Initial Investigation and Proposed Use-Cases of Contrast Dilution Gradient (CDG) analysis and 1000 fps High-Speed Angiography (HSA)

Kyle A. Williams, Allison Shields, Emily A. Vanderbilt, Ruth E. White, S.V. Setlur Nagesh, Daniel R. Bednarek, Stephen Rudin, Ciprian N. Ionita

INTRODUCTION

- Contrast dilution gradient (CDG) analysis is a velocimetry algorithm which relies on the principles of the convection equation and the capture of contrast media propagation through blood vessels using 1000 fps high speed angiography (HSA).
- CDG utilizes plots of contrast intensity vs time along a line to create velocity distribution estimations along that given line. These lines may be parallel lines which capture flow through simple linear arteries, or in a grid pattern, used to assess non-linear structures (Figure 1)
- HSA uses standard iodinated contrast media, a cadmium telluride photon counting detector, and a continuous exposure to image blood flow with unprecedented detail (at 1000 fps with a 100 µm pixel pitch), while maintaining dose to patient comparable to standard digitally-subtracted angiography (DSA)
- The injection technique used to generate HSA image sequences emphasizes functional information (related to patient hemodynamics) rather than the structural information typically obtained using DSA, meaning less contrast media needs to be injected into the patient, reducing the risk of poor contrast media clearance

OBJECTIVES

- Based on recent feasibility studies related to the CDG method, and the high temporal resolution offered by 1000 fps HSA, we propose the use of this quantitative angiography technique to derive velocity distributions in and around vascular pathologies of interest such as aneurysms and stenoses

METHODS

- Several *in vitro* HSA acquisitions were acquired using the XC-Actaeon and XC-Aries photon counting detectors (Varex), benchtop flow loop setups (Figure 2A) using patient-specific, 3D printed phantoms and standard iodinated contrast injections (Figure 2B)
- *In silico* HSA was acquired using passive scalar transport simulations in a Computational Fluid Dynamics software (ANYSYS). This was accomplished by first solving a steady-state flow condition for the vessel of interest, then simulating a passive scalar “contrast injection” which convects according to the velocity distribution in the vessel (Figure 2C)
- CDG analysis was performed on both *in vitro* and *in silico* HSA acquisitions using both parallel line and grid patterned line sampling
- CDG results were compared to velocity distributions obtained using CFD on corresponding arterial volumes

RESULTS

- Parallel line-sampled CDG showed good agreement with CFD in regions where the direction of the lines most closely aligned with blood flow direction. In regions with poor flow alignment, the method underapproximated velocity values (Figure 3)
- Grid line-sampled CDG also shows good relative agreement with CFD results, with increased robustness to more complex flow dynamics (relative to parallel line-sampled CDG), such as those within an aneurysm (Figure 4)

CONCLUSIONS

- This application has the potential to improve patient diagnoses and provide more targeted treatment plans leading to improved treatment efficiency and better patient outcomes.
- The high temporal resolution of this imaging modality also warrants investigation of cardiac applications of HSA, where the prevalent motion of the heart makes resolution of hemodynamic details difficult under standard imaging modalities. Since it is very easy to track the motion of the coronary vessels at such frame rates, algorithmic motion compensation or cardiac gating could be applied to resolve significant hemodynamic parameters, especially when combined with the CDG method.

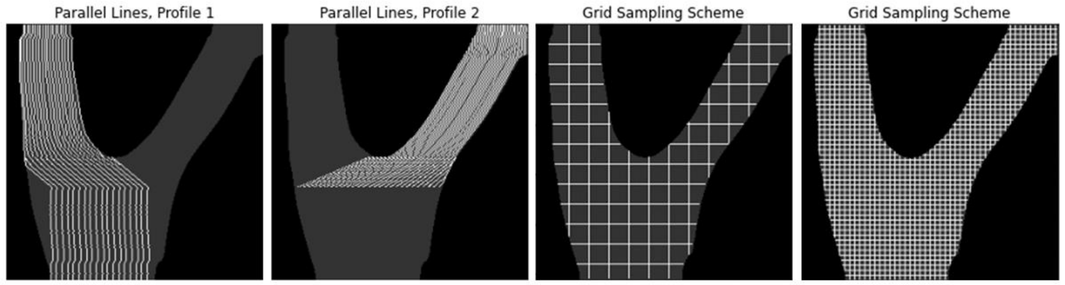

Figure 1: Demonstration of parallel line sampling (left two figures) and grid line sampling (right two figures). For parallel line profile sampling, line spacing is set at the inlet, then narrows according to vessel width. Bifurcating structures are separated into two separate sets of parallel lines. The right two figures show grid line sampling with varying line spacing (20 pixels versus 5 pixels).

