Summary of papers

Parameterisation of multi-scale continuum perfusion models from discrete vascular networks. Hyde, E.R., Michler, C., Lee, J. et al. Med Biol Eng Comput (2013) 51: 557. https://doi.org/10.1007/s11517-012-1025-2

- Coronary arteries geometry created by synthetic network
- Multi-compartment method using 3D Darcy's law for the porous medium and 1D models and Poiseuille flow for the coronary arteries
- Comparison of 3 parameterisation methods for multi-compartment K and beta
- Application of method in a subdomain of a rat's myocardium tissue

Points of interest for the coupling: Physical meaning of parameter beta

Multi-Scale Parameterisation of a Myocardial Perfusion Model Using Whole-Organ Arterial Networks. Hyde, E.R., Cookson, A.N., Lee, J. et al. Ann Biomed Eng (2014) 42: 797. https://doi.org/10.1007/s10439-013-0951-y

- Canine and porcine coronary arteries images obtained by cryomicrotome
- Multi-compartment method for coronary arteries-myocardium coupling, using 1D models and Poiseuille flow
- Application of the method described in: **Parameterisation of multi-scale continuum perfusion models from discrete vascular networks.** Hyde, E.R., Michler, C., Lee, J. et al. Med Biol Eng Comput (2013) 51: 557. https://doi.org/10.1007/s11517-012-1025-2
- Comparison of 5 parameterisation methods for multi-compartment K and beta *using anatomical data*
- Comparison of results with experimental data

Point of interest for the coupling: Order of magnitudes for beta and K.

Lee J, Cookson A, Chabiniok R, Rivolo S, Hyde E, Sinclair M, Michler C, Sochi T, Smith N. **Multiscale modelling of cardiac perfusion**. In: Quarteroni A, ed. Modeling the Heart and the Circulatory System. Cham, Heidelberg, New York, Dordrecht, London:Springer; 2015, 51–96.

- Elaboration of the ideas presented in the above 2 papers, including also a concise summary
- Focus on multi-compartment static Darcy method, poroelasticity model parameterisation of porous medium, 1D coronary blood flow.

Point of interest: Summary of the notions presented in papers with a few extra details

Shi, Y., Lawford, P., and Hose, R. **Review of zero-D and 1-D models of blood flow in the cardiovascular system.** Biomed. Eng. Online. 2011; 10: 33

Presentation of the state of the art on 1D-0D models:

- Suitability of 1D-0D models for different applications
- Limitations of each model
- Coupling of 1D-0D models

Point of interest: Useful in order to determine the blood flow modelling approach required, depending on the phenomena present in our system

Simulation of cardiac perfusion by contrast in the myocardium using a formulation of flow in porous media. J.R.Alves, R.A.B.deQueiroz, R.W.dosSantos (2016)

- Technical paper, describing in detail the numerical methods and algorithms used to solve the modelling equations
- 3D Darcy's law for the myocardium (one compartment)
- Extra equations for the modelling of the contrast agent

Point of interest: Interesting due to the additional chemical species (contrast) in the blood

The arterial Windkessel. Westerhof, N., Lankhaar, JW. & Westerhof, B.E. Med Biol Eng Comput (2009) 47: 131. https://doi.org/10.1007/s11517-008-0359-2

- Review/introductory paper to the lumped parameter model (0D).
- Explaining the historical evolution of the model, its main methods, assumptions and applications, as well as its limitations.

Point of interest: Excellent read for an overview of the lumped parameter model's utility

Computational modelling of 1D blood flow with variable mechanical properties and its application to the simulation of wave propagation in the human arterial system. SJ Sherwin, L Formaggia, J Peiro, V Franke, International Journal for Numerical Methods in Fluids 43 (6-7), 673-700

- Technical paper, describing in detail two numerical methods used to solve the 1D models.
- Emphasis on partial differential equations solving techniques, including weak forms expressions and determination of boundary conditions.

Point of interest: Only for those interested in numerical methods. Very technical.

