Computational Modeling Of Lymph Node Flow, Cell Transport, And Tissue Mechanics

R. Kandhai[1], J. Bridge[1]

[1]The University of the West Indies, St Augustine Campus, Trinidad and Tobago

Abstract

The lymphatic system plays a crucial role in immune surveillance, fluid balance, and the transport of immune cells. Lymph nodes, acting as filtration and immune activation hubs, are essential in detecting and responding to pathogens. Computational modeling of lymph node function offers valuable insights into lymphatic flow, immune cell migration, and mechanical interactions within the node, enhancing our understanding of immune responses and lymphatic disorders.

This study presents a computational model of lymph node dynamics developed using COMSOL Multiphysics. The model integrates fluid mechanics, species transport, and fluid-structure interactions to simulate key physiological processes. Specifically, the CFD Module analyzes lymphatic fluid flow in free domains, while Darcy's Law models flow through porous zones. The Transport of Diluted Species interface simulates the movement of lymph, T-cells, and B-cells across both free and porous regions. The Solid Mechanics Module is coupled via the Poroelasticity interface to assess mechanical stresses exerted by fluid flow on lymphatic tissue. These modules are linked through the Free and Porous Media Flow, Reacting Flow, Diluted Species, and Poroelasticity multiphysics couplings.

The model is constructed in 2D, based on a cross-sectional representation of a lymph node. The geometry was created manually within COMSOL Multiphysics. The lymphatic fluid is modeled as an incompressible, Newtonian fluid governed by the Navier-Stokes equations. Solute transport within the lymphatic fluid is described by the convection-diffusion equation. The Transport of Diluted Species interface simulates immune cell migration under the influence of fluid flow and diffusion forces, with sensitivity analyses exploring the effects of flow rate, diffusion coefficients, and tissue permeability. Boundary conditions include a constant velocity inlet at the afferent lymphatic vessel and a zero-pressure outlet at the efferent vessel, with no-slip conditions applied along interior surfaces to ensure physiological accuracy.

Model validation against experimental and literature data shows strong agreement in predicted versus observed velocity distributions, pressure gradients, and immune cell trajectories. Key findings include highest lymph flow velocities near the afferent vessel inlet, with a gradual decline through the porous node regions. Larger immune cells, due to increased drag forces, exhibit longer retention times. Furthermore, regions of high shear stress correspond to areas where immune cells aggregate, influencing antigen presentation and immune response activation.

By combining fluid mechanics, cellular transport, and mechanical interactions into a single framework, this study addresses limitations in existing lymph node models. The results have clinical relevance for conditions such as lymphedema and metastatic cancer, and inform strategies for improved drug delivery and immunotherapy. Future model developments will incorporate transient flow conditions, biochemical signaling pathways, and tissue heterogeneity to enhance physiological accuracy. The addition of chemokine gradients and receptor-ligand interactions will further improve the model's predictive power, offering deeper insights into immune cell activation and pathogen clearance.

This research highlights the potential of COMSOL Multiphysics for biomedical applications, demonstrating its effectiveness in capturing complex multiphysics interactions within the lymphatic system. Through computational modeling, the study establishes a platform for exploring lymph node function in both health and disease, with significant implications for clinical research and therapeutic development.

Figures used in the abstract

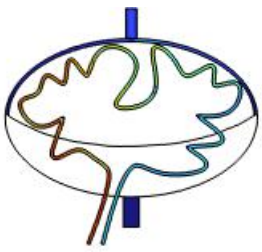

Figure 1 : Velocity magnitude distribution in the lymph node model showing lymph flow patterns through free and porous regions.