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Coronary arteries and angioplasty balloon mechanical behavior modeling

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The aim of this work is to assess the mechanical behavior of coronary vessels and angioplasty balloons during the angioplasty procedure, based on intravascular ultrasound (IVUS) and angiography data obtained for each patient individually. To treat atherosclerosis, a serious chronic inflammatory disease of the arteries characterized by the formation of atherosclerotic plaques, which causes vessel narrowing and impairs blood supply to tissues and organs, modern medical practice employs a minimally invasive endovascular procedure known as balloon angioplasty. Key aspects of modeling this procedure include understanding the behavior of patients' arteries and the balloons used during the intervention. Based on intravascular ultrasound and angiography data, a biomechanical model of an artery affected by atherosclerosis is developed. A finite element model of the arterial segment is constructed, accounting for its nonlinear hyperelastic behavior. To simulate the behavior of the angioplasty balloon, a mathematical model of the balloon is developed and validated against experimental data. An assessment of the stress-strain state of a specific patient's coronary artery and angioplasty balloon is performed. For a full-scale simulation of the angioplasty process, a mathematical model is developed that incorporates all three objects considered above: personalization of the artery model through the use of real patient data; a finite element model of the artery built based on of the personalized model, accounting for its nonlinear behavior; a finite element model of the angioplasty balloon. The developed mathematical models and the results obtained from them will further allow us to derive dependencies of key angioplasty parameters. These dependencies can be used to improve angioplasty techniques based on intravascular imaging data. Furthermore, the application of mathematical modeling methods will help reduce the number of clinical trials in this field.

Keywords: angioplasty, balloon, atherosclerosis, artery, mathematical modeling, intravascular imaging

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Ки&М

СПЕЦИАЛЬНЫЙ ВЫПУСК

УДК: 531/534: [57+61]

Моделирование механического поведения коронарных сосудов и ангиопластических баллонов

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Целью данной работы является оценка механического поведения коронарных сосудов и ангиопластических баллонов при проведении процедуры ангиопластики на основании данных внутрисосудистого ультразвукового исследования и ангиографии, полученных для каждого пациента индивидуально. Для лечения атеросклероза, представляющего собой серьезное хроническое воспалительное заболевание артерий с образованием атеросклеротических бляшек и вызывающего сужение сосудов и ухудшение кровоснабжения тканей и органов, в современной медицинской практике применяют малоинвазивную эндоваскулярную процедуру — баллонную ангиопластику, ключевым аспектом моделирования которой является понимание поведения артерий пациентов и баллонов, которые используют для ее проведения. На основании данных внутрисосудистого ультразвукового исследования и ангиографии была разработана биомеханическая модель артерии, пораженной атеросклерозом. Построена конечно-элементная модель участка артерии, учитывающая ее нелинейное гиперупругое поведение. Для моделирования поведения ангиопластического баллона была разработана математическая модель баллона, проведена валидация с экспериментальными данными. Проведена оценка напряженно-деформированного состояния коронарной артерии конкретного пациента и ангиопластического баллона. На основании разработанных математических моделей отдельных объектов в дальнейшем будет построена полномасштабная математическая модель процесса ангиопластики, включающая три рассмотренных выше объекта: персонифицированную за счет использования данных реального пациента модель артерии; построенную на основе персонифицированной модели конечно-элементную модель артерии, учитывающую ее нелинейное поведение и конечно-элементную модель ангиопластического баллона, а также их взаимосвязь. Разработанные математические модели и полученные на их основе результаты в дальнейшем позволят получить зависимости ключевых параметров ангиопластики, которые могут быть использованы для усовершенствования методики ангиопластики на основе данных внутрисосудистой визуализации, а применение методов математического моделирования позволит снизить число клинических испытаний в данной области.

Ключевые слова: ангиопластика, баллон, атеросклероз, артерия, математическое моделирование, внутрисосудистая визуализация

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1. Introduction

Atherosclerosis is a chronic inflammatory disease of large and medium-sized arteries, in which cholesterol, lipoproteins, and other cellular components are deposited and subsequently oxidized on arterial walls, forming atherosclerotic plaques [Libby, 2002; Libby, 2003; Hansson, 2005; Minelli et al., 2020]. When atherosclerotic plaques reach a certain size, they cause narrowing of the blood vessels and impair the blood supply to tissues and organs, which can lead to strokes and heart attacks over time. According to the World Health Organization, these diseases are the leading causes of death [WHO, 2025].

In modern medical practice, a minimally invasive endovascular procedure called balloon angioplasty, often combined with coronary stenting, is used to treat atherosclerosis and restore blood flow in atherosclerotic-affected arteries [Byrne et al., 2014; Patil, Nanjappa, 2017].

The balloon angioplasty was proposed in 1964 [Dotter, Judkins, 1964]. The first balloon angioplasty procedure was performed in 1977 [Grüntzig, 1978], and the first coronary stent was placed in 1986 [Puel et al., 1987]. Over the past sixty years, the development of angioplasty and stenting technologies has transformed these procedures from experimental to first-line treatments for atherosclerosis. As a result, there has been a need to optimize the characteristics and improve the procedures. With the development of software and technical equipment, it became possible to replace some of the clinical trials with virtual experiments, followed by validation using a limited number of clinical data. During this time, the approaches to building and detailing mathematical models of angioplasty balloons have undergone significant changes.

