

Microvessel Chaste: A Library for Multi-Scale Agent-Based Simulation of Tissues with Microvessels

James A. Grogan^{1*}, Anthony J. Connor^{1, 2}, Philip K. Maini¹, Helen M. Byrne¹, Joe Pitt-Francis²

1 Wolfson Centre for Mathematical Biology, Mathematical Institute, University of Oxford, Oxford, OX2 6GG, UK.

2 Department of Computer Science, University of Oxford, Oxford, OX1 3QD, UK.

* grogan@maths.ox.ac.uk

Abstract

Microvessel Chaste is an open-source software library for multi-scale agent-based modelling of tissues with microvessels. Development has focused on applications in spatial modelling of vascular tumours and wound healing. Problems of interest in these areas involve modelling blood flow, temporally evolving vessel network geometries and topologies and vessel interactions with diffusible chemicals. This library integrates discrete representations of microvessels with already re-usable components for agent-based modelling in Chaste, such as discrete cells, meshes and ordinary and partial differential equation (ODE/PDE) solvers. The aims of the library are to facilitate i) rapid model composition from a range of interchangeable sub-models, ii) management of a large number of input parameters from various literature sources and iii) integration of modelling with experimental observations. These aims are pertinent in the area of discrete vascular tissue modelling, where model cross-comparison and experimental validation are still in early stages. This article includes simple example applications of the library, which can be run on a desktop computer. The source code is available to download under an open source Berkeley Software Distribution (BSD) licence at <https://chaste.cs.ox.ac.uk/trac/wiki/PaperTutorials/Microvessel>, together with details of a mailing list and links to documentation and tutorials.

Introduction

Cancer, Heart And Soft Tissue Environment (Chaste) is an open-source C++ library for problems in computational physiology and biology. Chaste has been widely used in cardiac electrophysiology [2] problems and in developing multi-scale agent based tissue models for developmental biology [3] and cancer [4] problems. Microvessel Chaste is an ‘add-on’ project for Chaste, with functionality for including discrete microvessels in agent-based tissue models.

There are many dedicated software frameworks for agent-based cell modelling, including Chaste, CompuCell3D [7], EPISIM [8] and PhysiCell [9], however to the authors’ knowledge, there is currently no similar framework for agent-based modelling of tissue with microvessels. Such computational models are widely used in studying vascular tumour and wound healing [6], skeletal muscle [?] and orthopaedic [JG add ref] problems. Multi-scale agent-based modelling of tissue with microvessels introduces several requirements in addition to those of cell modelling software. For example, i) line

or surface based representations of vessels are needed in place of point or centre-based representations of cells, ii) blood flow and chemical transport problems are solved in vessel networks with constantly evolving vessel geometry and connectivity and iii) new vessels may form and migrate based on mechanical and chemical cues.

While there are many notable bespoke computational models of tissue microvasculature, including Secomb *et al.* [11], Anderson and Chaplain [12], Friboes *et al.* [13], Shirinifard *et al.* [14] and Welter and Rieger [15], the resulting software does not meet all of the following desirable attributes, i) availability under a permissive open source license, ii) API documentation and user tutorials, iii) capability for on- and off-lattice modelling of vessels in arbitrary geometries in two and three dimensions and iv) use of object-oriented design. These attributes are the focus of Microvessel Chaste development, which uses object oriented design for *extensibility*, C++ for computational *efficiency*, and Boost Units [10] for compile-time dimensional analysis and improved *reliability*.

The mentioned attributes allow future utilization of the library in addressing two outstanding challenges in tissue microvasculature modelling. *First*, the importance of rapidly constructing and cross-comparing multi-scale agent-based models of tissue microvasculature is well recognized, as are the challenges in developing software for such an endeavour [19,20]. Due to a lack of open-source, documented software, it is currently necessary to re-implement each computational model before application, delaying comparison studies and reducing reproducibility. *Second*, there is now a wealth of high resolution three-dimensional experimental imaging data against which model predictions can be compared [21]. To fully exploit this data it is necessary that three-dimensional tissue regions of reasonable volume with realistic geometries can be simulated, as per Grogan *et al.* [22]. There are few approaches developed for this purpose in the literature. This functionality is available in the Microvessel Chaste library, including previously unpublished methods for three-dimensional (3D) off-lattice modelling of sprouting angiogenesis.

