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СКІНЧЕННО-ЕЛЕМЕНТНЕ МОДЕЛЮВАННЯ СТАТИЧНОГО ДЕФОРМОВАНОГО СТАНУ АТЕРОСКЛЕРОТИЧНИХ СУДИН НА ОСНОВІ ДАНИХ ОСТ ЗОБРАЖЕНЬ

У роботі представлено методику оцінки напружено-деформованого стану атеросклеротичних судин на основі клінічних даних оптичної когерентної томографії (ОКТ). Розроблено алгоритм автоматизованої побудови параметричної геометрії судини. За допомогою методу скінченних елементів проаналізовано три типи бляшок: некальциновану, кальциновану та низької щільності. Встановлено зони концентрації напружень у «плечах» бляшки, що дозволяє прогнозувати ризик її розриву.

Ключові слова: *атеросклеротичні судини, МСЕ, бляшка, напружено-деформований стан*

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FE SIMULATIONS OF THE STATIC DEFORMED STATE OF ATHEROSCLEROTIC VESSELS BASED ON OCT IMAGE DATA

This study focuses on the biomechanical modeling of atherosclerotic vessels to predict the risk of plaque rupture, a primary cause of acute cardiovascular events. A methodology integrating clinical Optical Coherence Tomography (OCT) imaging with Finite Element Analysis (FEA) is proposed. An automated Python-based algorithm was developed to reconstruct patient-specific geometries of vessel layers (intima, media, adventitia) and plaque components directly from OCT images.

Numerical simulations were conducted for three different plaques cases under physiological pressure. The results revealed that maximum stresses are consistently localized at the plaque shoulders. The proposed approach provides a quantitative tool for assessing plaque vulnerability beyond geometric analysis.

Key words: *atherosclerotic vessels, FE, Plaque, stress strain state.*

Introduction. Atherosclerotic plaque is a common condition where the walls of blood vessels become thick and stiff, leading to an increased risk of cardiovascular diseases such as heart attack and stroke. Despite significant advances in the bio-medical understanding of the disease, its complex nature has some randomness, and early diagnosis and treatment are crucial for preventing the spread of atherosclerosis and its life-threatening complications. Mathematical and computer modeling can provide valuable insights into the complex processes of blood vessels' mechanical response considering inside plaque formation and growth. The main challenge of computational modeling here is the accurate reconstruction of patient-specific vessel geometry from diagnostic images, such as Optical Coherence Tomography (OCT), and its conversion into a parametric finite element model. This requires precise differentiation of vessel layers and plaque components to ensure the reliability of stress-strain analysis and the subsequent prediction of plaque vulnerability.

Furthermore, the widespread clinical application of such biomechanical analysis is currently limited by the complexity of model generation. Converting raw OCT images into finite element models typically involves tedious manual segmentation, which is time-consuming and subject to operator variability. Therefore, a pressing scientific and practical task is to automate this workflow. Developing a robust algorithm that can instantly translate diagnostic data into a parametric geometric model—preserving the anatomical features of layers and plaque components—is a key step toward making patient-specific rupture risk prediction a viable tool for real-time decision-making.

Analysis of the latest research and publications. There are numerous researchers considering the predictive modelling of the mechanics of human atherosclerotic blood vessels. Part of that involves investigating the process solely through the mathematical formulation of the problem, based on approaches to assessing the strength of a vessel with plaque. [2,3] The other investigations employ numerical methods to predict probable critical situations. [1,4,5-9].

One approach to assessing blood vessel strength is modelling residual stresses in arterial walls by simulating a radial cut through an unloaded artery. This simulation helps determine the strain gradient associated with residual stresses, which is then applied in subsequent simulations. Age-related changes, such as the widening of the thoracic aorta, affect vessel size and strength, with differences noted between sexes based on body size. [9].

