Modeling the effects of elastic compression on fluid dynamics in lower limb lymphedema

Maha Reda*[1] and Stéphane Avril[1]

[1]Centre Ingénierie Santé, Saint-Étienne – Ecole Nationale Supérieure des Mines de St Etienne – France

Abstract

Introduction

Under normal conditions, interstitial fluid (IF) pressure in the lower leg is maintained at or slightly below atmospheric levels, thanks to a delicate balance between fluid filtration from blood capillaries and reabsorption by the lymphatic vessels. However, factors such as increased capillary pressure or venous insufficiency can lead to lymphedema, a condition characterized by IF accumulation in the tissue space (1,2). In the early stages of lymphedema, fluid accumulates primarily within the subcutaneous space. This accumulation inhibits the natural pumping mechanisms present in healthy lymphatic vessels, resulting in inefficient fluid drainage. To this end, compression therapy stands as one of the primary treatments for early stages lymphedema. To better understand fluid dynamics in lymphedematous tissues and under therapeutic compression, computational modeling has been widely used (3,4). However, due to the complexity of the lymphatic system and the multifactorial nature of the disease, modeling the whole network of lymphatic vessels remains challenging.

Methods

In this study, we developed a patient-specific three-dimensional finite element model of the lower limb. We adopted a continuum approach based on poroelasticity where the subcutaneous tissue of the lower limb was modeled as a biphasic medium comprising a solid matrix and a fluid phase representing, respectively, the tissue components and the interstitial fluid. The model was reconstructed after the segmentation of three-dimensional magnetic resonance imaging (MRI) data of the lower limb. The fluid phase in the subcutaneous tissue was based on Darcy's law and the solid matrix was modeled as linear elastic. Capillary and lymphatic vessels were incorporated as distributed sources and sinks within the domain, in accordance with Starling's principle. All other soft tissues were represented as linear elastic. Bones were treated as rigid structures, and their inner part was neglected. Boundary conditions were applied such that the surfaces of the bones were clamped, while the longitudinal displacement of the bottom surface was constrained by symmetry conditions, leaving the top surface free. Gravitational forces were included to account for their impact on both solid and fluid components. Simulations were conducted using COMSOL® 6.0, using porous media and structural mechanics modules. This implementation enabled the analysis of fluid flow, interstitial fluid pressure (IFP), and tissue deformation under varying lymphedematous conditions.

Results and discussion

---

*Speaker

The model demonstrated its ability to replicate key pathological phenomena associated with lymphedema. For instance, increasing capillary pressure led to a significant rise in IFP and tissue volume, consistent with clinical observations. Furthermore, the model allowed the study of the effects of compression therapy. External compression was simulated by applying pressure on the skin, calculated using the Laplace law to account for the curvature of the limb. Under compression, the model successfully predicted a reduction in limb volume and a decrease in IFP, with the magnitude of these effects varying with the level of applied pressure. To extend the analysis, muscle activity was incorporated to simulate the effects of the calf muscle pump on fluid drainage during gait. This was achieved by applying a periodic internal pressure on the fascia to mimic muscle contraction and relaxation cycles. The results showed the role of muscle activity in restoring equilibrium to IFP, particularly in the presence of external compression. The model however presents several limitations. For instance, blood and lymphatic vessels were not explicitly represented, which limits the model's ability to provide detailed insights into fluid transport within these vessels. Additionally, the uniform distribution of sources and sinks in the tissue does not fully capture the heterogeneity of the vascular network. Addressing these limitations in future iterations could further enhance the model's accuracy and predictive power.

Conclusion

In conclusion, this patient-specific finite element model provides a robust framework for studying fluid dynamics and tissue mechanics in lymphedema. By simulating both pathological conditions and therapeutic interventions, the model offers valuable insights into the management of lymphedema, particularly the efficacy of compression therapy.

1. Oliver et al, Genes & Development, 16(7):773-83, 2002.

2. Moore et al, Annual Review of Fluid Mechanics, 50(1):459–482, 2018.

3. Heppell C et al, Bull Math Biol 75, 49–81 (2013).
4. Baish JW et al, Sci Rep 12, 4890 (2022).