According to [Bukala et al., 2017], in the period 2000–2008, balloons were not explicitly taken into account, and a number of assumptions were made during modeling: the rigidity of the balloon was neglected in comparison with the rigidity of the stent; pressure was applied directly to the stent itself, or the stent was expanded by setting the movements. The balloon is taken into account in the works starting from 2005. In the period from 2005 to 2009, mainly cylinders of simple cylindrical shape are considered. Starting from 2008, a number of studies already contain folded cylinders, allowing to take into account the nonlinear behavior during the opening.

Depending on their radial compliance, angioplasty balloons are divided into several types. Our study will focus on balloons that can expand up to 30 % of their initial diameter when subjected to bursting pressure. These balloons are typically made from thermoplastic polymers (Pebax), synthetic polyamides (Nylon), and polyurethanes [Amstutz et al., 2023], which exhibit nonlinear hyperelastic behavior from a mechanical standpoint. A number of scientific studies have shown that the use of hyperelastic material models is justified for modeling the mechanical behavior of such structures.

On the other hand, of special interest, as confirmed by a series of works by other authors [Gervaso et al., 2008; Geith et al., 2019; Li et al., 2023; Kwakman et al., 2025], is the modeling of the interaction between the balloon and the walls of an atherosclerotic vessel in order to describe its mechanical behavior and assess its stress-strain state. Given the multi-layer structure of the coronary vessels and their anisotropic behavior, hyperelastic material models are also suitable for describing their mechanical behavior [Mooney, 1940; Rivlin, 1948; Ogden, 1972; Yeoh, 1993; Holzapfel et al., 2002]. A series of studies have demonstrated a good correlation between the results of numerical experiments and experimental data [Ovsepyan et al., 2023].

At the same time, the use of mathematical modeling methods [El Khatib et al., 2019; Vassilevski et al., 2022; Antonova et al., 2026] in describing the angioplasty process and the behavior of the balloon and vascular tissues is a truly relevant task, the results of which will form the basis for a comprehensive mathematical model that will be used in the future to optimize the parameters of complex medical interventions without increasing the number of clinical experiments.

2. Coronary arteries personalized biomedical model development

A coronary artery is one of the key elements of myocardial blood supply. It delivers oxygen and essential nutrients to the heart. The progression of atherosclerosis, which is characterized by the formation of plaques within the vessel wall, leads to narrowing of the arterial lumen. This affects the blood flow in a severely negative way and results in a cardiovascular disease. While the behavior of coronary arteries and other vessels depends on their physiological properties even when belonging to a healthy person, it is essential for the model to include individual characteristics of the specific patient [Lee et al., 1993; Matsumoto et al., 2019; Noble et al., 2020; Wang et al., 2022; Curcio et al., 2023; Derycke et al., 2023; Ramella et al., 2024]. The current research is based on the results of the intravascular ultrasound study (IVUS), virtual histology based on this ultrasound study and biplanar angiography. The above-mentioned procedures are classified as intravascular visualization methods and are widely used for the atherosclerotic vessel condition assessment. This provides grounds for medical decision making in terms of the necessity of performing angioplasty and stenting [Luk-Pat et al., 1999; Li et al., 2017].

Compared to a regular coronary angiography, intravascular ultrasound study facilitates analysis of a vessel cross-section structure, which enables identification of the cause of lumen narrowing. The results of an intravascular ultrasound study present a set of detailed grayscale images of an artery cross-section. Virtual histology based on these images provides an ability to perform a detailed analysis of the vessel wall condition and to get a colored map of a vessel cross-section, where every color or its range corresponds to a certain type of tissue of the vessel wall or an atherosclerotic plaque. Biplanar angiography results, which can also be used as a source of detailed information about vessel condition and characteristics, are being used to obtain the centerline of an artery and to position the cross-sections along it.

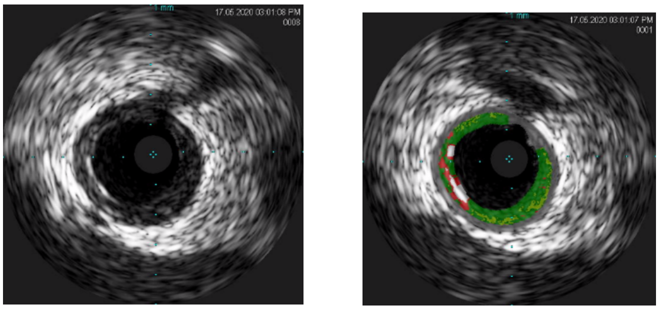
Examples of the images used in the current research are presented in Fig. 1.

Data processing is performed by several custom Python scripts as well as an open-source software [Molony, Samady, 2019; Warren et al., 2022]. The first step consists of the segmentation of the grayscale IVUS images. This is carried out to get lumen and outer border contours of the vessel. An example of such segmentation is shown in Fig. 2.