Research shows that age-related changes also affect the size and strength of blood vessels. For example, the thoracic aorta typically widens with age and was larger in people with larger frames. Differences in aortic diameter between sexes are associated with differences in body size. In individuals without significant aortic disease, aortic growth was faster in younger individuals with a smaller indexed diameter [3].

To assess plaque vulnerability, three-dimensional finite element models are used that take into account biomechanical factors such as capsule thickness, lipid core stiffness, remodeling index, blood pressure, and the presence of microcalcifications in the capsule tissue. Within the framework of this technique, a vulnerability index was determined based on the ratio of maximum stresses to the tensile strength of the capsule tissue. The most significant factors were capsule thickness and lipid core rigidity. This technique was able to predict the risk of human atheroma rupture under different conditions [4].

Beyond the plaque itself, the microenvironment—specifically neovascularization—reshapes local lipid and inflammatory profiles. Simultaneously, physical forces such as pulsatile hemodynamics and arterial wall stiffness contribute to intimal hypoxia. These mechanical factors ultimately determine the distribution of Wall Shear Stress (WSS), thereby regulating the pathological entry of monocytes and plasma LDL into the lesion [5].

Simulation studies show that reducing slice thickness in MRI studies does not always lead to improved measurements of the lumen, vessel wall, or necrotic lipid core size. In some cases, a more important factor is to obtain anisotropic voxels to improve measurement accuracy and estimate stresses in the plaque capsule. Such studies are needed to quantify the benefits of different MRI techniques [6].

Mathematical modeling of the process of formation of atherosclerotic plaques makes it possible to simulate various dynamic behaviors in various clinical cases. The model system can determine the critical conditions separating stable and unstable plaques. The most important parameter for maintaining system stability is the rate of proliferation of smooth muscle cells. If the proliferation rate exceeds a certain threshold, the system can become unstable, increasing the risk of cardiovascular disease. [7].

Modeling of atherosclerotic plaque growth, including both macroscopic and molecular and cellular processes, allows the interaction between the blood flow and the arterial wall to be taken into account. The model uses the TAWSS dependence of endothelial permeability to describe the entry of substances from the bloodstream and subsequent accumulation of elements such as LDL, macrophages and foam cells. The influence of initial geometry and various model parameters on plaque growth highlights the importance of a multi-level approach to solving the problem [2].

Finally, modeling of hemodynamics and mechanical properties of arterial walls with different types of plaques shows that WSS around calcified plaques (low stenosis) is lower than around lipid plaques (high stenosis). This can lead to further accumulation of new plaques around the calcified areas. Lipid plaques, on the other hand, cause WSS fluctuations in healthy areas behind them, which can initiate the formation of new plaques in these areas. The maximum stress is usually located at the shoulder of the plaque, which is considered to be the site of plaque rupture [1, 8].

To summarize all of the above the purpose of the work is: to create the methodology of prediction rupture of human blood atherosclerotic vessels with plaque based on diagnostic of real patients using numerical methods.

