Personalizing Cardiovascular Simulations for Wearable Health Sensing

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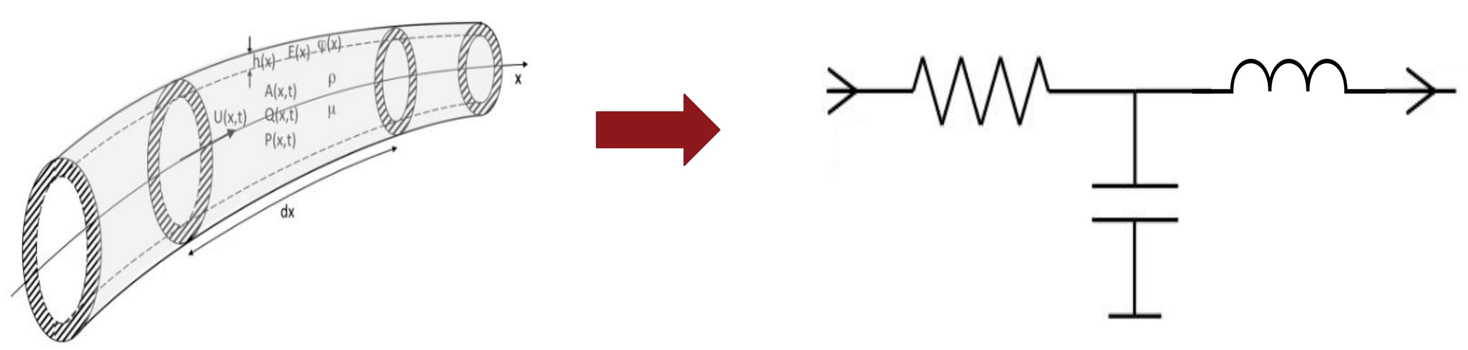
Introduction

The continuous, patient-specific data that wearable technology provides presents a unique opportunity for sensing the dynamic cardiovascular system. Prior literature has utilized this data for predicting various individual cardiovascular metrics,[1] but this research explores whether this data can fit personalized, simulated cardiovascular models—"digital twins."

We propose modeling a digital twin using a 0D cardiovascular model. These 0D models leverage the analogy between fluid dynamics and electrical circuitry, representing each blood vessel with a resistor (R), inductor (L), and capacitor (C).[2] Fitting these RLC parameters to an individual's physiology produces their personalized "digital twin."



Alastruey, J., Parker, K. H., & Sherwin, S. J. (2012). Arterial pulse wave haemodynamics. In S. Anderson (Ed.), *11th International Conference on Pressure Surges* (pp. 401-443). Virtual PiE Led t/a BHR Group.

Charlton PH, Mariscal Harana J, Vennin S, Li Y, Chowienczyk P, Alastruey J. Modeling arterial pulse waves in healthy aging: a database for in silico evaluation of hemodynamics and pulse wave indexes. Am J Physiol Heart Circ Physiol. 2019 Nov 1;317(5):H1062-H1085.

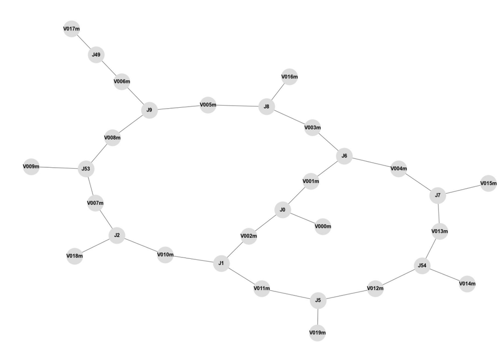
This research makes two contributions towards realizing cardiovascular digital twins: first, in studying methods of reducing 0D model complexity, and second, by prototyping an algorithm for fitting models to individuals.