While the authors have previously developed and applied a range of multi-scale agent-based microvessel models in the areas of cancer [16,17,22] and angiogenesis [18], their incorporation in Microvessel Chaste is the first time such models have been made available open-source, with documentation and tutorials. Code design and implementation are discussed in the next section, followed by two sample applications. The sample applications are designed to be quickly run on a desktop PC, in practice more expensive simulations are usually performed. Examples can be run by downloading the project from <https://chaste.cs.ox.ac.uk/trac/wiki/PaperTutorials/Microvessel> and following the installation instructions.

Design and Implementation

This section briefly summarizes available algorithms by demonstrating how the library can be used to construct and solve a typical multi-scale agent-based microvessel problem. A dedicated article should be consulted for further details on algorithms related to core Chaste functionality, including discrete cell modelling [1]. The library can be used with Linux only, with virtual machines required for use on Microsoft Windows and Mac OS X. To install Microvessel Chaste it is necessary to build from source after downloading and setting up dependencies. This can take up to an hour the first time.

Algorithm Overview

The library is designed for composing multi-scale agent-based tissue problems with microvessels using on- and off-lattice representations of cells and vessels. While the library attempts to minimize the imposition of a definitive model structure on the user, it is helpful when introducing algorithms to consider a concrete use case.

Fig 1 shows how the library can be used to *compose* a problem of interest in vascular tumour modelling. For further details on models of this type the reader can refer to Owen *et al.* [6]. Here, an initial vessel network and cell population are constructed, transport PDEs for diffusible chemicals configured and rules for vessel growth or shrinkage due to blood flow defined, along with rules for vessel sprouting and endothelial tip cell migration in a stimulus field. The ability to compose a model from a collection of sub-models and sub-sub models is noted. There is a high degree of interaction between components. Once a domain, which is a geometrical feature in two-dimensions (2D) or 3D, is defined it can be used in the construction of vessel networks and cell populations through multiple space-filling or boolean operations, and in the generation of a computational grid (mesh) for use in the solution of partial differential equations (PDEs). Sub-models can be collected in hierarchical structures, for example a ‘Structural Adaptation Solver’ can manage a ‘Flow Solver’ and is itself managed by a ‘Microvessel Solver’. Alternatively, sub-models can be executed in isolation, for example to simply solve a PDE with cell location dependent sink terms.

Fig 2 shows how the library can be used to *solve* a problem of interest in vascular tumour modelling. Again, it is emphasised that the user need not follow the shown solution ordering, but can decide on ordering themselves by suitably over-riding ‘Solve()’ and ‘Increment()’ methods. The steps on the left-hand side of Fig 2 are already implemented as part of the agent-based cell modelling functionality in Chaste [1]. The Microvessel Chaste library interacts with the cell based solver as a plug-in (called a ‘SimulationModifier’ in Chaste), by modifying the contents of a cell population once per time step. In the example problem shown in Fig 2 vessels interact with (non-vessel) cells only via their shared influence on the solutions of chemical transport problems. Cell birth, death and cell-cycle progression can be affected by the PDE solution, which is sampled by each cell during the ‘CellDataUpdate’ step. More detailed interactions, such as cell-vessel spatial occlusion, or forming vessels from collections of discrete cells, are also possible.