Patient-Specific modeling of blood flow and pressure in human coronary arteries. Kim, H.J., Vignon-Clementel, I.E., Coogan, J.S. et al. Ann Biomed Eng (2010) 38: 3195. https://doi.org/10.1007/s10439-010-0083-6

- 3D non-stationary Navier-Stokes for coronary arteries...
- ...coupled with lumped parameter models as *outflow boundary conditions* (using the coupled multidomain method presented in **Outflow boundary conditions for three-dimensional finite element modeling of blood flow and pressure in arteries.** Vignon-Clementel, I E ; Figueroa, C A ; Jansen, K E ; Taylor, C A .In: COMPUTER METHODS IN APPLIED MECHANICS AND ENGINEERING, Vol. 195, No. 29-32, 01.06.2006, p. 3776-3796.
- Combination of lumped parameter and closed-loop model as *inlet boundary conditions.*
- Application of the above methodology in geometries with stenosis

Point of interest: Coronary flow model using complex boundary conditions

A poroelastic model valid in large strains with applications to perfusion in cardiac modeling. Chapelle, D., Gerbeau, JF., Sainte-Marie, J. et al. Comput Mech (2010) 46: 91. https://doi.org/10.1007/s00466-009-0452-x

- Technical paper, describing in great detail the modelling approach used (assumptions,equations,boundary conditions) and the numerical techniques to solve the system of governing equations.
- 3D poroelastic equations for the myocardium! (porous medium + elastic medium)

Point of interest:
- Values for porous medium parameters
- 4.3 section explaining the source term

One-dimensional models for blood flow in arteries, Formaggia, L., Lamponi, D. & Quarteroni, A. Journal of Engineering Mathematics (2003) 47: 251. https://doi.org/10.1023/B:ENGI.0000007980.01347.29

- Introductory paper to 0D models, detailing their assumptions and their derivation.
- Discussion on the the constitutive law's used (wall mechanics), discussing simple and more complex models.
- Boundary conditions, bifurcation geometries and numerical discretisation are detailed.

Point of interest: Excellent paper to understand the main assumptions and the derivation of 1D models.

Outflow boundary conditions for three-dimensional finite element modeling of blood flow and pressure in arteries. Vignon-Clementel, I E ; Figueroa, C A ; Jansen, K E ; Taylor, C A .In: COMPUTER METHODS IN APPLIED MECHANICS AND ENGINEERING, Vol. 195, No. 29-32, 01.06.2006, p. 3776-3796.

The summary for this paper is a bit more detailed. Sorry about that, it is one of my favourite papers.

Remarks about outflow BCs:

- Outflow BCs are *extremely* important, as they represent vessels downstream of the modelled domain
- Our solution is highly dependant on outflow BCs

Types of outflow BCs:

- Constant pressure
- Constant traction
- Prescribed velocity profile

However, the above BCs are not always known. Thus, we are forced to use other types of outflow BCs:

- Coupling with 0D model (lumped parameters)
- Coupling with 1D model

Why do we use coupling with 1D and 0D?

- Downstream bed too complex to simulate in 3D, *but* we cannot ignore completely its effect ---> 3D model of large arteries coupled with 1D model for downstream bed

<u>What has been done so far in 3D-1D coupling:</u>

- Coupling for simple geometries and iteratively

<u>What is proposed in this paper:</u>

- Try more complex geometries using linear wave propagation theory (impedance BC)
- Implicit coupling for better convergence

<u>What has been done so far in 3D-0D coupling:</u>

- Coupling for geometries with few outlets and iteratively
- No direct relationship between lumped parameters and anatomy of downstream bed

<u>What is proposed in this paper:</u>

- Direct relationship between lumped parameters and anatomy of downstream bed
- Many outlets

<u>Contribution of this paper:</u>

Main problems to realistic prediction of pressure in 3D:

1. Inadequate outflow BC
2. Rigid wall models

In this paper the wall deformability (problem 2) is **not** addressed. We focus on and address the (problem 1).

Point of interest: Fundamental method used for the coupling of 3D and 1D-0D models, also known as “coupled multidomain method”. Quite technical.