recent studies have shown the presence of axial contrast concentration gradients in obstructed arteries, but the mechanism responsible for this phenomenon is not well understood. We use computational fluid dynamics to study intracoronary contrast dispersion and the correlation of concentration gradients with intracoronary blood flow and stenotic severity. Data from our CFD patient-specific simulations reveals that contrast dispersions are generated by intracoronary advection effects, and therefore, encode the coronary flow velocity. This novel method- Transluminal Attenuation Flow Encoding (TAFE) - is used to estimate the flowrate in phantom studies as well as preclinical experiments.

Methods

- Patient-specific models were extracted from CT images using Mimics©
- Stenosis geometry was manually created from the normal vessel to mimic 70% stenosis. Number of tetrahedral elements ~ 4.55 x 10^5 (Figure 1)
- Used ANSYS for CFD solutions: 2nd order backward Euler scheme, $\Delta t = 0.01$ s
- Used Arterial Input Function (AIF) and Transluminal Attenuation Gradient (TAG) from CT images (Figure 2) to solve for the flow rate analytically :TAFE (Figure 3 and EQ 1).

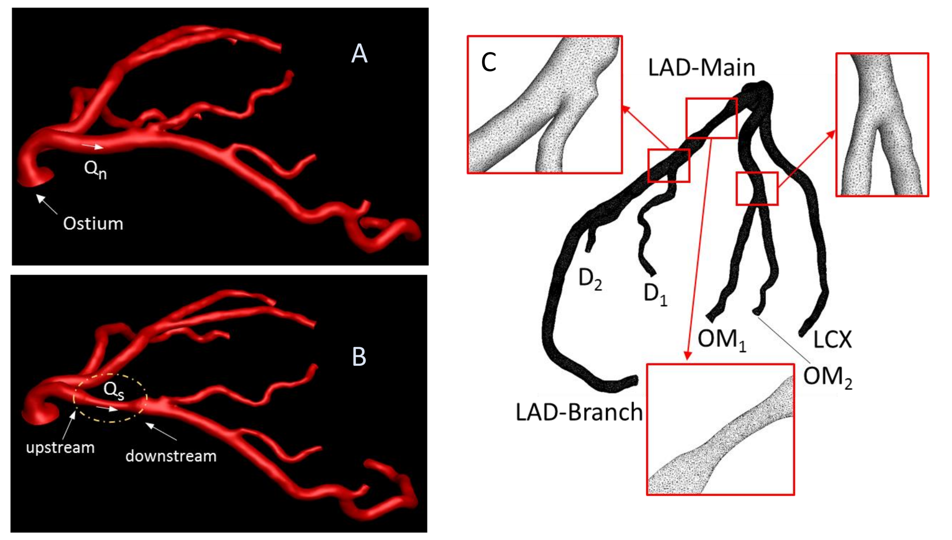
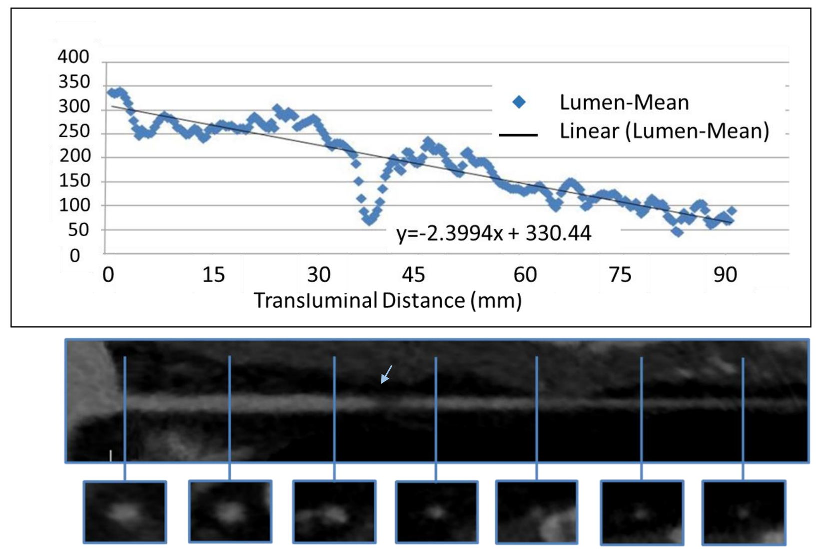