Model Reduction

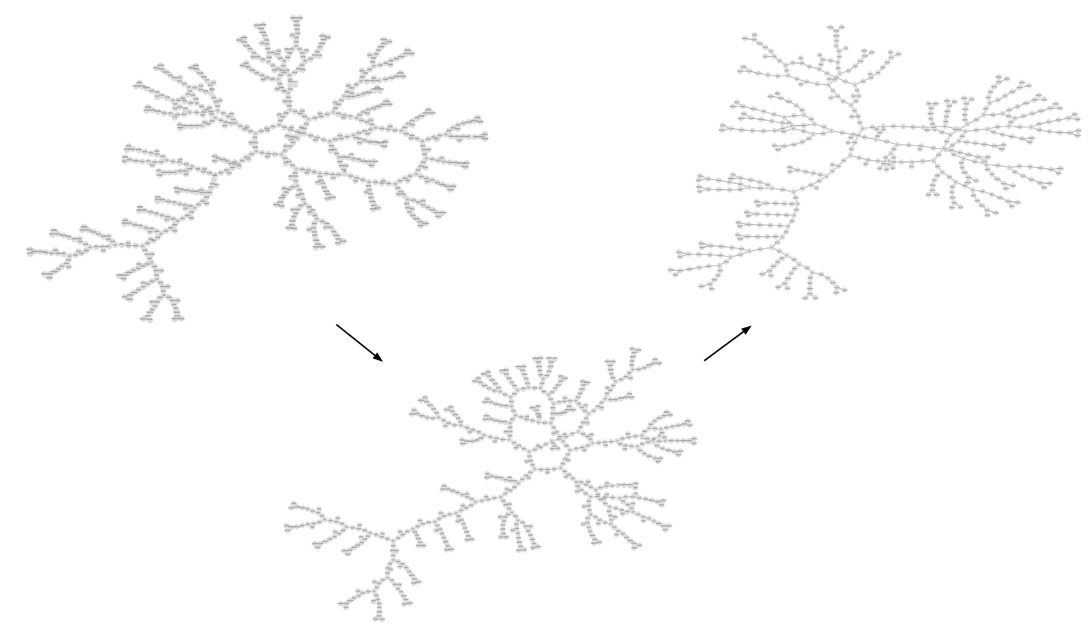
Methods

We start with an existing cardiovascular model containing 116 arteries,[3] which in 0D form has 448 parameters to fit. To simplify model fitting, we sought to simplify the model while preserving the aortic-to-radial transfer function. We explored two methods of model reduction:

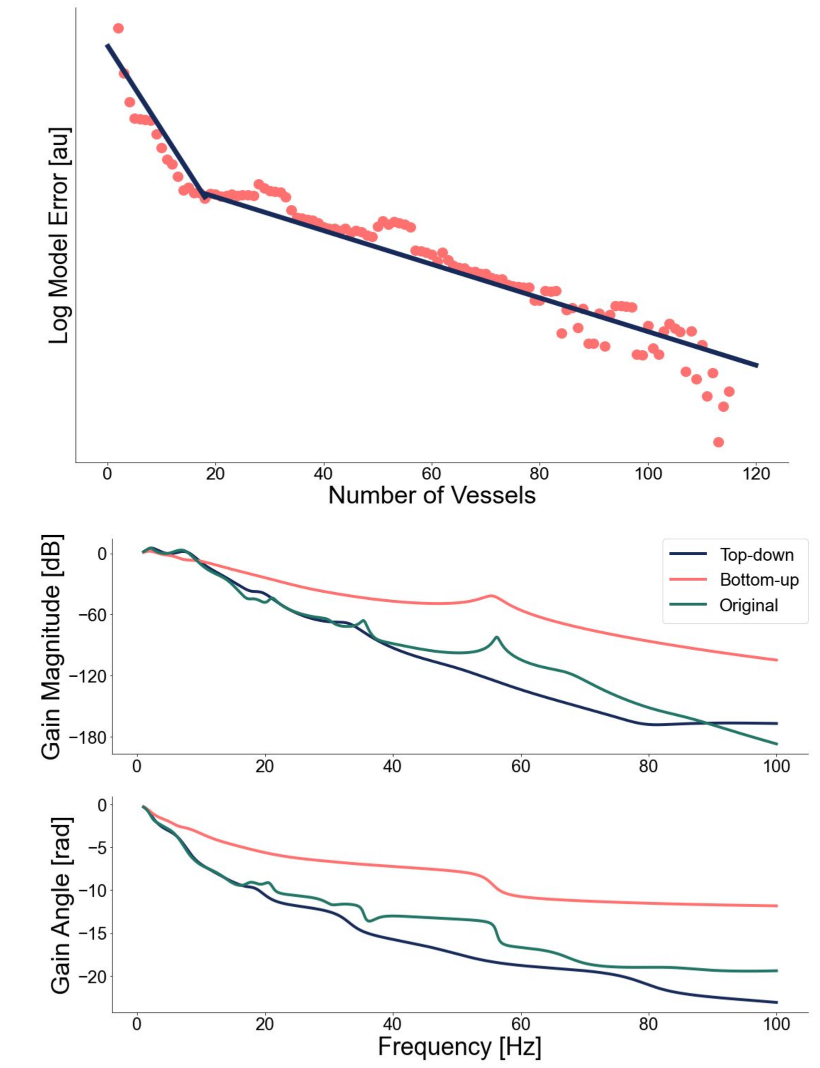
Bottom-Up Method
Design custom 0D models based on domain knowledge.