Code Layout And Design

The components of the library are as follows:

- geometry – code for generating and describing 2D and 3D geometries using piece-wise linear complex (PLC) descriptions for direct use in Triangle [JG add ref] and Tetgen [JG add ref] meshing software,
- mesh – code for automated finite element meshing of 2D and 3D geometries and interpolation of vessel and cell locations onto meshes and regular grids,
- ode – ode models for cell-cycling in vascular tumour problems,
- pde – descriptions and solvers for steady state linear and non-linear PDEs with discrete sinks and sources for vessels and cells. Solvers use finite differences, finite element methods and Green’s function methods [11] based on Boost uBLAS and PETSc for vector and matrix operations.
- population – Code for describing, reading, writing and generating vessel networks,

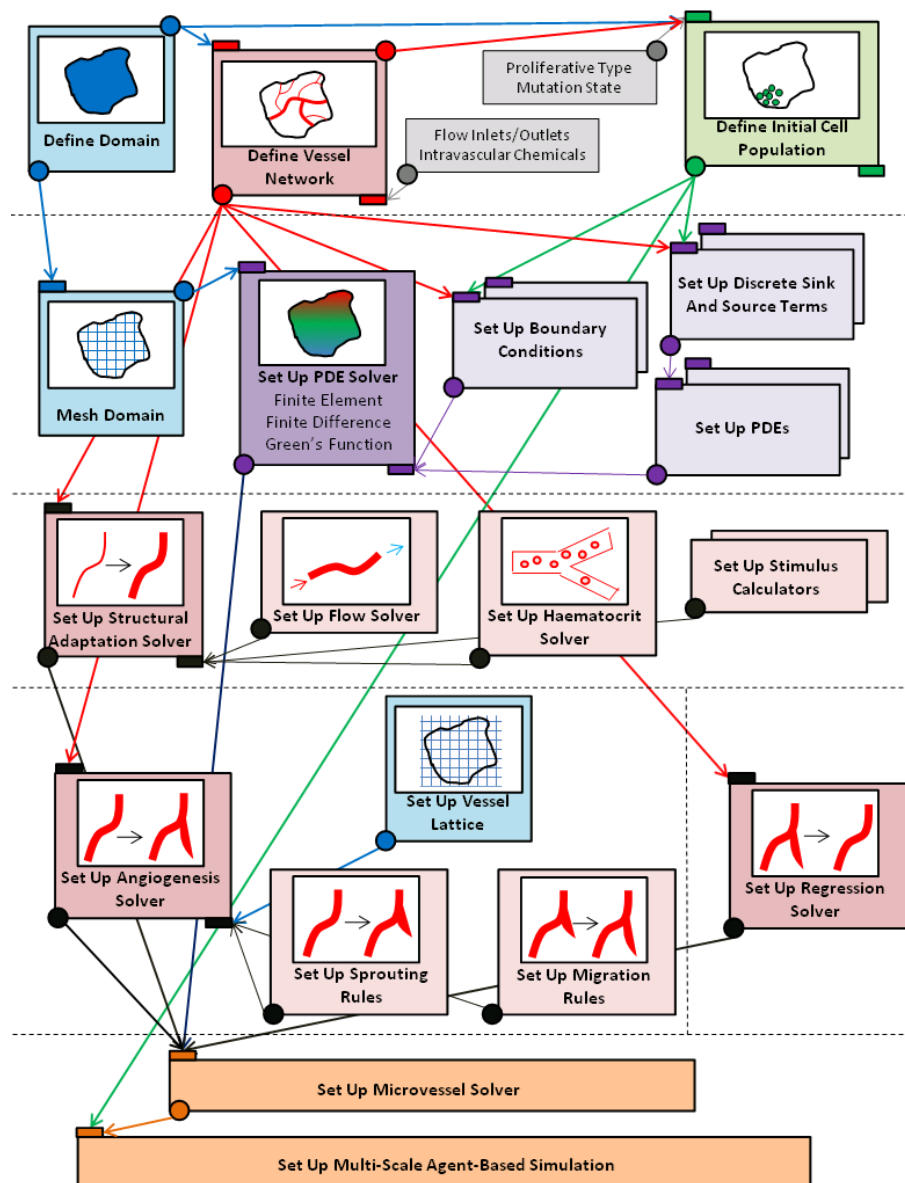


Fig 1. An example of how a microvessel model can be composed using Microvessel Chaste. A schematic showing the composition of a vascular tumour growth model using Microvessel Chaste. The ability to compose a model from a collection of sub-models and sub-sub-models is noted.