Figure 1: (A) 3-D model of a patient specific coronary artery for the normal (unstenosed) case. (B) Model of the artery with 70% stenosis. (C) Computational meshes employed in the various segments of the model.



HU	343.5	270.8	284.7	198.0	144.4	109.4	92.5
Area (mm²)	7.17	6.83	4.66	2.90	2.13	1.40	1.11

Figure 2: *Example of transluminal contrast gradient for a stenosed artery. Luminal cross sections are sampled and plotted over the vessel length to obtain an axial variation of cross-sectional averaged attenuation (HU) (top figure). Bottom figure shows the axial and cross-sectional visualizations of lumen area by contrast agent.*

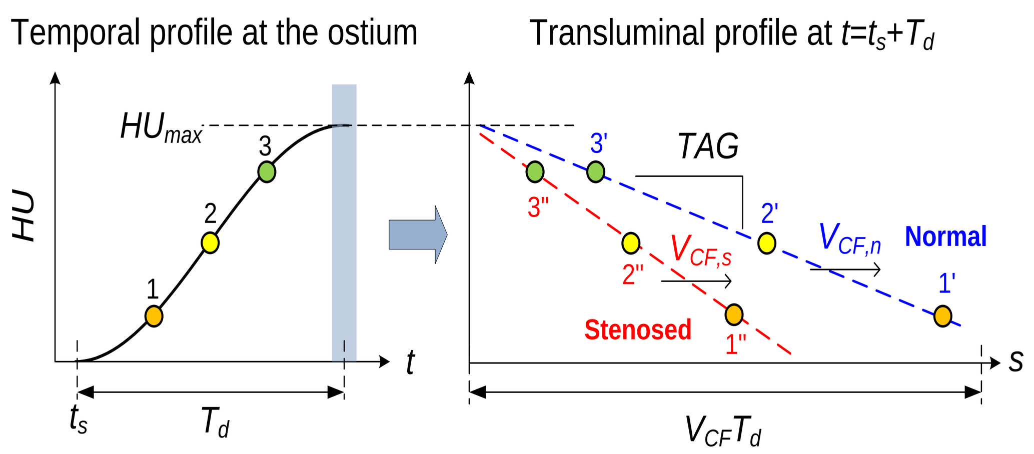


Figure 3: *AIF (left) and Transluminal (right) profile of the contrast agent. TAG is the slope of concentration of contrast agent vs the distance along the vessel plot.*

TAFE Formulation

Transport of Contrast:

$$\frac{\partial C}{\partial t} + (\boldsymbol{U}.\boldsymbol{\nabla})C = D\nabla^2 C \xrightarrow{\text{1D Equation Approximation}} \frac{1}{Q(t)}\frac{\partial C}{\partial t} + \frac{1}{A(s)}\frac{\partial C}{\partial s} \approx 0$$

TAFE Formula for predicting CFV from TAG

$$TAG = \frac{\partial C}{\partial s} == \frac{A(s)}{\bar{Q}}\frac{\partial C}{\partial t} \longrightarrow \boxed{\bar{Q} = -A(s)\,\frac{\partial C}{\partial t}\Big/\frac{\partial C}{\partial s} \qquad EQ.(1)}$$

