Establishing a massively parallel, patient-specific model of cardiovascular diseases

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Recent years have witnessed a dramatic increase in computational fluid dynamic (CFD) simulations for diagnosing cardiovascular diseases, which continue to dominate healthcare costs and are projected to be over 1 trillion dollars by 2035. However, current frameworks face three key technical challenges:

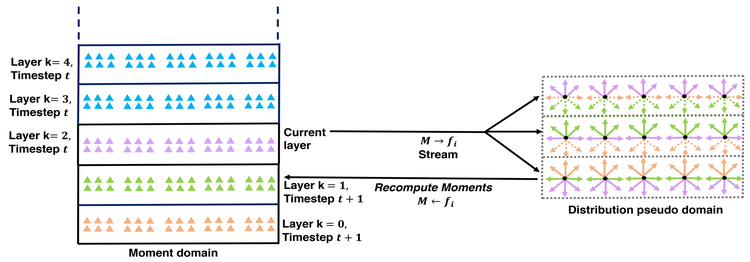
Challenge 1: Simulations are memory intensive with high time-to-solutions

Phase 1: Build a memory-light algorithmic representation that 1) reduces the memory requirements by 74% and 2) maintains excellent parallel scalability

Storing data as moments reduces needed doubles from 38 to 10.

$$\rho = \sum_{i}^{19} f_i(x,t) \qquad \rho u = \sum_{i}^{19} c_i f_i(x,t) \qquad \Pi = \sum_{i}^{19} Q_i f_i(x,t)$$

Zeroth Order Moment: Density | First Order Moment: Momentum | Second Order Moment: Stress

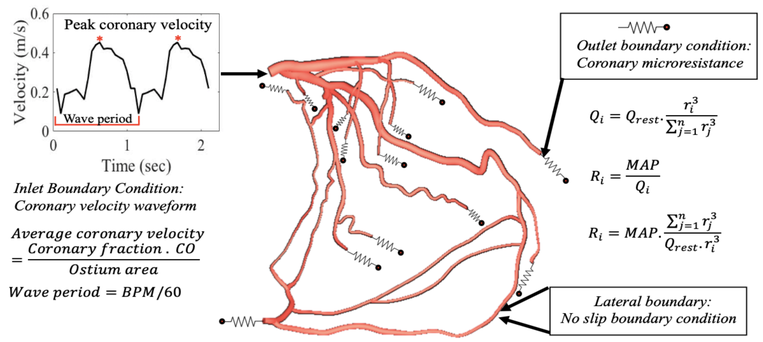


Moment space algorithm

Challenge 2: Need for validation against *in vivo* clinical measurements

Phase 2: Validate our CFD framework through a multicenter, clinical study comparing invasive pressure measurements to calculated values for 200 patients

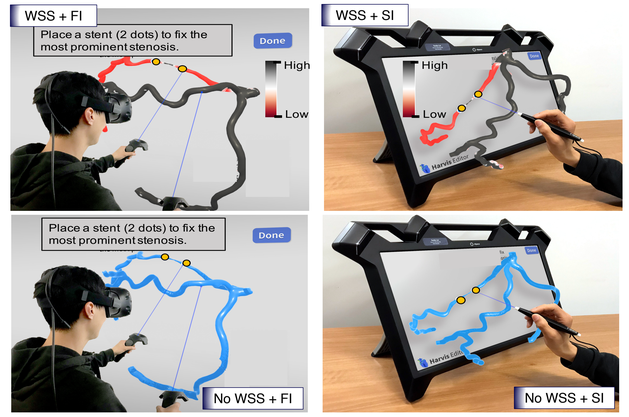
Fractional flow reserve, post-stenotic pressure gradient, is the clinical gold-standard to determine the severity of coronary artery disease.



Personalized flow simulations for patient-derived coronary artery at resting and hyperemic state with tuned velocity waveforms and total coronary microresistance to derive FFR

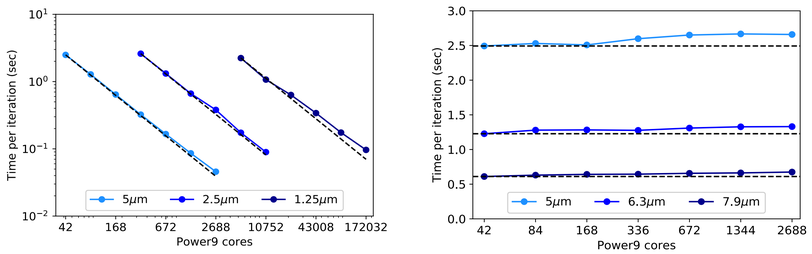
Challenge 3: Lack of methods for clinicians to intuitively interact with simulation results

Phase 3: Assess how physicians interact with large-scale CFD simulation data and present a virtual reality platform for scientific visualization to aid treatment planning

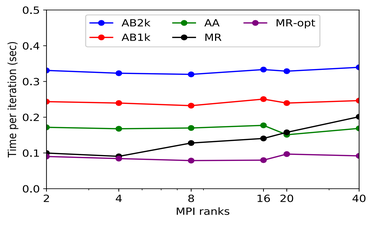


VR-CFD-based medical planning system for coronary interventions. Arterial geometries overlaid with flow data (WSS - wall shear stress) displayed on the HTC Vive HMD (fully immersive - FI) and zSpace monitor (semi-immersive - SI) with and without WSS