Top-Down Method
Sequentially remove the least impactful vessels with beam search.



Results



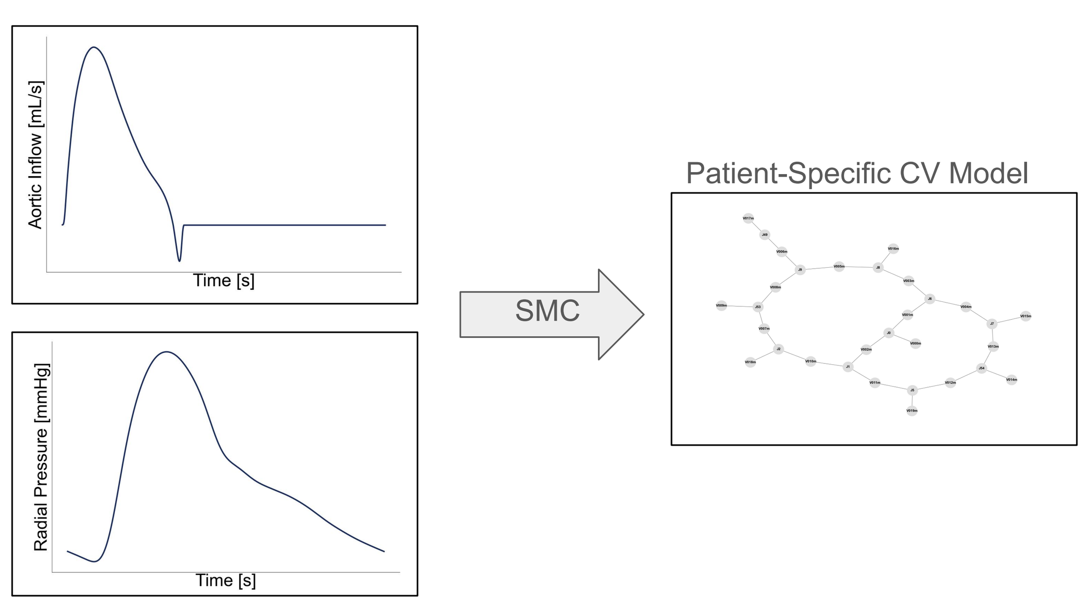
Using the top-down method, we found an inflection in the rate of model accuracy degradation at 20 vessels. So, we choose 20 vessels as a target model size.

We evaluated reduced models by their ability to reproduce the original model's aortic-to-radial transfer function, which characterizes the relationship between pulse waves at the heart and in the wrist. By this metric, the top-down approach was superior.