During the following stage, virtual histology frames, corresponding to these grayscale images, are cut with the contours to get rid of the areas not containing any tissue. After the cut, color range reduction is performed. Only a designated set of colors is left. While developing a finite element model of an artery, this color map is used to define areas with different material properties. An example of the final processed image is shown in Fig. 3.

After finishing the processing of a full dataset of images according to the aforementioned algorithm, a personalized biomechanical model of an artery is created using a set of coordinates describing the centerline of an artery. As mentioned above, this set of coordinates is based on the results of angiography. The resulting model incorporates heterogeneous mechanical properties of the vessel tissue and plaque.

The above-mentioned algorithm of patient-specific biomechanical artery model development will provide an ability to obtain appropriate stress and strain fields in artery walls.



(a) (b)

Figure 1. Initial data forms a set of the following data: intravascular ultrasound study, virtual histology based on IVUS data facilitating an assessment of the plaque structure

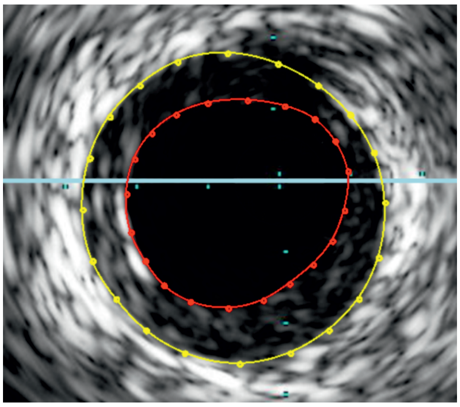


Figure 2. Outer border and lumen contours of an artery, obtained with specialized open-source image segmentation software

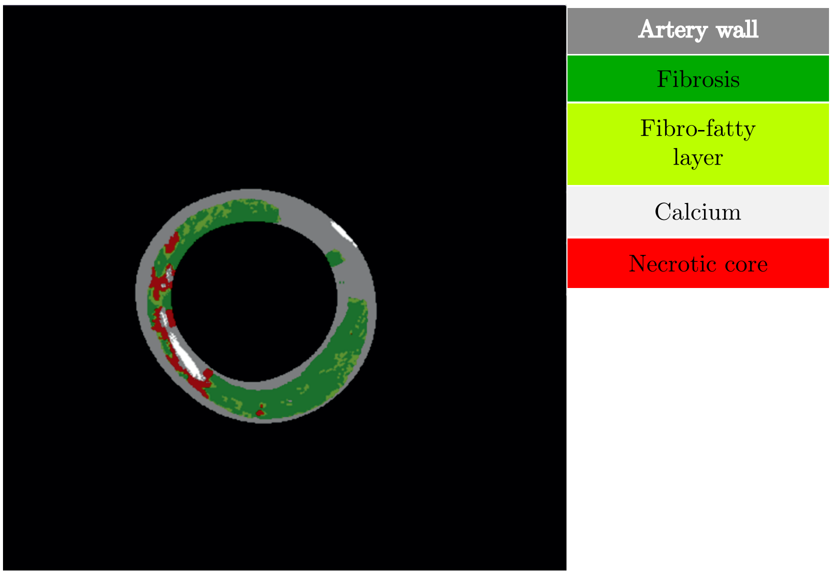


Figure 3. Processed artery cross-section image, obtained by cutting parts of an image not containing any vessel tissue or plaque and by color range reduction performed for a better segmentation of tissues: Artery wall, fibrosis, fibro-fatty layer, calcium and necrotic core

3. Modeling of the mechanical behavior of a coronary artery affected by atherosclerosis

This part of the study is devoted to the analysis of the mechanical behavior of an artery affected by atherosclerosis. The biomechanical model of the artery described above is used as the input data. Since coronary vessels have a complex anatomical structure [Kalita, Schaefer, 2008; Kobielarz et al., 2020], the question of selecting an adequate mathematical model that describes their behavior with allowance for their nonlinear properties comes to the fore [Holzapfel et al., 2004; Akyildiz et al., 2014; Holzapfel et al., 2014; Barrett et al., 2019; Dol, 2023]. An analysis of the literature has shown that various material models are used to describe the biomechanical behavior of the arterial wall: isotropic elastic models [Wong et al., 2012; Narayanan et al., 2021; Warren et al., 2022], the hyperelastic Yeoh model [Narayanan et al., 2021], the fifth-order Mooney – Rivlin model [Teng et al., 2015], as well as modified Mooney – Rivlin models [Teng et al., 2015], and the Holzapfel – Gasser – Ogden model [Holzapfel et al., 2002; Huh et al., 2019]. In modeling fibrosis and the fibro-fatty layer, a number of studies [Teng et al., 2015; Narayanan et al., 2021; Warren et al., 2022; Latorre et al., 2023] employ an isotropic elastic material, as well as the hyperelastic Neo-Hookean, Yeoh, and Mooney – Rivlin models of various orders. A similar approach — the use of isotropic elastic medium and the Yeoh potential — is used to describe the mechanical properties of calcified regions [Narayanan et al., 2021; Warren et al., 2022]. To describe the necrotic core and the outer layer of the artery, which is required to stabilize the solution, an isotropic elastic material model is used.

