Cloud Computing at Scale: Tracking 4.5 Million Heartbeats of 3D Coronary Flow via the Longitudinal Hemodynamic Mapping Framework

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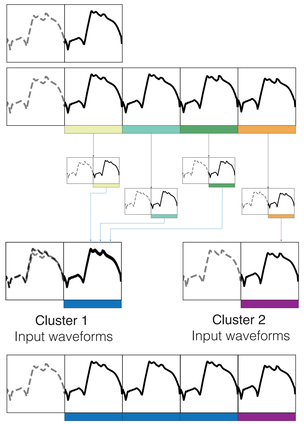
1 Introduction

- Personalized 3D blood flow digital twins limited to single heartbeat metrics/maps
- Tracking hemodynamic responses to treatment/stimuli over long periods is a grand challenge
- Personalized 3D blood flow digital twins limited to single heartbeat metrics/maps
- Enabling longitudinal hemodynamic mapping would pave way for better risk assessment in treatment planning/recovery and identify more complex, personalized, and accurate biomarkers
- ***Overall goal*** is to enable tractable computation of longitudinal hemodynamic maps

Challenges

- **Computationally intractable using explicit methods [1]**
- **Informing physical states from wearables**
- **Robust validation**
- **High-throughput simulations using heterogeneous systems**

2 Deconstructing time order to establish LHMF



Literature standard: one hemodynamic unit (HU)

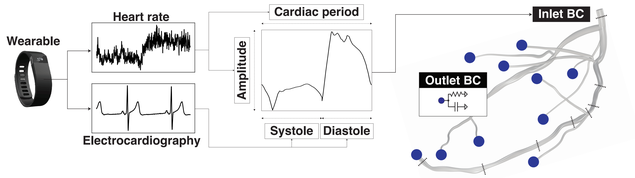
Explicit method: simulate heartbeats in time order

LHMF: deconstruct sequence into HUs and perform simulations in parallel on cloud instances

LHMF$_C$: minimize redundant simulations by clustering hemodynamically-similar HUs

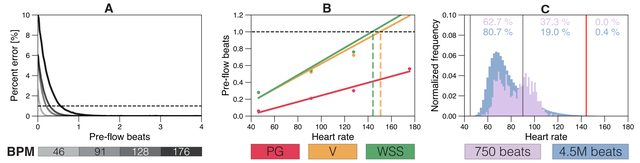
Re-assembly: Results are used to re-assemble a longitudinal sequence of cardiac cycles, enabling the first longitudinal hemodynamic maps (LHMs)

3 Wearable-driven 3D coronary digital twins



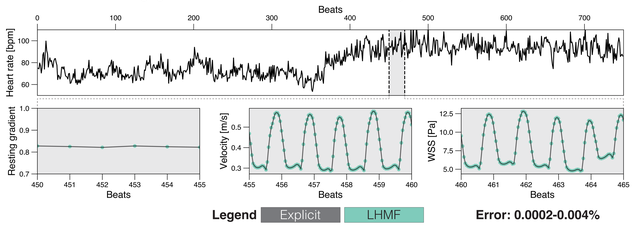
4 Evaluating temporal convergence

- **Goal:** Demonstrate that all HUs are temporally converged over all activity states
- Evaluated temporal convergence for pressure gradient (PG), velocity (V), and wall shear stress (WSS) over four representative heart rates
- Need two pre-cardiac cycles for V and WSS when heart rate is over 140 bpm



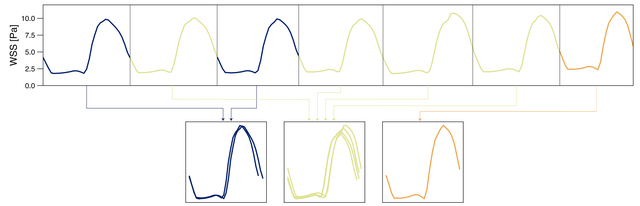
5 LHMF recapitulates explicit methods

- **Goal:** Validate LHMF vs. an explicit simulation of 750 heartbeats (exceeds literature by ***10x***)
- Explicit ground-truth run on the Duke Compute Cluster
- HUs simulated in parallel on hpc6a.48xlarge insances, OLCF Summit, and TACC Stampede2
- Percent errors were negligible: 0.0002-0.004% for all hemodynamic metrics