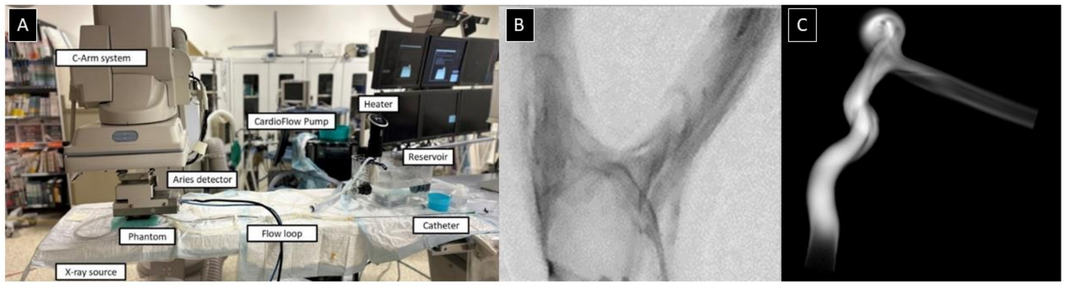

Figure 2: The benchtop flow loop HSA setup (A) includes a circulation system which transports a 40:60 glycerol-water solution through a patient-specific, 3D printed vascular phantom. The system includes a heating element and a pump which simulates realistic cardiac waveforms to simulate *in vivo* conditions. The high speed detector is mounted to our system’s C-arm, and contrast media, introduced via catheter injection, is imaged at 1000 fps to generate *in vitro* HSA data (B). In addition, we simulate 1000 fps HSA data using computational fluid dynamics (CFD) velocity distributions and a subsequent passive scalar transport simulation (C).

1000 fps high-speed angiography provides unparalleled high fidelity qualitative flow information. Paired with contrast dilution gradient analysis, high fidelity, quantitative assessment of neurovascular flow may potentially improve diagnostic imaging capabilities.

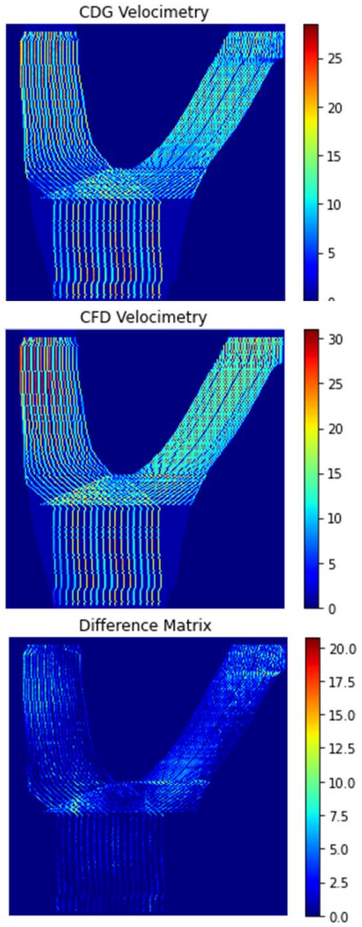

Figure 3: Parallel line profile-based CDG velocimetry for the *in vitro* carotid bifurcation HSA acquisition shown in Figure 2B (top), shown with its corresponding CFD distribution (middle). In order to obtain a 1:1 comparison between these methods, the same parallel lines used to generate CDG results were used to sample the CFD velocity distribution. We observe relatively good agreement between CDG and CFD results, with minor global underapproximation by the CDG approach and the largest error in regions with improper line profile direction, shown in the difference matrix (bottom). We postulate that the global underapproximation of CDG results is likely caused by averaging correct velocities with temporal regions in which no contrast exists in the vessel, leading to velocities close to zero.

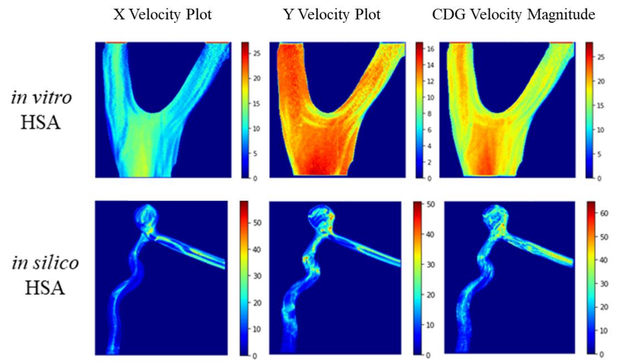

Figure 4: The x- and y-components, as well as the magnitude, of velocities calculated using the grid line-sampled CDG method, for both *in vitro* HSA (top row) and *in silico* HSA. Despite line profile independence during CDG calculations, we observe noticeable continuity in the resulting distributions, and see the ability of the method to handle non-linear geometries, such as the *in silico* aneurysm HSA acquisition. Additionally, the relative magnitudes of the x- and y-velocity components agree well with expected distributions based on the direction of flow qualitatively observed in the raw HSA data.

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Contact Author

Kyle A. Williams, Research Assistant – Canon Stroke and Vascular Research Center (University at Buffalo)
Email: kaw25@buffalo.edu