In this study, the hyperelastic Yeoh and Neo-Hookean material models were used. The physical and mechanical parameters of these components were adopted in accordance with the results of [Warren et al., 2022].

The hyperelastic materials under consideration are models in which the strain energy density is defined as a function of the first invariant of the strain tensor, which makes them a particular case of polynomial models. The Neo-Hookean model, (1) for $N = 1$, is the simplest variant and includes a single parameter related to the shear modulus, whereas the Yeoh model, (1) for $N = 3$, extends it by adding higher-order nonlinear terms, which allows the material behavior under large deformations to be described more accurately. Both models can be supplemented with a volumetric elasticity parameter to account for the slight compressibility of the material:

$$U = \sum_{i=1}^{N} C_{i0}(\bar{I}_1 - 3)^i + \sum_{i=1}^{N} \frac{1}{D_i}(J_{\mathrm{el}} - 1)^{2i}, \tag{1}$$

where c_{i0}, D_i are the material constants, $\bar{I}_1$ is the first invariant of the deviatoric strains, and J_{el} is the elastic volumetric strain.

A segment of an artery affected by atherosclerosis was considered. Regions of the artery and the atherosclerotic plaque possessing different physical and mechanical properties were identified. The numerical computations were performed using the finite element method implemented in the Simulia Abaqus software package. A series of finite element models was created. A convergence study was carried out. For further analysis, a model consisting of 1 175 743 first-order elements was selected. Table 1 presents the material parameters used in the computations for the various regions of the model.

The problem of expansion of the coronary artery under the action of internal pressure simulating the pressure of the balloon during angioplasty was solved. As boundary conditions on the boundaries of the model under study, a constraint on displacements in all degrees of freedom was imposed. Figure 4 shows the field of total displacements of the artery affected by atherosclerosis, from which it can be

Table 1. Parameters of the hyperelastic and isotropic elastic materials used in the computations for the various regions of the artery

Coronary artery part	Material model	Parameters		
Arterial wall	Yeoh	C_{10}, kPa	C_{20}, kPa	C_{30}, kPa
		5.64	1812	162
Fibrosis	Neo-Hookean	C_{10}, kPa	D_1, kPa^{-1}	
		103.45	0.001	
Fibro-fatty layer		C_{10}, kPa	D_1, kPa^{-1}	
		1.72	0.06	
Calcification	Isotropic elastic	E, MPa	ν	
		10	0.48	
Necrotic core		E, MPa	ν	
		0.02	0.48	
Outer layer		E, MPa	ν	
		0.4	0.48	

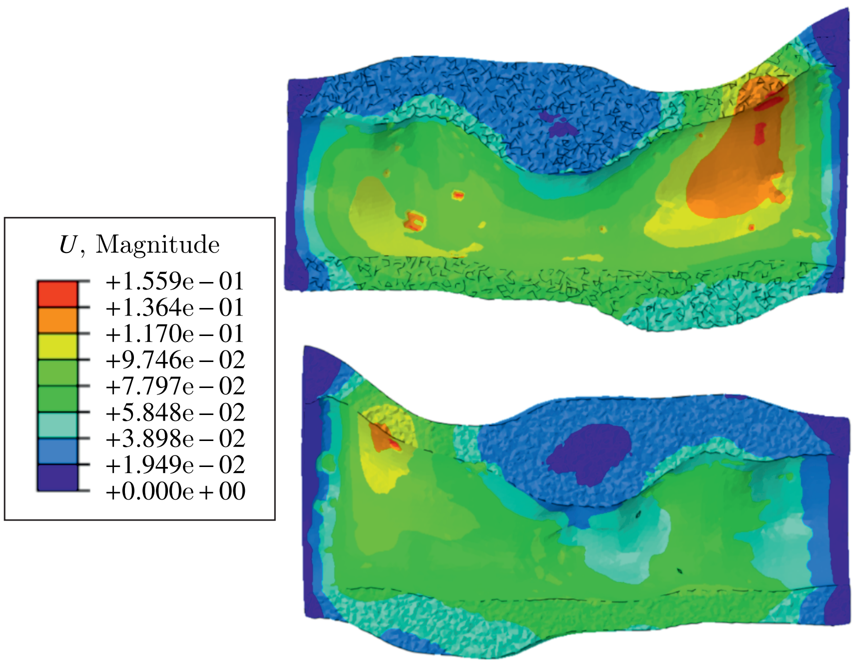


Figure 4. Field of total displacements of the artery affected by atherosclerosis. The maximum displacements are observed in the region of the necrotic core

observed that the maximum displacements occur in the places where the necrotic cores are located near the inner surface of the artery.

Figure 5 shows the field of von Mises equivalent stresses for the artery affected by atherosclerosis, from which it can be observed that the maximum stresses occur in the places where calcium deposits form.

The results obtained at this stage make it possible to assess the stress-strain state of the coronary artery of a specific patient.