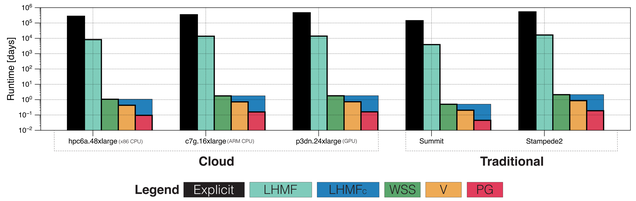
6 LHMF$_C$ minimizes redundant simulations

- **Goal:** Establish LHMF$_C$, a refinement to LHMF, that minimizes running redundant HUs
- Want hemodynamically equivalent results while allowing as much variance in the inputs
- Clustered outputs to inform salient features in the input velocity waveforms



7 LHMF is effective on heterogenous systems

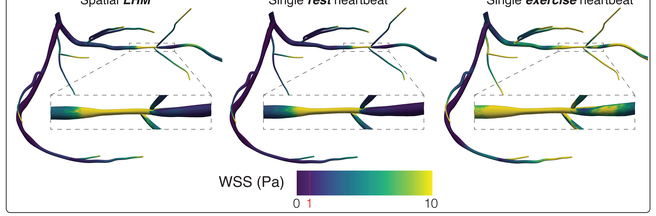
- **Goal:** Demonstrate that LHMF and LHMF$_C$ can tractably analyze 4.5 million heartbeats across heterogenous systems
- Explicit method requires > 10^5 days; LHMF requires > 10^3 days; LHMF$_C$ requires ***43 hours*** across both cloud and traditional systems
- WSS needed the most HUs (and runtime), followed by V and PG



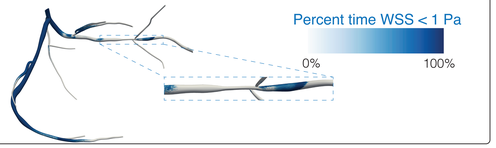
8 Application of LHMF$_C$ for capturing 1.5 months

- **Goal:** Show the need for LHMs over single heartbeat maps and study WSS as a case example
- Low WSS (< 1 Pa) is linked to the development of atherosclerotic plaque [3]
- Applying LHMF$_C$ to the 4.5 million heartbeats, we only required simulating 1160 HUs
- Simulations on hpc6a.48xlarge (38,400 cores), OLCF Summit, and Duke Compute Cluster
- Spatial LHM (averaging WSS maps over 1.5 months of activity) is statistically different to single rest heartbeat maps ($p < 0.001$) and single exercise heartbeat maps ($p < 0.001$)
- We established a temporal LHM (showing fraction of time spent with WSS < 1 Pa), enabling identification of sites with persisting low WSS that could be conducive to disease progression

A Comparing spatial distributions of WSS - *LHM vs. single heartbeat maps*



B Temporal LHM identifying sites of low WSS for 4.5 million heartbeats



References:

[1] Amanda Randles, Erik Draeger, Tomas Oppelstrup, Liam Krauss, and John A Gunnels. Massively parallel models of the human circulatory system. In Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis, pages 1–11, 2015.

[2] Noelia Grande Gutiérrez, Mark Aber, Andrew M Kahn, Jane C Burns, Mathew Mathew, Brian W McCrindle, and Alison L Marsden. Computational modeling of blood component transport related to coronary artery thrombosis in kawasaki disease. PLoS computational biology, 17(9):e1009331, 2021.

[3] Habib Samady, Parham Eshtehardi, Michael C McDaniel, Jin Suo, Saurabh S Dhawan, Charles Maynard, Lucas H Timmins, Arshed A Quyyumi, and Don P Giddens. Coronary artery wall shear stress is associated with progression and transformation of atherosclerotic plaque and arterial remodeling in patients with coronary artery disease. Circulation, 124(7):779–788, 2011.

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