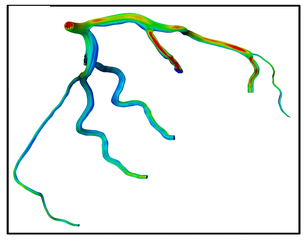
Results: Scaling, performance and patient-specific simulation



Strong scaling and weak scaling on Summit's Power 9 CPUs for cylindrical geometry at three resolutions

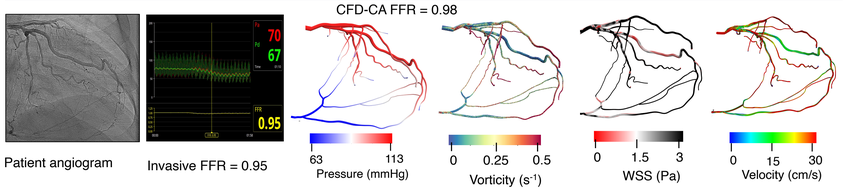


Performance of MR and MR-cache-opt outperforms other distribution patterns

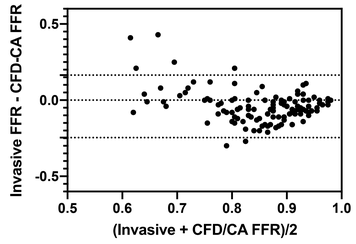


Velocity streamlines using the MR scheme for a complex left coronary arterial geometry

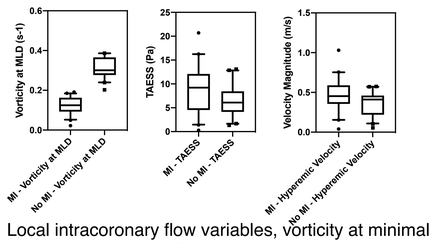
Results: Massively parallel CFD simulations – Clinical trial



Comparison of invasive and CFD-CA FFR. Important hemodynamic risk factors, wall shear stress and vorticity, can also be accurately derived using CFD-CA framework to provide physicians complete physiological landscape of arterial anatomy.

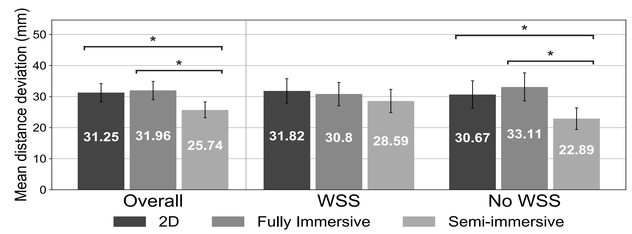


Bland-Altman plot demonstrates the accuracy of CFD-CA FFR values by comparing to invasive FFR

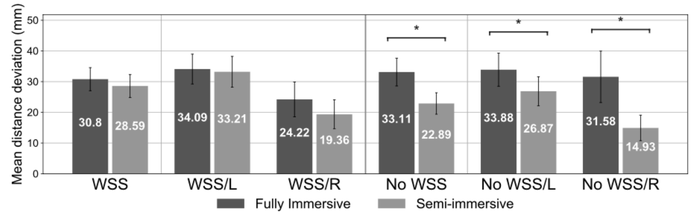


Local intracoronary flow variables, vorticity at minimal luminal diameter (MLD), time averaged shear stress (TAESS) and hyperemic velocity magnitude, differ between patients with prior myocardial infarction (MI)

Results: VR-CFD-based medical planning system



SI device has significantly lower distance deviation compared to FI device and 2D desktop. Thus, semi-immersive virtual environments improve user accuracy for identifying stent location relative to that of the 2D and FI displays



Complexity differences and distance deviation, showing LCA (L) and RCA (R) results with WSS and without WSS. Brackets=p<0.05. Error bars=SE.

Impact and Outlook

- The entire simulation state can be represented using only moment data to retrieve second order accurate Navier-Stokes equation, thus accuracy and computations are similar to traditional LBM approach
- This work presents a new scheme for improving both time to solution and the scale of the problem that can fit in memory
- Looking forward to GPUs, this scheme holds immense potential as available memory continues to be a limitation on GPUs

Impact and Outlook

- CFD vs invasive measurements resulted in 10% average error, 93% positive predictive value and 81% accuracy and successfully meets the current FDA standard for the clinical deployment of CFD-based method to diagnose patients
- Completion of this clinical study required millions of compute hours on state-of-art HPC systems. This work establishes the critical step for translating the use of massively parallel simulation-driven diagnostics and treatment planning to the clinic

Impact and Outlook

- In this study, we evaluated the effect of using different VR devices upon treatment planning when viewing both anatomic and CFD simulation data
- Findings demonstrate CFD simulations can guide physicians in treatment planning procedures
- We believe a unified CFD-VR based rehearsal training platform could diminish subjectivity arising from differences in procedural skill sets