3D MODELLING AND STRUCTURAL SIMULATION OF SCAFFOLDS FOR CARDIOVASCULAR IMPLANTS

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ABSTRACT
Cardiovascular disease remains as one of the main problems in contemporary health care worldwide. Several studies of the cardiac prostheses have been held since 60s with the advent of cardiopulmonary bypass. The mechanical properties of blood vessels, arteries and valves depend on collagen and elastic fibers, as well as on smooth muscle cells and ground substances. Many works about three-dimensional finite element model of the arterial wall segment and the heart valves assume the biological material to be homogeneous and isotropic. This configuration is a simplified way to reduce the complexity of biological structures. The primary purpose of this study was to assess the effects of fiber design and orientation on the stress distribution in a 3D model for cardiovascular implants and predict the elastic modulus of scaffolds designed.

KEY WORDS
3-Dimensional Modelling, Medicine, Cardiovascular Implants, Structural Simulation

1. Introduction
Cardiac tissue engineering is a new and exciting field with many obstacles to be surmounted before start of clinical trials. Cardiovascular disease remains as one of the main problems in contemporary health care worldwide. Several studies of the cardiac prostheses have been held since 60s with the advent of cardiopulmonary bypass. The mechanical properties of blood vessels, arteries and valves depend on collagen and elastic fibers, as well as on smooth muscle cells and other substances.

The cardiovascular system has a very complex structure typically characterized by multiple physical scales both in space and in time. Extensive biomechanical studies of native and enzymatically dissociated (by selective enzymatic treatment with collagenase or elastase) porcine and human cardiovascular tissue (coronary arteries, aortic heart valve leaflets and ventricular myocardial tissue) performed by Mironov and Kasyanov in 2009 [1], demonstrated that cardiovascular soft tissues have non-linear anisotropic material properties. The physical non-linearity of arterial material is characterized by an increasing stiffness as strain increases. This characteristic is determined by composite structure that includes a complex geometrical organization of two main load-bearing structural components of extracellular matrix such as rigid but wavy collagen and pre-stretched elastic elastin [2]. The origin of this behavior is found to be in the mechanical properties of the basic structural components of arteries, as well as in the architecture of the cardiovascular tissue.

This architecture is composed of a specialized set of cells, namely endothelial cells (VECs) and interstitial cells (ICs) and an extracellular matrix that includes collagen, elastin and glycosaminoglycans (GAGs) (Figure 1) [3, 4].

Figure 1. The cellular architecture of a normal aortic valve. Adapted from [3].

Some works about three-dimensional finite element model of the arterial wall segment and the heart valves assume the biological material to be homogeneous and isotropic. They studied different vascular tissues and reported data on mechanical properties of the tissues collected [5, 6, 7]. Furthermore, others studies using biomaterial were realized to produce viable prostheses [8, 9]. However, only a few studies report about modeling the mechanics of tissue-engineered constructs or scaffolds made of biomaterials and the mathematical models can provide valuable information to assess and evaluate the...
mechanical behavior of tissue-engineered constructs and scaffolds for cardiac implants.

The primary purpose of this study was to assess the effects of fiber design and orientation on the stress distribution in a 3D model for cardiovascular implants and predict the elastic modulus of scaffolds designed.

For tissue engineering applications, it is essential that the mechanical properties of the artificial scaffold mimic those of the native extracellular matrix. The parameters found for the mechanical properties of an artery wall can be used only for an approximate evaluation of the corresponding parameters.

The use of the Finite Element Methods (FEM) in the studies concerning mechanical properties of the scaffolds, along with materials science, will be a key feature in helping to bring the potential of tissue engineering into a clinical reality.

2. Materials and methods

2.1 Modelling conditions and material parameters

Three-dimensional models of the artery wall and heart valve were modeled in the Rhinoceros® 5.0 (McNeel North America, Seattle, WA, USA) software, and the ‘.stp’ ISO Standard file format were imported into Ansys 16.2 (ANSYS Inc, Houston, TX, USA) for the finite element analysis (FEA).

The properties of the artery wall, heart valve and biomaterials (polyurethane - PU and polycaprolactone – PCL) were considered isotropic, linear, and homogeneous. The correspondent values of density, viscosity, Young's Modulus and Poisson's ratio are presented in the Table 1.

Table 1
Summary of material properties used on simulations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus (artery wall)</td>
<td>100</td>
<td>KPa</td>
<td>[10]</td>
</tr>
<tr>
<td>Poisson's ratio (artery wall)</td>
<td>0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young's modulus (PU)</td>
<td>51</td>
<td>MPa</td>
<td>[12]</td>
</tr>
<tr>
<td>Poisson's ratio (PU)</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young's modulus (PCL)</td>
<td>0.4</td>
<td>GPa</td>
<td>[13]</td>
</tr>
<tr>
<td>Poisson's ratio (PCL)</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Boundary conditions of the artery wall and 3D models

The fiber diameter of the 3D models analyzed was fixed at 400µm. The fiber spacing (200, 400 and 600µm) and fiber orientation (angles - 20°, 45°, 60° and 90°) were varied as described in the figure 2. By changing these parameters, it was possible to change the porosity and the architecture of the scaffold. The porosity of 3D models was calculated as

\[ P = 1 - \frac{V_{scaffold}}{V_{cube}} \]

where \( P \) is the scaffold porosity, \( V_{scaffold} \) is the volume of the scaffold and \( V_{cube} \) is the volume of the cube.