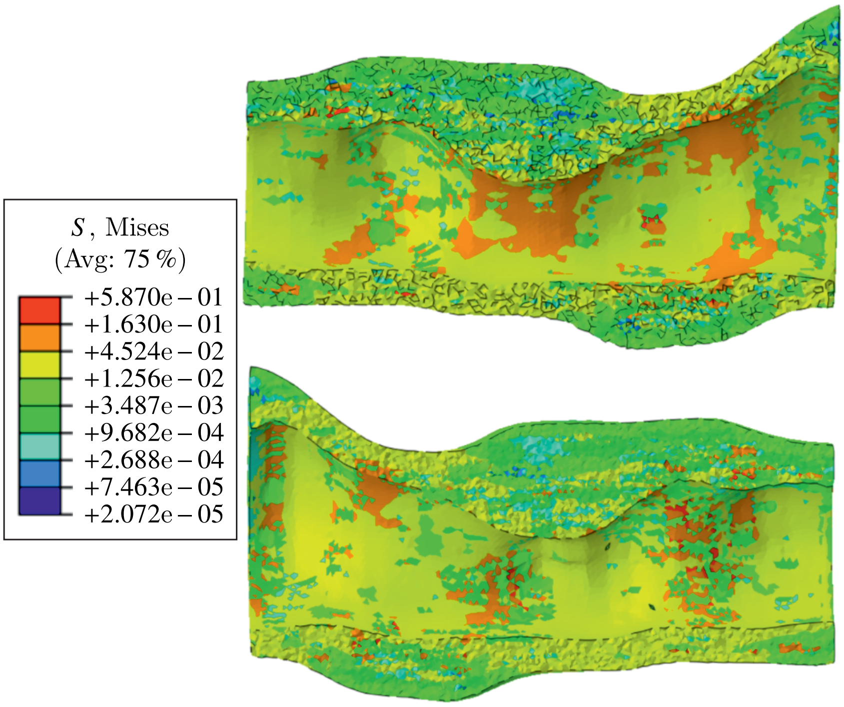


Figure 5. Distribution field of von Mises equivalent stresses of the artery affected by atherosclerosis. The maximum stresses occur in the region of calcium deposition

4. Modeling of the angioplasty balloon behavior

The angioplasty procedure is a minimally invasive surgical intervention aimed at restoring the lumen of narrowed arteries affected by atherosclerosis. Through a small puncture, a balloon (balloon catheter) is inserted to the site of narrowing, which, upon inflation, expands the vessel. In some cases, this is sufficient to restore blood flow, but often, to maintain the result, a stent is placed in the zone of narrowing.

High-pressure balloon catheters are key medical devices used in angioplasty to eliminate stenoses of the coronary arteries. The device is a thin-walled polymer shell (nylon, PET, polyurethane) designed to operate under internal overpressure. One of the key design features is the need to minimize the transverse profile of the catheter for its unobstructed delivery to the stenosis zone. This is achieved by forming a folded configuration of the shell: at the first stage the blank is given a “trefoil”-type cross section, after which the petals are tightly pleated around the central axis.

The mechanics of deployment of such a predeformed structure are characterized by extreme deformations and significant geometric nonlinearity [Sadeghi, Le, 2021; Stratakos et al., 2023; Nappi et al., 2025]. The process of transition from a compact folded configuration to a cylindrical one is accompanied by repeated changes in the contact areas between the inner surfaces of the shell. From the standpoint of computational mechanics, the problem is complicated by the need to account for the nonlinear hyperelastic behavior of the material and to ensure numerical stability during the unfolding of the tightly packed folds. Nonuniformity in the unfolding of the petals can cause the occurrence of local stress concentrations, which critically affects the mechanical integrity of the device and the safety of the medical intervention performed.

Taking into account the above, from the standpoint of mechanics, the greatest interest lies in the development of a model that correctly describes the interaction between the coronary artery and the balloon during its deployment. Before proceeding to the solution of the problem of contact interaction between the coronary artery and the balloon, the problem of deployment of the angioplasty balloon "in air" was solved in order to validate the mathematical model with the results of full-scale tests performed for one of the angioplasty balloons widely used in medical practice.

Figure 6 shows a general view of the device during the experiment. The angioplasty balloon is made of polyamide.

