Coupled heterogeneous models accounting for arterial-venous circulation: monolithic and iterative approaches

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The cardiovascular system (CVS) can be regarded as the integration of different physiological mechanisms rendering a rather complex structural and functional behavior. One of the most clear examples of this is the arterial-venous closed loop circulation system. These different components operate in an integrated manner, and although some studies can be conducted by considering the constituent systems operating independently, there are many situations in which it is not possible to segregate the different systemic phenomena. In the present work we account for the coupled arterial-venous blood circulation by means of heterogeneous models, namely, one-dimensional models for the systemic arteries and zero-dimensional models for the venous counterpart. These two systems are coupled through specific models for the peripheral microvascular circulation at the distal location and by virtue of lumped models for the cardiac and pulmonar circulation at the proximal location. Eventually, three-dimensional models of any part of the CVS can be incorporated in the formulation, from which the system would turn out to be a coupled 3D-1D-0D mathematical representation. In this manner, it is possible to address several aspects of blood flow arising when physiological and/or pathophysiological conditions are established for the arterial and venous systems, as well as for the coupling models in between them (microvascular and cardiac-pulmonar circulation). Furthermore, such closed loop models provide the most complete picture that allows for a better understanding of the behavior of the CVS.

In addition, and due to the distinctive characteristics of those heterogeneous models (0D, 1D and ultimatelly 3D), it is desirable to have at hand proper black box solvers that are responsible for the independent solution processes, and which are tuned according to the physical conditions observed in each case. Therefore, in the present work we also explore some iterative procedures to decouple these two systems, resulting in standalone, but strongly coupled, homogeneous sub-problems. Such iterative strategies are based on the description of the whole coupled problem in terms of coupling variables, being those the flow rate and the pressure. According to the arterial-venous segregation the CVS is split into two parts: at the microvascular level and at the level of the cardiac circulation. Hence, the coupling variables are defined at those corresponding levels, that is flow rate and pressure at the points which perform the junction between the arterial and venous systems. Several decomposition strategies are compared and some guidelines are given concerning the choice of the best iterative solver.