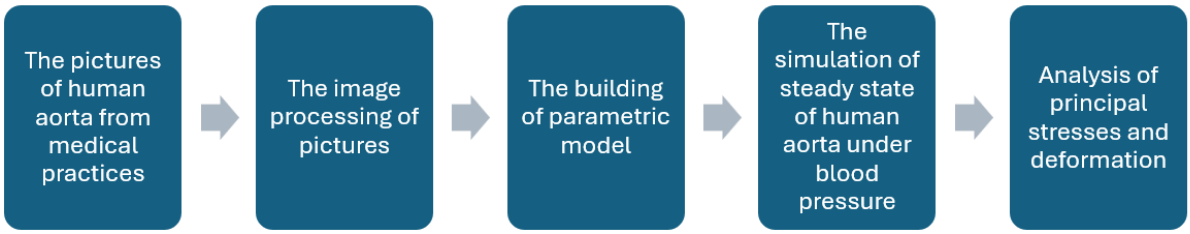


Fig.1. **The general scheme of research**

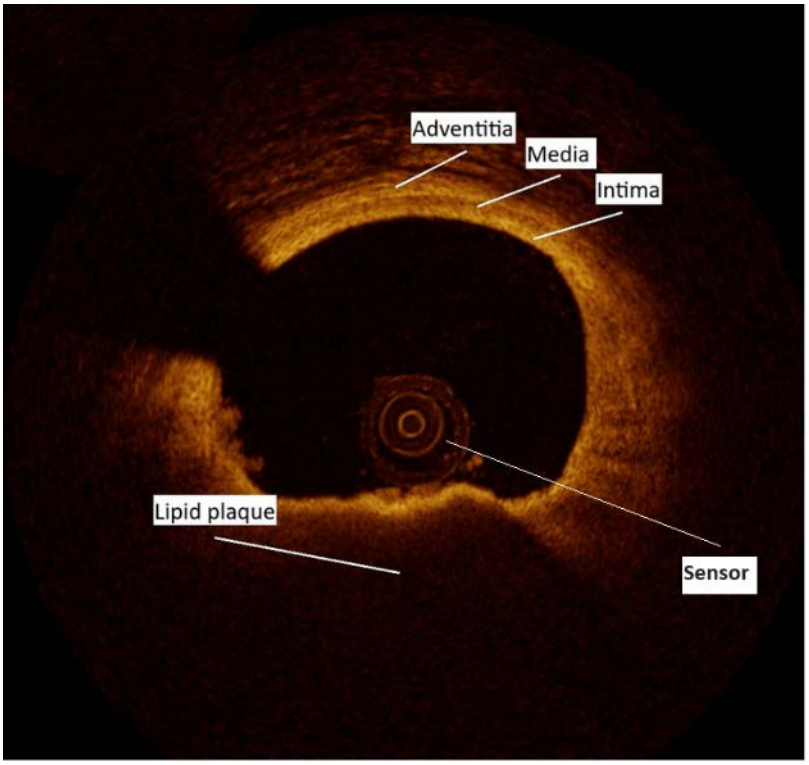
OCT Image Processing and Model Reconstruction.

As initial data for the paper, the results of patient vessel observation were provided by Optical Coherence Tomography (OCT) in the form of pictures of the vessel cross-section. Coronary plaques are classified into three different categories: calcified, non-calcified, and low-density non-calcified plaques. Idealized plane models of longitudinal atherosclerotic arteries are used to investigate the impact of stenotic severity on the circumferential stress exerted on plaque.

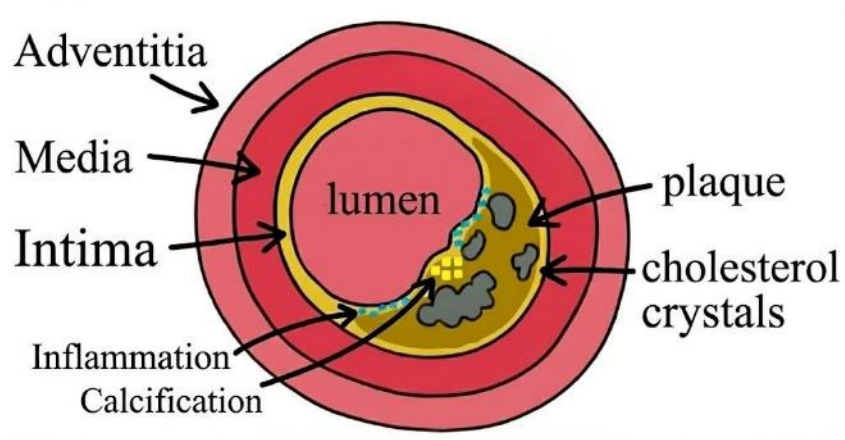
The vessel model with plaque consists of three layers (Intima, Media, and Adventitia layers) and the plaque itself (Fig. 2).