- simulation – flow, structural adaptation and angiogenesis solvers. Also code for managing integration of discrete vessel simulations with discrete cell populations from Chaste.
- utility – Dimensional analysis and collection of literature parameters of interest for tissue microvasculature simulations.

As per the remainder of Chaste, object oriented programming, including templating in C++ are heavily utilized. Input and output of vessel networks, grids and PDE results are in VTK (Paraview) format, which allows use of standard tools for

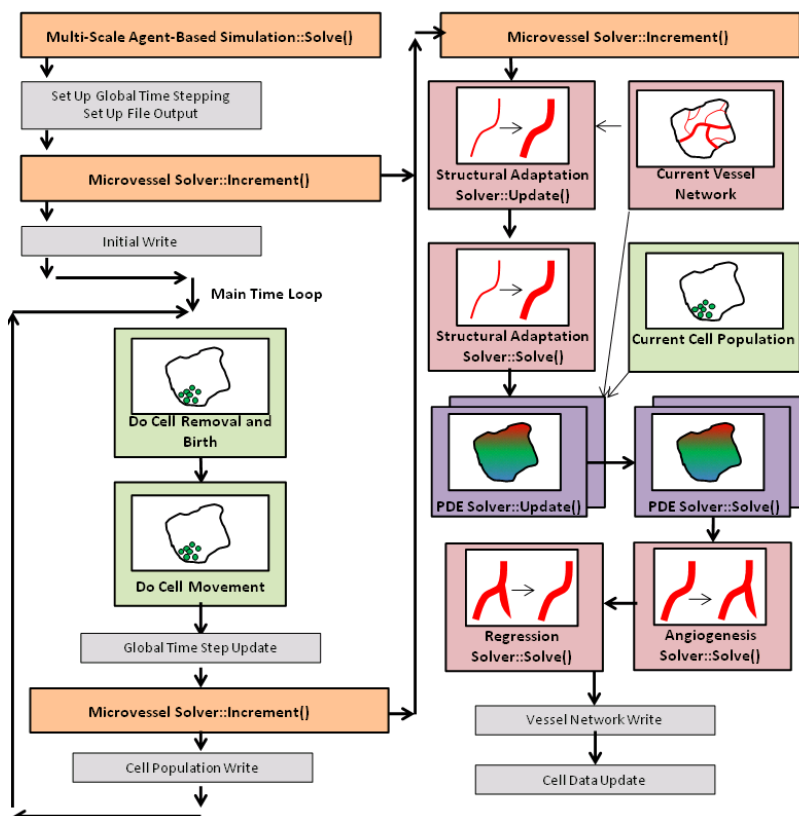


Fig 2. An example of how a microvessel model can be solved using Microvessel Chaste. A schematic showing the solution of a vascular tumour growth model using Microvessel Chaste. It is noted that solution ordering can be readily changed by the user.

visualization and post-processing. Python bindings are generated automatically using Py++ with a CASTXML back-end. Pre-compiled C++ classes can be overloaded in Python, without the need to re-compile the full framework. This allows for automated, dynamic model (or sub-model) generation, for example based on the contents of a mark-up language based input file. Given the variety of modelling paradigms and large number of input parameters used in problems of interest, there is much potential for miss-use of units. Microvessel Chaste uses low-cost compile-time unit checking to ensure dimensional consistency and automatic solver-specific non-dimensionalisation through the Boost Units framework. The latter is useful for minimizing floating pointer errors during the solution of PDEs and flow problems.

Results

In this section two sample multi-scale agent-based problems are demonstrated, and are available for reproduction following wiki-based tutorials at <https://chaste.cs.ox.ac.uk/trac/wiki/PaperTutorials/Microvessel>.