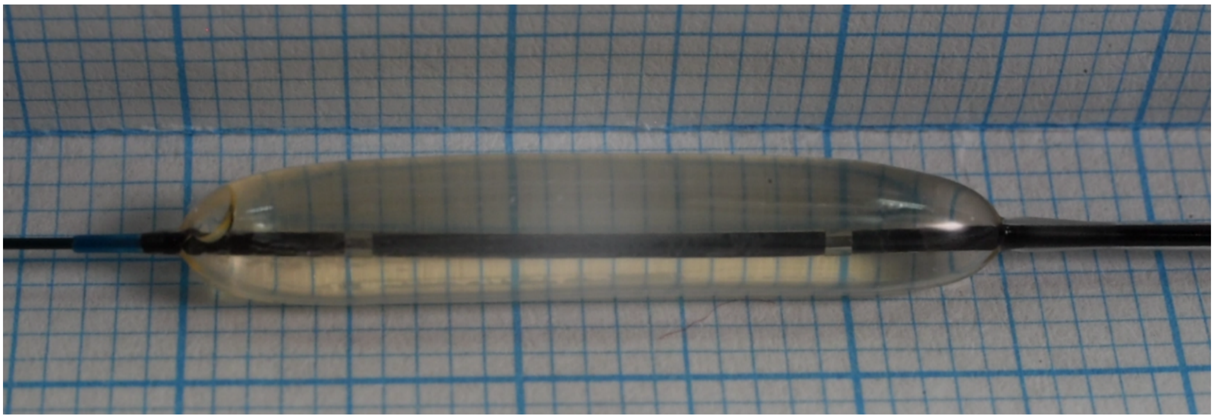


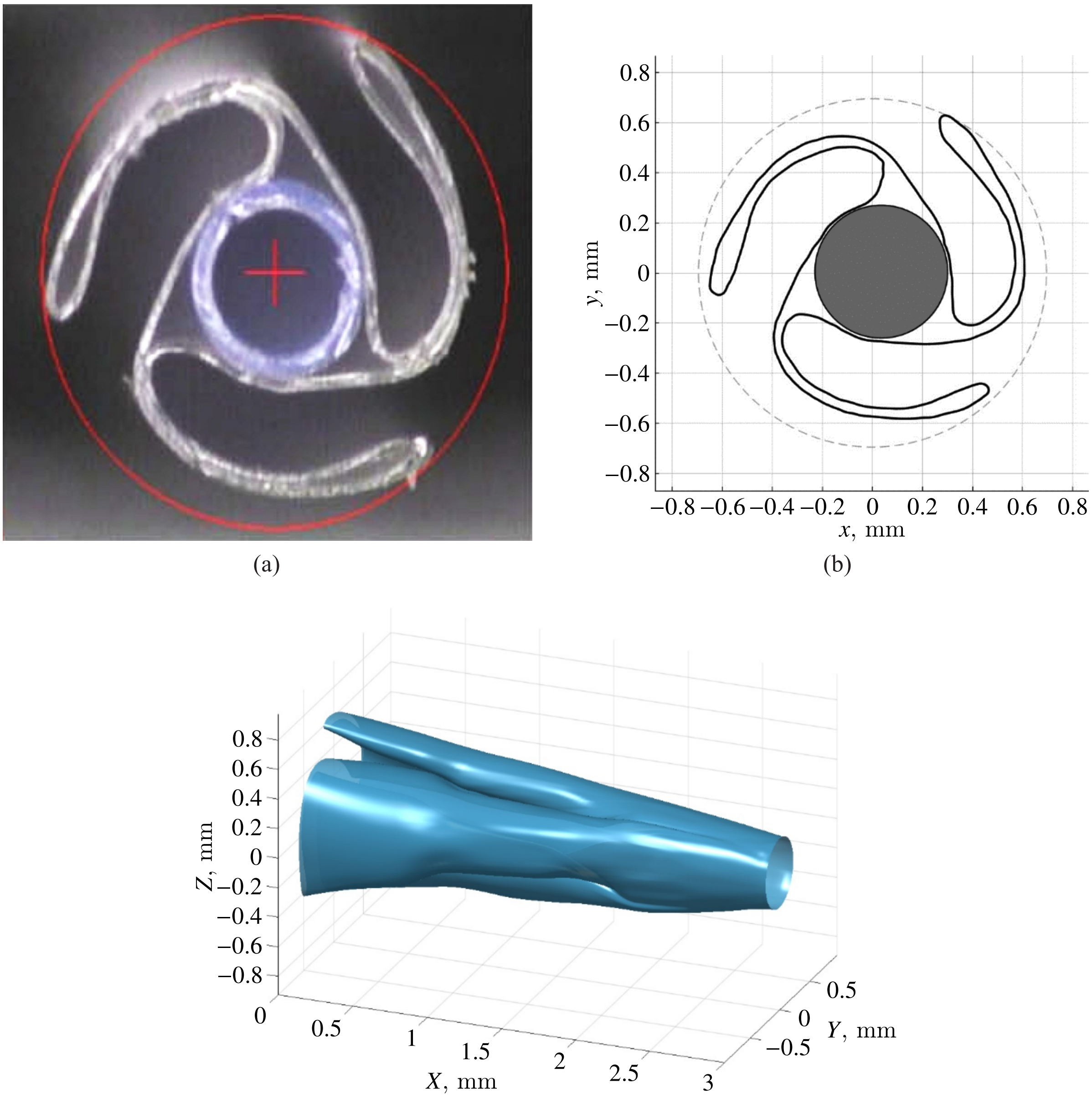
Figure 6. Angioplasty balloon during the experiment

The development of the finite element model of the folded balloon was carried out in two stages. As input data, the cross section of the medical device in the "trefoil" configuration was used (Fig. 7, *a*) — the standard folding pattern of balloon catheters in clinical practice, in which three petals are tightly packed around the axis, providing a minimal profile during delivery of the device to the stenosis area [Rahinj et al., 2022]. This cross section was reconstructed in the MATLAB environment (Fig. 7, *b*); the central part of the balloon has a constant cross section, and geometric models of the proximal and distal ends of the balloon were additionally designed and constructed (Fig. 7, *c*). This approach provided full control over the topology of the balloon and the accuracy of reproduction of the fold geometry.