Computational Results

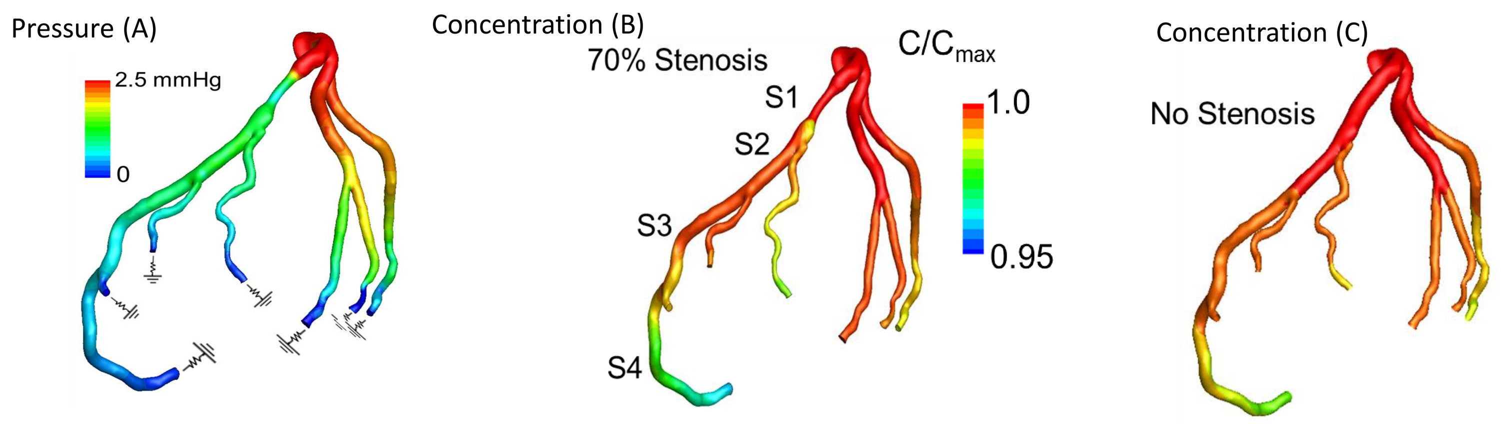


Figure 4: *Patient specific computational results: Pressure (A), normalized contrast agent concentration (C/C_{max}) for the stenosed case (B) and no stenosis case (C)*