Description of algorithm for building the parametric model of vessel. To analyze the structure of the vessel with plaque components, numerical simulation is applied to illustrate the variation in mechanical properties due to the lipid core. An algorithm is proposed for building the geometrical model of a vessel

with plaque based on OCT results.



a)



b)

Fig. 2. **Schematic definition layers and plaque of vessel a) OCT results, b) schematic view**

The dimensions and coordinates of all vessel layers and plaques are determined based on OCT images using a Python script for image processing.

The Media and Adventitia layers are represented as a ring, corresponding to OCT pictures. The Intima layer and Plaque are represented as spline parameters, which are defined according to the proposed algorithm, as shown in fig.2. The Intima layer consists of an arc and a spline. The ends of the arc are connected by a spline, which can take various shapes, simulating different forms and thicknesses of the plaque cap. The plaque is represented by spline parameters, which are defined according to the proposed algorithm, as shown in Fig. 3. The geometry of the plaque is created using two splines (upper and lower). These splines, similar to the cap spline, can take various shapes, simulating different structures and positions of the plaque.

The detailed description of the main stages of the algorithm for determining the geometrical parameters of vessel layers and plaque is shown in fig.3.

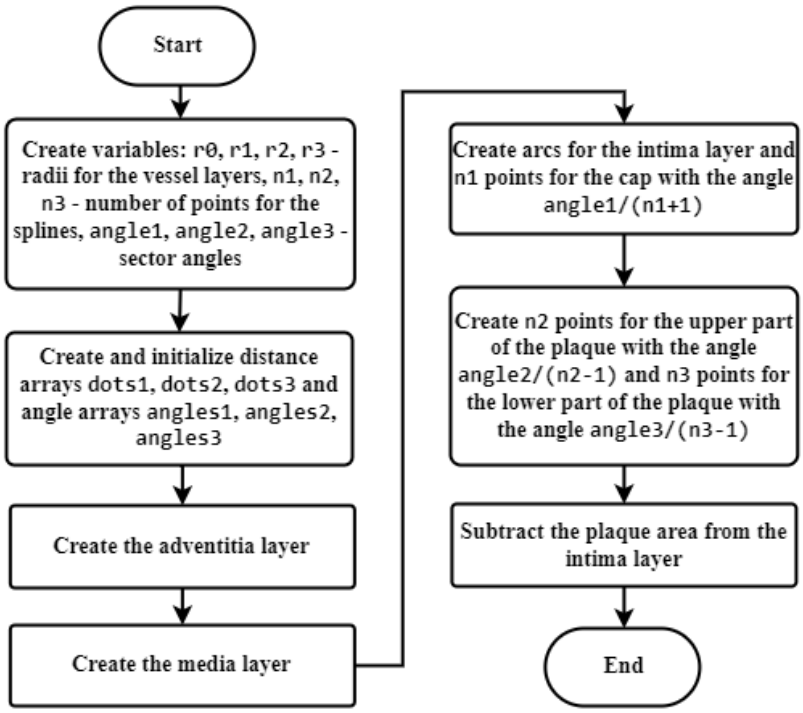


Fig.3. **The algorithm of determining geometrical parameters of vessel with plaque**