The final finite element model of the folded balloon is presented in Fig. 8 and consists of 1 083 914 S4R elements — shell elements based on the Mindlin – Reissner theory [Reissner, 1945; Mindlin, 1951].

Since the materials from which angioplasty balloons are manufactured exhibit nonlinear hyperelastic behavior, in order to describe their behavior, as in the case of the coronary artery, it is very important to make a correct choice of the balloon material model that takes into account the features of its behavior during deployment.

To describe the behavior of the balloon material, the polyamide Grilamid L25, a first-order hyperelastic Ogden model was used [Helou et al., 2021]. The choice of this model is justified by the results of the comparative analysis presented in a series of works [Helou et al., 2021; Rahinj et al., 2022; Bhave et al., 2023], in which various options for describing polymers were considered, including Ogden potentials (1st and 4th orders) and polynomial models. Within the framework of the current task, preference was given to the first-order model, since it provides more stable convergence under extreme deformations and complex contact interaction. This model is well suited for reproducing the large nonlinear deformations characteristic of polymer materials: owing to its flexible parameterization through power-law dependences of the principal stretches, it provides a more accurate description of the



(c)

Figure 7. Geometry of the balloon catheter in the “trefoil” configuration: (a) cross section of the medical device [Rahinj et al., 2022]; (b) reconstructed cross section in the MATLAB environment; (c) geometric models of the proximal and distal ends of the balloon. The x, y, z axes are spatial coordinates

Table 2. Parameters of the hyperelastic Ogden model used to describe the behavior of the balloon

Order of the Ogden model	μ_1, MPa	α_1	D_1
1	1.72	4.55	0

material behavior compared with the Neo-Hookean or Mooney – Rivlin models. The model parameters are given in Table 2.

The computation was performed in the Simulia Abaqus software package using the explicit dynamics method (Abaqus/Explicit), since it is well suited for problems involving large deformations and complex contact interaction.

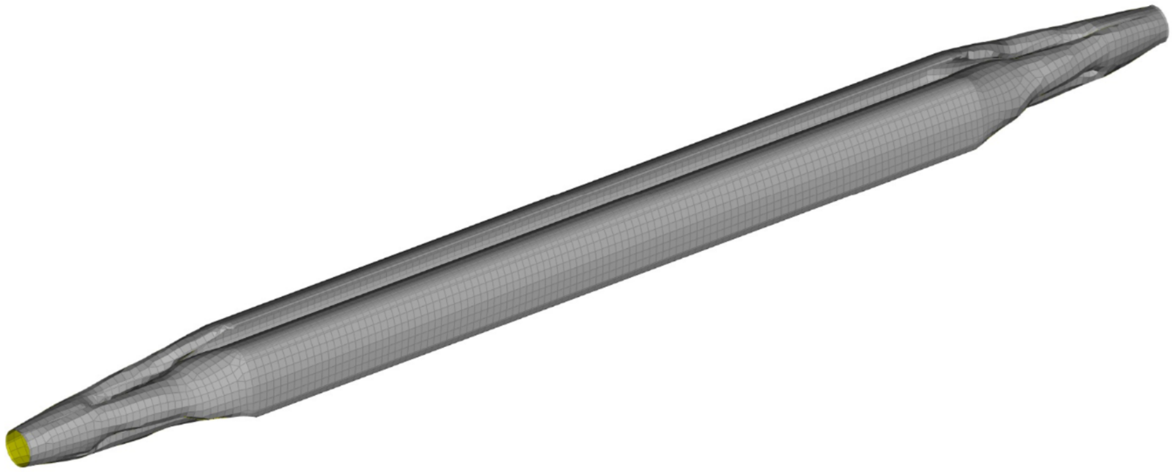


Figure 8. Finite element model of the balloon catheter in the folded state. Geometry of the balloon shell before the start of the deployment process

Loading was applied in the form of a uniformly distributed internal pressure increasing from zero to ~ 2.23 atmospheres according to a nonlinear dependence based on experimental data. A formulation with the following boundary conditions was considered: the distal end of the balloon was constrained against radial and longitudinal displacements, and the proximal end only against radial ones.

Figure 9 shows the deformed shape of the balloon.

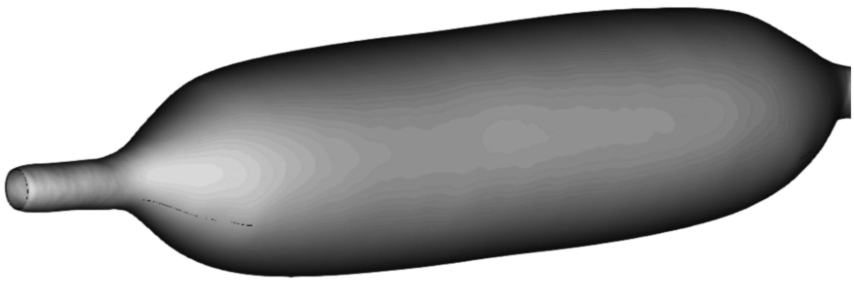


Figure 9. Deformed shape of the angioplasty balloon

Figure 10 demonstrates the cross section of the balloon in the deployed state compared with the undeployed configuration.