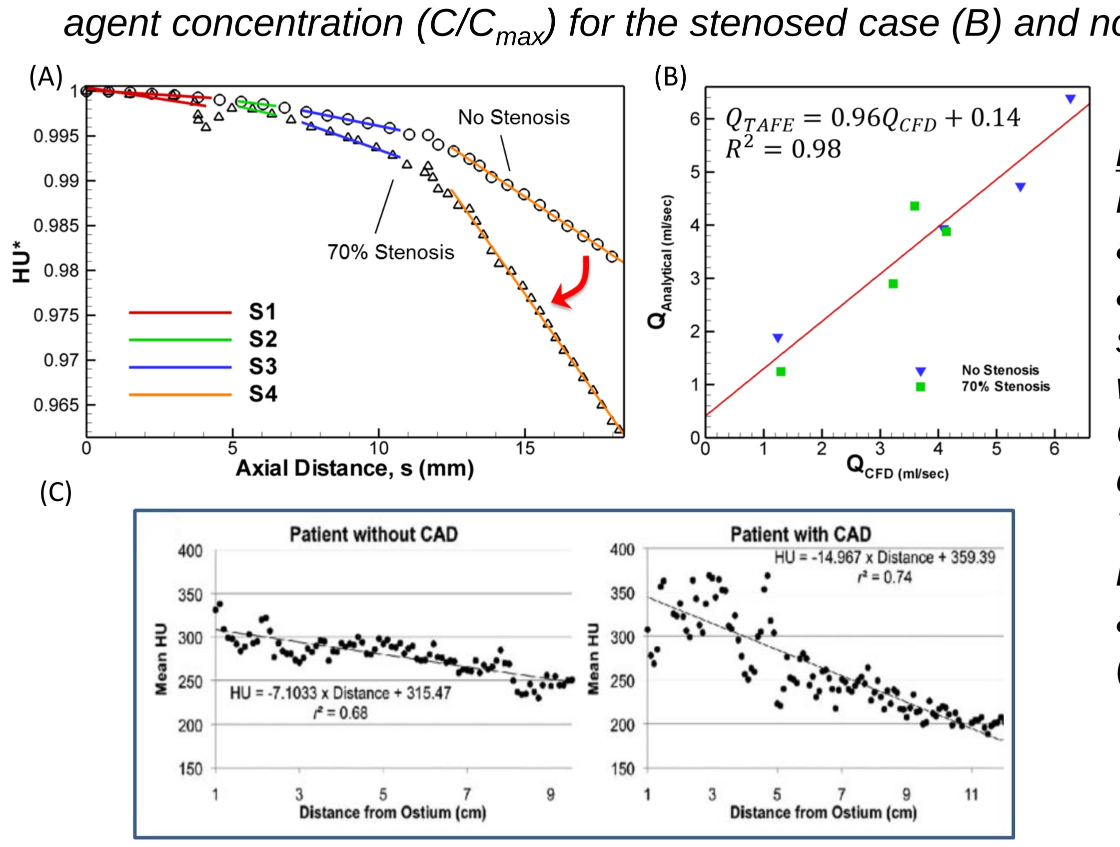
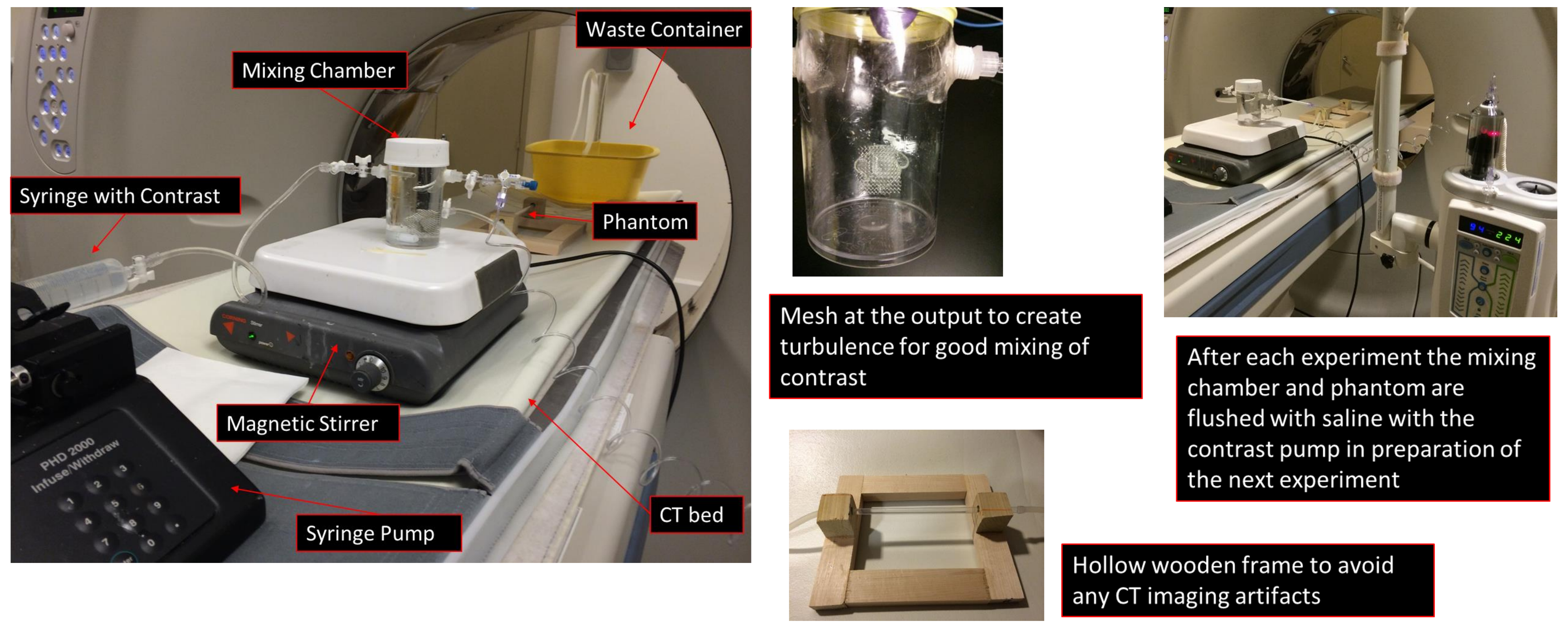