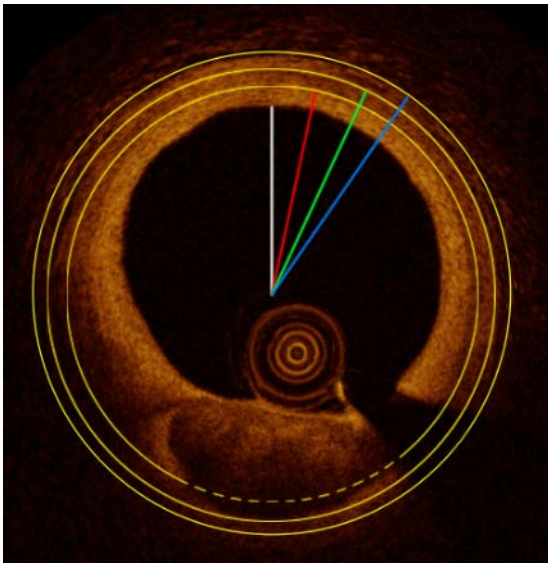


Fig.4. **The Media and Adventitia layers of vessel with plaque**

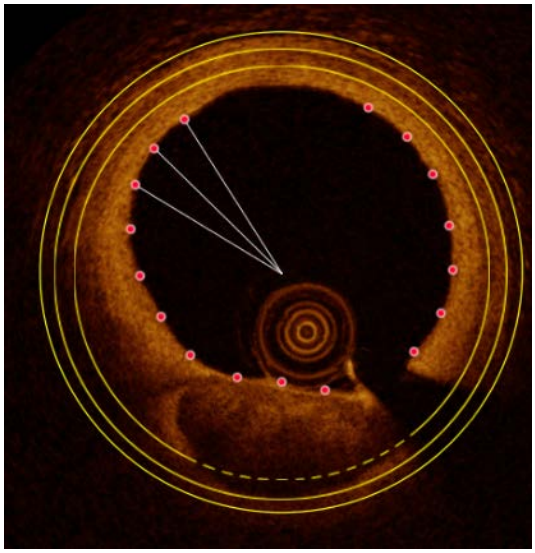


Fig.5. **The intima layer of vessel with plaque**

The detailed description of algorithm is presented below:

1. The artery's geometry is idealized to a circle with a constant diameter for further numerical modeling.
2. The midpoint of the idealized artery is determined at the intersection of the circle's diameters. The outer radius of the adventitia (outer layer) is identified. (fig.4)
3. Key parameters are defined, such as the thickness of the intima layer (inner layer, fig.5), the thickness of the media layer (middle layer), and the thickness of the adventitia (outer layer).
4. Using the midpoint of the artery, the sector of the plaque cap is determined.
5. An application is used to construct the cap over the plaque, determining the distance and angle of inclination relative to the artery's midpoint.
6. For constructing the upper part of the plaque (fig.6), an application is used to determine the distance and angle of inclination relative to the artery's midpoint.
7. For constructing the lower part of the plaque (fig.7), an application is used to determine the

distance and angle of inclination relative to the artery's midpoint.