A 2D Lattice Based Vascular Tumour Simulation

The first example is a 2D lattice-based vascular tumour growth simulation following from Owen et al. [6], but with some simplifications to reduce computational expense.

This example demonstrates the feasibility of replicating a well known vascular tumour growth simulation, which typifies many others in the literature (JG: add some model refs). It also demonstrates how the library interfaces with the functionality of the Chaste discrete cell modelling software.

The problem is initialized with two large, parallel, counter-flowing vessels, positioned on a regular lattice. A cellular automaton based cell population is used to fill all lattice sites, with 'cancer' cell types assigned to a central circular region and 'normal' types to the remainder, as shown in Fig 3. Due to their distance from the large vessels, the tumour cells will become hypoxic and release growth factor (VEGF). This stimulates the growth of new vessels, which migrate preferentially towards the tumour due to growth factor gradients. As shown in Fig 3, the sprouts can merge if they meet. Vessel diameters can change over time due to flow induced stimuli, with low flow vessels eventually pruned. New vessels allow for increased oxygenation of the tissue and eventual tumour growth at the expense of immediately surrounding 'normal' cells.

There are many potential additions to models of this type which have been explored in the literature, including chemo-therapeutic and anti-angiogenic drugs[], radiotherapy[] and use of 3D domains[].

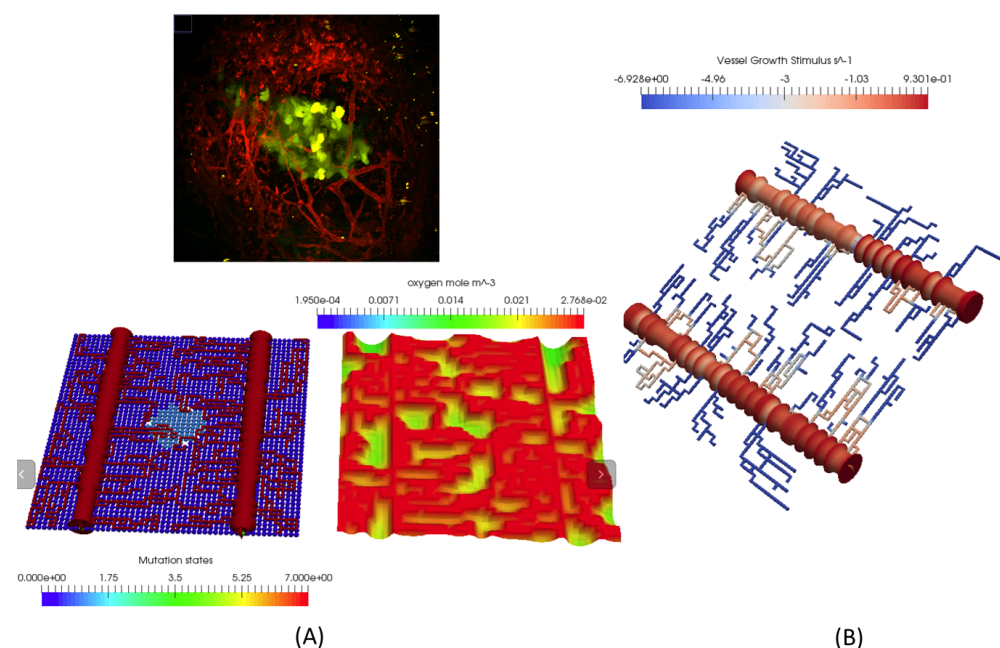


Fig 3. A 2D lattice based vascular tumour simulation performed using the Microvessel Chaste library. (A) Top is a sample in-vivo image of tumour cells (green) surrounded by tumour promoted microvasculature (red), obtained by multi-photon imaging. Bottom is a corresponding computational model of vascular tumour growth showing discrete vessels, cells labelled by mutation state and a corresponding oxygen map. (B) A snapshot of the predicted vessel growth stimulus field in response to blood flow. [JG: Scale bars, re-color bottom right to match experimental image. Maybe more specific that not actually modelling the experiment here.]