The layer thickness of each structure is equals to 1.12 mm.

Figure 2. Configurations of the 3D models used in the finite elements analysis (FEM).

After designing the models, we imported into the ANSYS 16.2 software for the stress analysis of all different porosity ranges. The displacement of 100µm was imposed to every model in the direction of X-axis and the direction of Y-axis (figure 3).

Structural analysis of bodies composed of materials with complex micro-structural behavior can become an overwhelming computational task. By using "averaging" methods such as homogenization to determine macroscopic material behavior, complexity of analysis can be reduced dramatically. The basic idea of homogenization (or averaging) is to "smear out" complicated micro-structural behavior of periodic materials, such that the material behavior can be described by the (macroscopic) homogenized constitutive matrix \([E^H]\) [14].

Homogenization theory is a powerful method for modelling the complex microstructure of materials, including scaffolds composed of fibers. In this study, elastic moduli of elastic material were calculated using homogenization process, where the material can be idealized as being effectively homogenous in a representative volume element (RVE) [16].
In our case the Y direction coincide with circumferential stress of the arterial wall, as you can see in the figure 4.

Due to its direct relationship with the intravascular pressure, circumferential stress has always received a lot of attention, while axial and radial stresses were practically ignored. Since a few years, however, biological processes induced in arterial walls by axial stress changes are increasingly studied. For these reasons, in our studies, we will focus only on analyzes involving the circumferential and axial stress of the arterial wall.

3. Results and Discussion

In this study, a computational approach is presented to study and evaluate the mechanical behavior of 3D models with different properties. When the researchers use computational simulations to predict and understand a biological behavior, are achieved several insights.

For tissue engineering applications, it is essential that the mechanical properties of the artificial scaffold mimic those of the native extracellular matrix [17]. The parameters found for the mechanical properties of an artery wall (table 2) can be used only for an approximate evaluation of the corresponding parameters.

Our results indicated that applying a displacement in the direction of X-axis (axial stress), the Young's modulus of 3D models decrease drastically with increasing porosity (figure 5) for both materials (PU and PCL).

Figure 3. Discretized displacement and symmetry axis of the Finite Element Methods (FEM).

Figure 4. Definition of circumferential (Y-axis) and axial (X-axis) wall stress.

Figure 5. Comparison of Young's modulus vs. fiber orientation (angles - 20°, 45°, 60° and 90°) of the several models analyzed with displacement in the direction of the X-axis (axial stress). a) Predicted Elastic Modulus of polyurethane (PU) scaffolds and b) predicted Elastic Modulus of Polycaprolactone (PCL) scaffolds.
Considering the displacement in the direction of the Y-axis (circumferential stress), our results showed that the Young’s modulus ranges mainly due to porosity and the fiber orientation (Figure 6). Moreover, the results of the PU models presented lower values than PCL models. This analysis was used to evaluate circumferential stress between effective Elastic modulus in the Y-axis of the many models with different structures and two biomaterials. The values of elastic modulus are compared with artery wall value of Elastic modulus and we observed that all PU models with fiber orientation of 20º presented similar values to the artery wall.

Figure 6. Comparison of Young’s modulus vs. fiber orientation (angles - 20º, 45º, 60º and 90º) of the several models analyzed with displacement in the direction of the Y-axis (circumferential stress). a) Predicted Elastic Modulus of polyurethane (PU) scaffolds and b) predicted Elastic Modulus of Polycaprolactone (PCL) scaffolds.

As expected, increasing the amount of material increases elastic properties for a particular scaffold design. However, for a given porosity, different scaffold microstructures will lead to different effective stiffness. This analysis further demonstrates that material arrangement (different angles - 20º, 45º, 60º and 90º) determines what mechanical properties may be achieved within the bound set by material chemistry.

4. Conclusion and Future Work

There are many steps to finalize this major work, mainly the validation using 3D scaffolds printed, but this first phase has a computational character. The computer simulations allows a prediction and a best choice of scaffold or prosthesis as geometry, diameter, angle and properties for clinic use. The design of controlled porous matrices is an important requirement for efficient tissue engineering process, especially when it is intended for cardiovascular substitutes. Hence, the use of the Finite Element Methods (FEM) in the studies concerning mechanical properties of the scaffolds, along with materials science, will be a key feature in helping to bring the potential of tissue engineering into a clinical reality.

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References