8. The modeled geometry of the artery with the lipid plaque is created in ANSYS software.

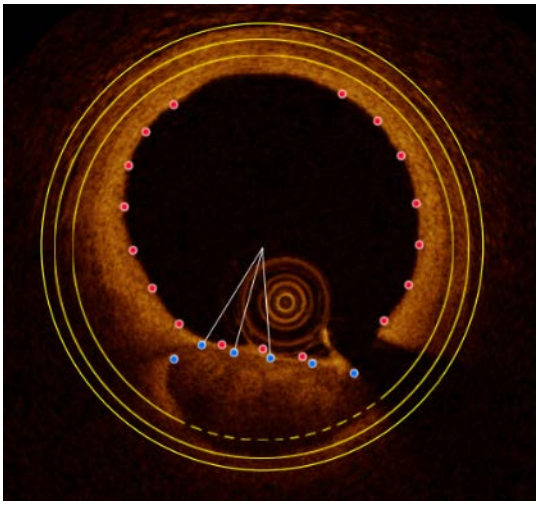


Fig.6. **The upper part of the plaque**

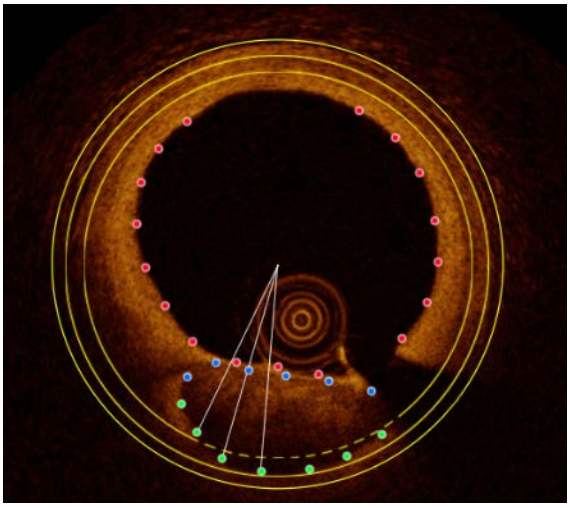


Fig.7. **The lower part of the plaque**

All layers and plaque are created as separate areas but considering geometry of each other as well as all of them has a different material properties. The material properties as Young's modulus (E_r, E_θ, E_z), shear modulus ($G_{r\theta}$, $G_{\theta z}$, G_{rz}) and Poisson's ratios ($\nu_{r\theta}$, ν_{rz},$\nu_{\theta z}$,) are presented of the plaque constituents are consolidated from Wong [1] and shown in table 1.

Table 1

Material properties for vessel layers and plaque

Parameter	Vessel layers			Plaque (Lipid pool)
	Intima	Media	Adventitia	
E_r, E_z kPa	300	100	350	E = 10 kPa (isotropic)
E_θ, kPa	3000	1000	3500	
$G_{r\theta}$, kPa	1500	500	2000	
$G_{\theta z}$, G_{rz}, kPa	150	50	200	
$\nu_{r\theta}$, ν_{rz}, -	0.01	0.01	0.01	ν = 0.45
$\nu_{\theta z}$, -	0.27	0.27	0.27	

Numerical results. The Finite element method were used for determining the stress strain state of vessel with plaque. The single layer model was set in solid plane strain, structural, linear, isotropic quadrilateral elements (8 node PLANE 183) throughout the analysis as shown in fig. 8.

The study was conducted for different plaque geometries based on OCT results and subjected to a pressure of 16,200 Pa, corresponding to normal human systolic pressure.

The proposed approach for building FE-model was applied for three different cases.

The simulation results reveal the complex nature of stress and strain distribution within the vessel wall and plaque components. Figure 9 illustrates the contour plots of the 1st principal stress for three clinical cases. The results indicate that the maximum stress concentrations are consistently located at the "shoulders" of the plaque (the transition zone between the plaque and the normal vessel wall).

In case 1 the stress distribution (fig.9) is relatively uniform compared to other cases. The maximum 1st principal stress reached approximately 236 kPa. The deformation pattern follows the geometry of the fibrous cap without critical localization (fig.10). In case 2 the maximum 1st principal stress reached approximately 537 kPa

Case 3 exhibited the most critical behavior in terms of deformation. Figure 10 shows the distribution of the 1st principal elastic strain. Due to the low stiffness of the lipid core, the plaque underwent significant deformation under systolic pressure. The maximum elastic strain reached 0.157 (15.7%), while the peak stress was recorded at approximately 160 kPa. Such high strain levels indicate a significant stretching of the thin fibrous cap, marking it as highly vulnerable to rupture.