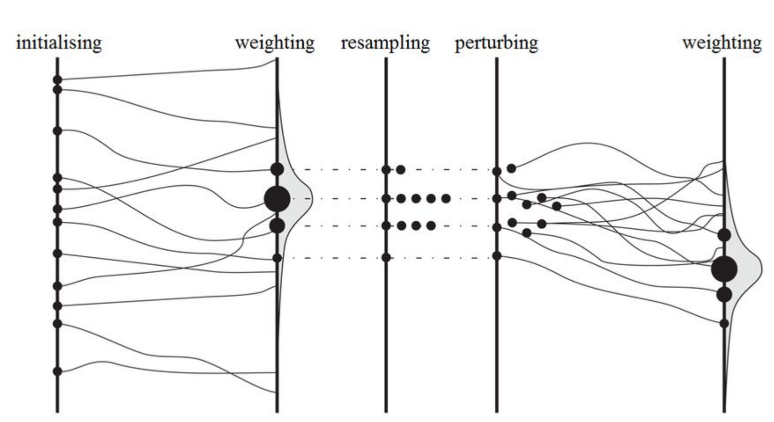
Model Fitting

Methods

The algorithm for fitting the model's parameters to an individual takes two inputs: the system's inflow from the aorta and the radial pressure pulse wave.



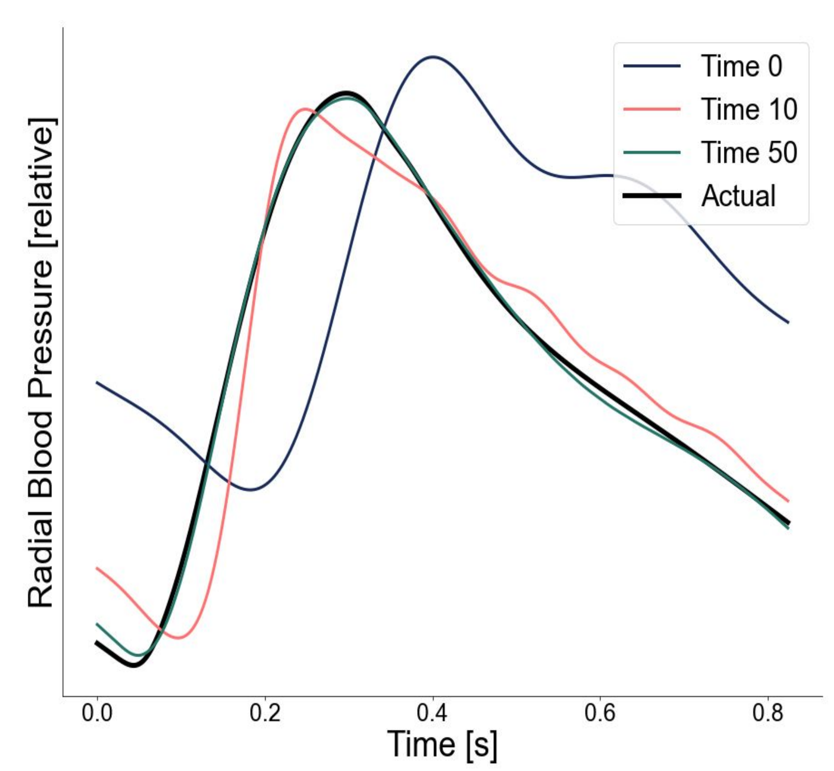
The fitting process uses Sequential Monte Carlo (SMC) to find the RLC parameters for each vessel which best reproduce the provided radial pulse wave with the provided aortic inflow.