A 3D Off-Lattice Angiogenesis Simulation

The second example is a 3D off-lattice simulation of angiogenesis on a curved surface, shown in Fig 4. This example demonstrates more advanced features of the library in

terms of geometry manipulation, 3D off-lattice angiogenesis and the solution of PDEs on arbitrary 3D domains. The application is in modelling the widely used corneal micropocket assay in the study of angiogenesis [18]. In this assay a pellet containing a vessel growth stimulus (for example, VEGF) is implanted in the cornea. New vessels sprout from an existing limbal vessel at the base of the cornea and migrate toward the pellet along VEGF gradients. In the computational model discrete cells are excluded. This reduces computational expense for the purposes of generating a tutorial, and corresponds to a widely used modelling paradigm in which cells are treated as a continuum but vessels are modelled discretely [11]. Extensions to this simple model include addition of discrete cells, and multiple vessel growth factors, as per the 2D model in Connor *et al.* [18].

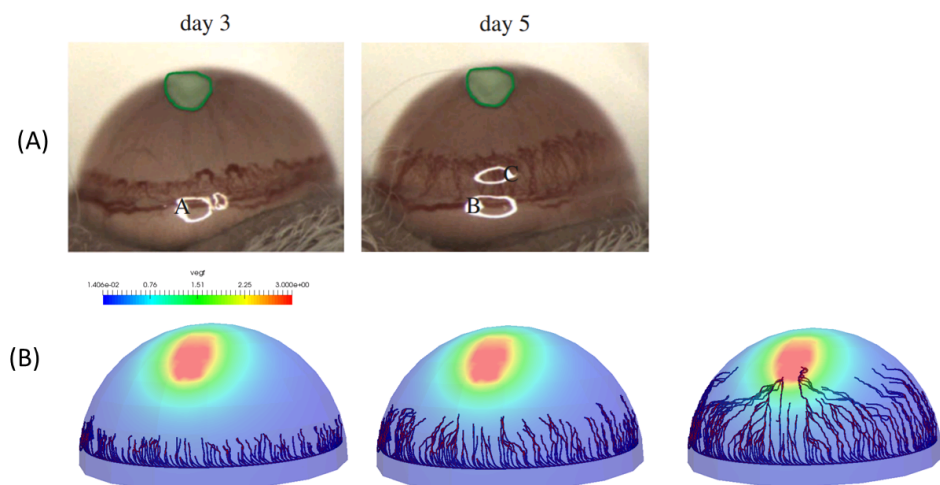


Fig 4. A 3D lattice based vascular tumour simulation performed using the Microvessel Chaste library. (A) An example of a corneal micropocket assay highlighting the pellet (green) and growing microvessels (dark red). (B) A corresponding computational simulation showing a predicted VEGF concentration field (nM) and growth of new vessels towards the pellet. [JG add scale bars, fill top right gap with another figure?]

Availability and Future Directions

Microvessel Chaste is available to download from <https://chaste.cs.ox.ac.uk/trac/wiki/PaperTutorials/Microvessel> under an open source Berkeley Software Distribution (BSD) licence. Additional functionality for semi-automated 2D and 3D image segmentation and meshing is under development, to aid integration with experimental studies. Porting to Windows and Mac OS X are of interest, with future availability of Python packages for each likely. At present, algorithms operate in serial only, however there is scope for distributed memory parallelisation for both C++ and Python interfaces. All PDE and flow solvers are based on PETSc [] structures and vessel network components may be communicated using existing serialization functionality in Chaste [?] or through VTK based serialization.

How to Become an Active Developer

As discussed in Mirams *et al.* [1], contributions are welcome via the main Chaste website, which includes a developer wiki, mailing list details and the ability to open and

comment on work tickets.

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Acknowledgments

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[JG Add acknowledgements and funding. Chaste team. Need to ask Bostjan for image permission, then acknowledge. Discuss image permissions with AJ.]

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