COMPUTATIONAL MECHANICS 2021
36th conference with international participation
Srní
November 8 - 10, 2021

Generation of artificial vascular trees – constrained constructive optimization approach

V. Lukeš

Faculty of Applied Sciences, University of West Bohemia, Univerzitní 8, 301 00 Plzeň, Czech Republic

Modelling of blood perfusion in an organ usually requires having a suitable geometrical model of the vascular system embedded in the organ. The vascular structures identified in CT or MR scans often suffer from incompleteness, unreliability and are only available up to a certain vessel size. Constrained constructive optimization (CCO) techniques are able to generate artificial vascular trees that mimic the real structures and preserve their main features.

The artificial vascular tree models are generated in such a way to minimize the total blood volume inside the tree structure and to fulfil the physiological boundary conditions and constraints regarding flows and input/output pressures. The radii of branching vessels can not be arbitrary, to conserve flow through the tree, the branching law for vessel radii must be satisfied. The branching law contains the so-called flow exponent, by the choice of which we can achieve uniform shear stress on the vessel walls or minimize wave reflection of the pulse waves.

The algorithm published in [1] starts generating a tree with one root node and many leaves (terminal nodes), which are connected directly to the root at the beginning of the tree generation process. The leaf positions are placed randomly with the uniform distribution in a given volume, while the root position is usually defined as an input parameter to the algorithm. The generation process consists of relaxing, merging, and splitting steps which are repeated until a local optimization criterion is met. The above steps are done iteratively many times on each tree node to get the optimal branching (bifurcation, trifurcation, . . .) at the nodes and to adjust the node positions. In order to get the optimum at the global level, the hierarchical iterations involving pruning and reconnecting steps, which lead to topological changes of the tree, are applied. See [1] for details.

Another CCO algorithm, published in [2, 5], starts with a root segment, representing the entry vessel to an organ, and repeatedly connects randomly placed terminal nodes to the existing tree structure. When a new leaf is created, the algorithm finds the appropriate existing vessel segment, minimizing a cost function, and connects the new leaf to that segment. The optimal position of the newly created bifurcation must be calculated to ensure given bifurcation rules and to minimize total intravascular volume. This "growing" approach produces binary vascular tree models while the algorithm [1] allows for multifurcations in the tree.

Artificial vascular trees are crucial for hierarchical modelling of tissue perfusion as discussed in [4]. The upper hierarchy of a generated tree, representing larger vessels in an organ, can be used for 1D computation of blood flow through the perfusion tree. The lower hierarchies, i.e. a wide range of small vessels, can be employed in calculations of tissue permeabilities which are involved in the complex multi-compartment models, see e.g. [3].

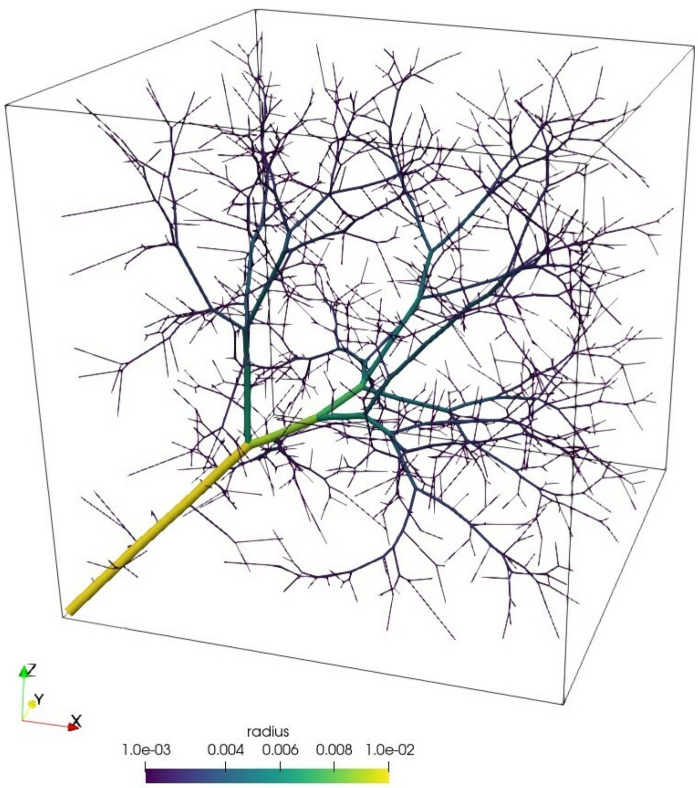

Fig. 1. Example of a generated vascular tree, 16×10^3 terminal segments (leaves)

Acknowledgement

The work was supported from European Regional Development Fund-Project "Application of Modern Technologies in Medicine and Industry" (No. CZ.02.1.01/0.0/0.0/17_048/0007280).

References

[1] Georg, M., Preusser, T., Hahn, H. K., Global constructive optimization of vascular systems, Technical Report: WUCSE-2010-11, Washington University in St. Louis, 2010.

[2] Karch, R., Neumann, F., Neumann, M., Schreiner, W., A three-dimensional model for arterial tree representation, generated by constrained constructive optimization, Computers in Biology and Medicine 29 (1) (1999) 19-38.

[3] Michler, C., Cookson, A. N., Chabiniok, R., Hyde, E., Lee, J., Sinclair, M., Sochi, T., Goyal, A., Vigueras, G., Nordsletten, D. A., Smith, N. P., A computationally efficient framework for the simulation of cardiac perfusion using a multi-compartment Darcy porous-media flow model, International Journal for Numerical Methods in Biomedical Engineering 29 (2) (2012) 217-232.

[4] Rohan, E., Lukeš, V., Jonášová, A., Modeling of the contrast-enhanced perfusion test in liver based on the multi-compartment flow in porous media, Journal of Mathematical Biology 77 (2) (2018) 421-454.

[5] Schwen, L. O., Preusser, T., Analysis and algorithmic generation of hepatic vascular systems, International Journal of Hepatology 2012 (2012) No. 357687.