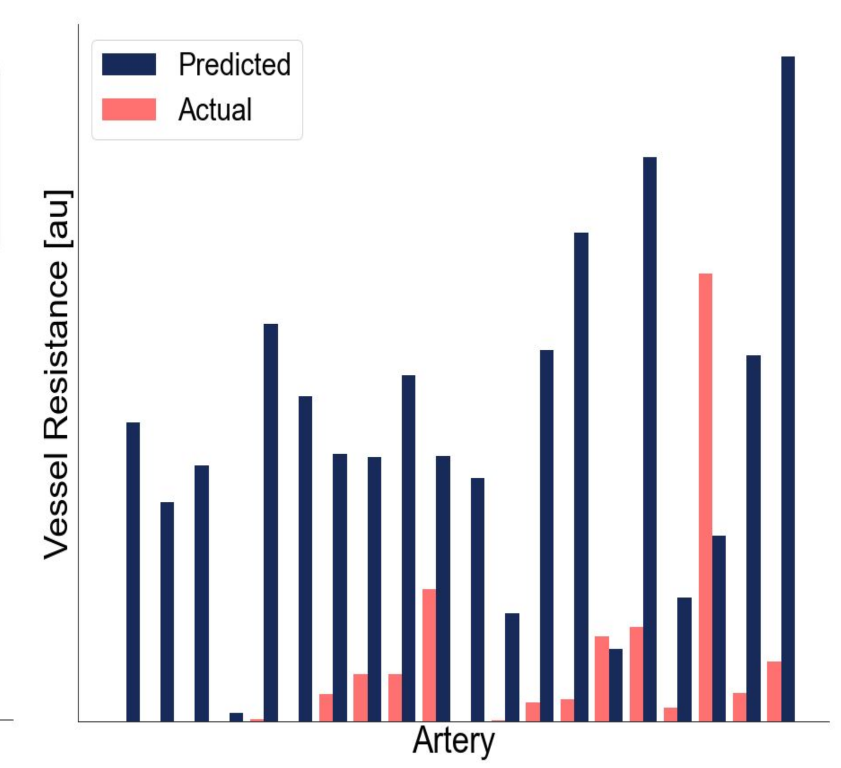


Montzka C, Pauwels VRN, Franssen H-JH, Han X, Vereecken H. Multivariate and Multiscale Data Assimilation in Terrestrial Systems: A Review. *Sensors*. 2012; 12(12):16291-16333. https://doi.org/10.3390/s121216291

Results

SMC succeeds in fitting RLC parameters that reproduce the radial pulse wave (below left); however, fitted parameters are not equal to the parameters used to generate the radial pulse wave (below right).





Conclusion

We demonstrate the possibility of reducing 0D models while preserving valuable properties—specifically, the aortic-to-radial transfer function. Future work should iterate more on the bottom-up model design and calibrate top-down-simplified models to reproduce ground-truth blood flow.

We also experiment with an SMC-based algorithm for model fitting; however, the challenge remains of distinguishing between the multiple parameter configurations which produce the same radial pressure pulsewave. Future work resolving this ambiguity should incorporate priors or other metrics, in addition to pressure, at the wrist. Furthermore, in order to make model fitting possible non-invasively, future work should modify the fitting algorithm such that it does not require an aortic inflow curve.

The model reduction and model fitting algorithms used here may contribute to a larger toolkit realizing digital twins for predicting cardiovascular health.

References

[1] Jason P Burnham, Chenyang Lu, Lauren H Yaeger, Thomas C Bailey, Marin H Kollef, Using wearable technology to predict health outcomes: a literature review, *Journal of the American Medical Informatics Association*, Volume 25, Issue 9, September 2018, Pages 1221–1227
[2] Mahdi Esmaily Moghadam, Irene E. Vignon-Clementel, Richard Figliola, Alison L. Marsden, A modular numerical method for implicit 0D/3D coupling in cardiovascular finite element simulations, Journal of Computational Physics, Volume 244, 2013, Pages 63-79, ISSN 0021-9991
[3] Charlton PH, Mariscal Harana J, Vennin S, Li Y, Chowienczyk P, Alastruey J. Modeling arterial pulse waves in healthy aging: a database for in silico evaluation of hemodynamics and pulse wave indexes. Am J Physiol Heart Circ Physiol. 2019 Nov 1;317(5):H1062-H1085.