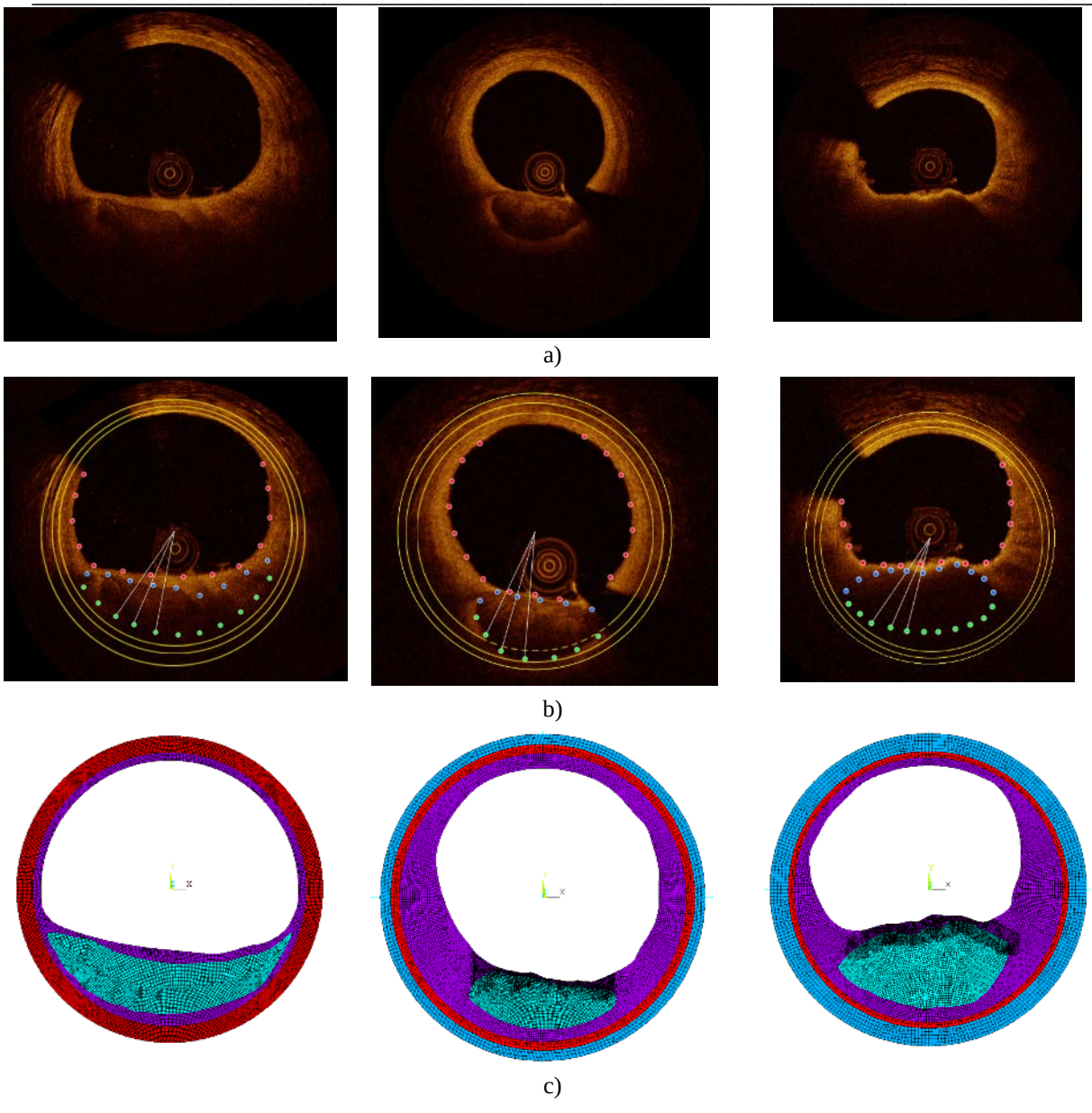


Fig.8. **The vessel models: a) initial data, b) schematic view of vessel parts separation, c) mesh models based on provided data and build by proposed algorithm**