Analysis of the obtained results showed that the maximum von Mises equivalent stresses are localized in the zones of fold straightening. The developed mathematical model correctly reproduces the dynamics of deployment of the hyperelastic balloon from the “trefoil” configuration, makes it possible to identify critical stress zones and to assess the uniformity of petal unfolding — a necessary condition for preventing balloon ruptures and ensuring correct positioning in the vessel lumen.

The results obtained at this stage are used to validate the mathematical model of the balloon. Figure 11 presents a comparison of the curves of the balloon deployment diameter versus pressure for the numerical and full-scale experiments, demonstrating good qualitative agreement, but requiring refinement of the mathematical model at the next stage.

Figure 10. Cross section of the balloon compared with the undeployed configuration

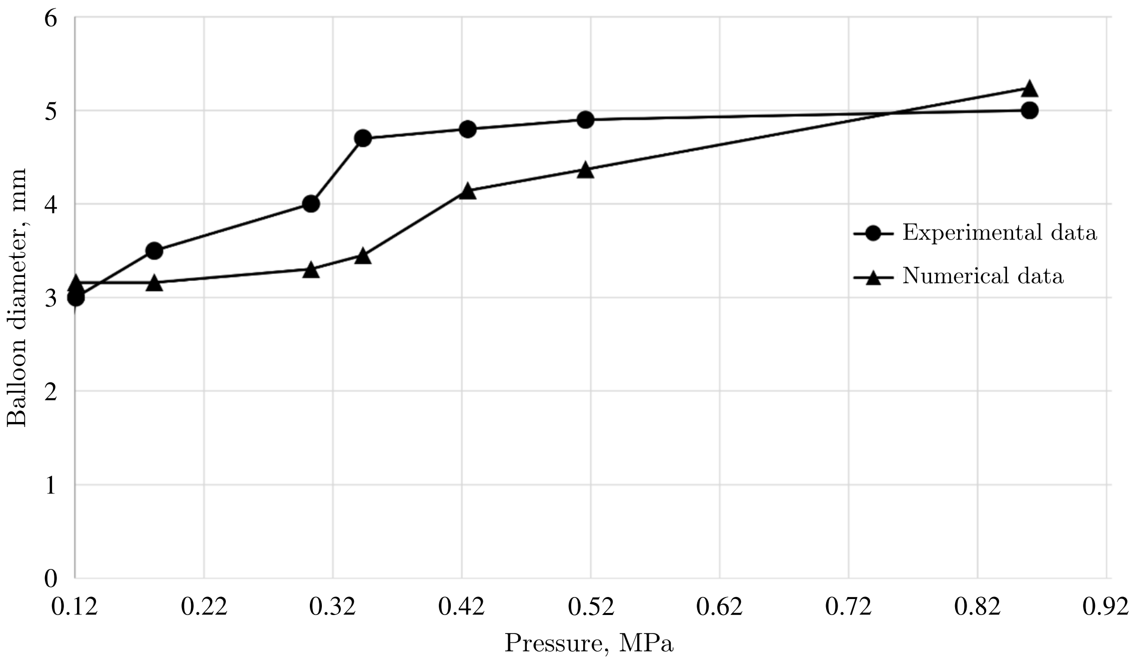


Figure 11. Plot of the balloon deployment diameter (mm) versus the pressure in the balloon (MPa)

On the basis of the analysis of the results presented above, it can be concluded that the developed mathematical model correctly reproduces the dynamics of deployment of the hyperelastic balloon from the "trefoil" configuration. Stress concentrations were identified in the fold zones and near the distal end of the balloon; the obtained results make it possible to assess the uniformity of petal unfolding and to identify the critical zones necessary for preventing local damage and ensuring correct positioning in the vessel lumen.

5. Conclusion

A biomechanical model of the artery was developed, considering the heterogeneous physical and mechanical properties of the artery and plaque. Also, a mathematical model was developed and validated, correctly reproducing the dynamic nonlinear hyperelastic behavior of an angioplasty balloon when it is opened from the "trefoil" configuration, allowing further generalization of this approach to a series of angioplasty balloons.

The developed mathematical models, the obtained results, and the proposed algorithms will be used in the next stage for full-scale modeling of the angioplasty. The key aspect of this and subsequent research in this field is the personalization of the developed arterial models by using real patient intravascular imaging data. By considering the nonlinear physical and mechanical properties of coronary arteries and angioplasty balloons using adequate, validated, and verified material models, it is possible to accurately describe the mechanical behavior of these objects.

In the future, the obtained results are planned to be used to improve the angioplasty technique based on intravascular imaging data, to justify the necessary changes in medical intervention regulations, and the use of mathematical modeling methods will reduce the number of clinical trials in this area.

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