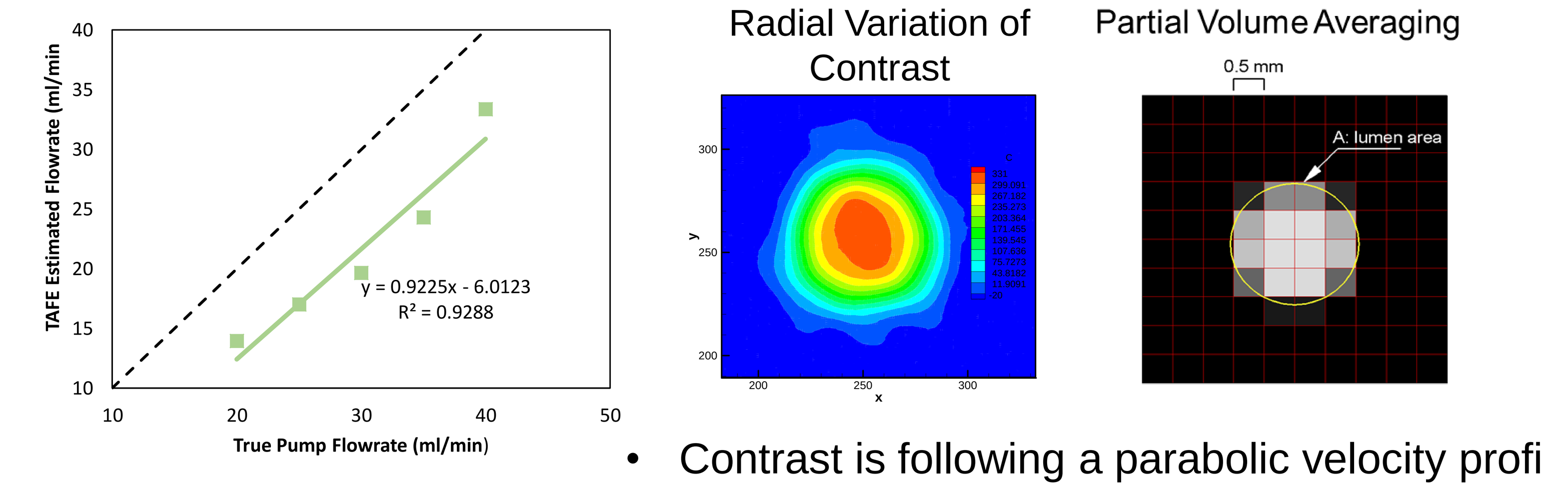
Figure 5: *Patient specific normalized transluminal attenuation profiles along the axial direction of main arterial segment in LAD (steady flow) with P_A=3 and P_B=0 mmHg. (A) Correlation between CFD calculation of flow rate and TAFE calculation of the flow rate in the no-stenosis (normal) and 70% area stenosis cases. (B) and (C) Steigner et. al.*

Experimental Setup



TAFE Validation

Phantom Study



- Contrast is following a parabolic velocity profile
- CT imaging artifacts, ex: PVA and filtering