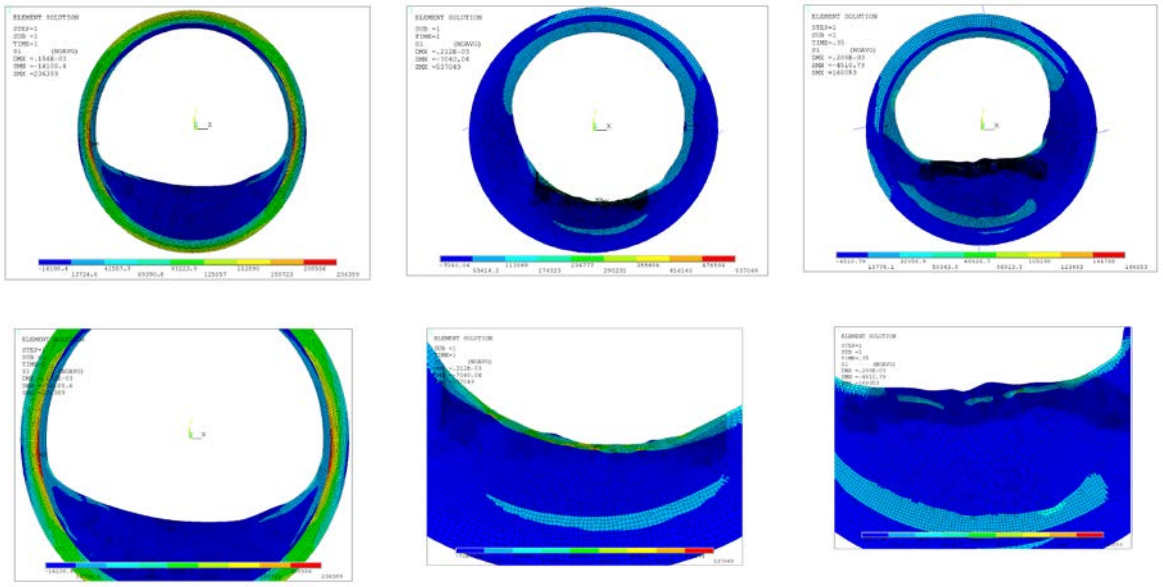
Conclusions and prospects for further exploration in this direction. In this study, a methodology for the patient-specific finite element modeling of atherosclerotic vessels based on Optical Coherence Tomography (OCT) data was developed and implemented. The following conclusions can be drawn: an algorithm using Python scripting was successfully created to process OCT images and automatically generate parametric geometric models of the vessel layers (intima, media, adventitia) and plaque components. This approach reduces manual processing time and preserves the anatomical accuracy of patient-specific data.

Finite element analysis of three models with plaques showed that mechanical stress is distributed unevenly. Maximum stress concentrations are localized at the edges of the plaques, which are considered to be the weakest points.

Future research in this direction will focus on:

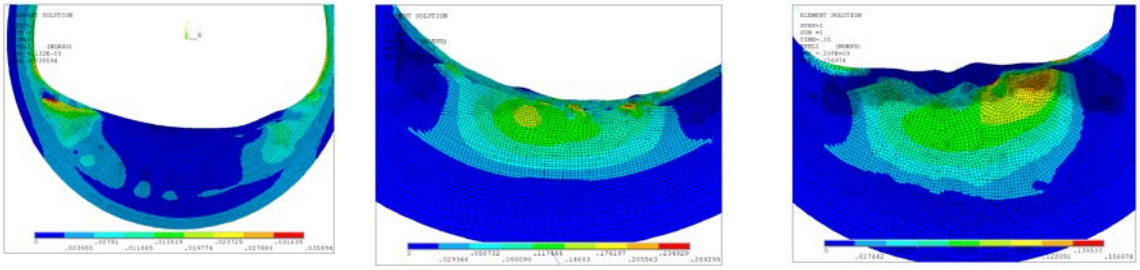
- refining the load applied to the vessel walls and better simulate blood pulsation;
- expanding the current 2D cross-sectional models to fully three-dimensional reconstructions to account for the longitudinal variability of the plaque;
- implementing hyperelastic material models (e.g., Mooney-Rivlin or Ogden) to better

describe the behavior of arterial tissues at higher strain levels.



Case 1 Case 2 Case 3

Fig.9. **Contour plot of the 1st principal stress**



Case 1 Case 2 Case 3

Fig.10. **Contour plots of the 1st principal elastic strain. Maximum values are localized in the plaque contact area**

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