Figure 6: *Correlation between TAFE estimate velocity and the true pump velocity. The correlation is far from the 45 degree angle because of radial variation of contrast because of specific gravity and imaging artifacts such as partial volume averaging*

Pre-clinical Study

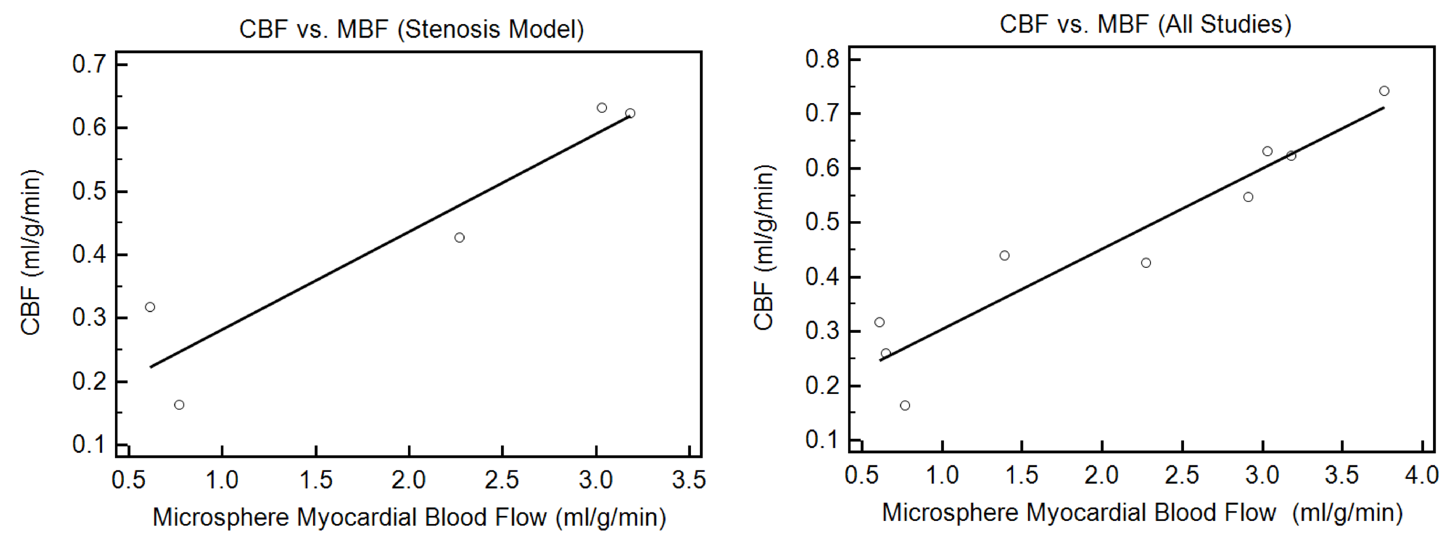


Figure 7: *Correlation between coronary blood flow (TAFE estimated), indexed to myocardial mass and microsphere myocardial blood flow (measured data)in the stenosis model (A) and MI models added to the stenosis model (B).*

Conclusions

- CFD analysis provides insights into the hemodynamic mechanism for TAG generation
- Insights and mathematical analysis lead to
  - Identification of key control variables
  - Formula for quantification of CFV from TAG (TAFE)
- TAFE does NOT require:
  - Anesthesia
  - Catheter placement
  - Sophisticated CFD modeling and hardware
  - CT data to be sent outside of the hospital for analysis
- Phantom studies for a straight tube and pre-clinical studies demonstrates a promising validation of the TAFE formulation with the assumption of linear AIF

Acknowledgement & Conflict of Interest

RM & ACL would like to acknowledge support from the Coulter Foundation for this work. PE is funded by the Graduate Partnership Program fellowship at NIH. RM and ACL have other significant financial interests in technologies associated with contrast agent gradient based flow assessment.