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Original Research Article

Numerical analysis of stent expansion process in coronary artery stenosis with the use of non-compliant balloon

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ABSTRACT

In the paper the authors present an applied methodology, data and numerical results for numerical analysis of the stent crimping process and stent implantation in the coronary artery stenosis with the use of a non-compliant angioplasty balloon. The authors focused on the modeling methodology of balloon angioplasty with minimum possible simplification, i.e.: a full load path (compression and inflation in single analysis), 3D unsymmetrical geometry and discretization, highly nonlinear material models (hyperelasticity, plastic kinematic formulation, crushable foam) and sophisticated contact models (bodies with highly different stiffness). The use of a highly compressible crushable foam material model for an arterial plaque is considered as the most original part of the work. The presented results allow for better understanding of the mechanisms governing stent crimping and implementation.

1. Introduction

Heart diseases are a leading cause of hospitalization and death in developed countries (33% of all deaths in 2011). Percutaneous coronary intervention (PCI), is a non-surgical procedure used to treat the stenotic coronary arteries of the heart found in coronary heart disease. It has revolutionized the treatment of ischemic heart diseases (heart attack and angina) over the past 20 years [1]. A cardiologist feeds a deflated balloon on a catheter from the inguinal femoral artery or radial artery until they reach the site of a blockage in the heart. At the blockage, the balloon is inflated to open the artery, allowing blood to flow. A stent is often placed at the site of the blockage to open the artery permanently.

The use of angioplasty has increased rapidly since 1990 in most of OECD33 countries, overtaking coronary bypass surgery as the preferred method of revascularization around the mid-1990s – when the first published trials of the efficacy of coronary stenting appeared. On average, across OECD33 countries, angioplasty now accounts for 78% of all revascularization procedures (with average ratio of 180 procedures per

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100,000 population). Germany (350 procedures per 100,000 population), Israel, Norway, Netherlands, Belgium had the highest rates of angioplasty in 2011. Poland is close to the average with 125 coronary angioplasty per 100,000 population [1].

Presently, significant scientific efforts are being made in the field of stents biocompatibility as well as drug eluting applications and biodegradable coronary stents [2–5].

Computer Aided Engineering (CAE) is a branch of scientific expertise, which seems to be especially useful in biomedical engineering. In particular, analyses performed using various numerical methods. With an advanced finite element approach it is possible to simulate non-linear problems, characterized by high displacements and deformations, nonlinear material properties and sophisticated contact mechanisms [6]. The relative low cost of such research methods compared to experiments in vivo (Latin for "within the living") should also be noted [7]. The applied methods also allowed determination of values obtaining of which, using empirical tests, would be extremely difficult or even impossible (e.g., the stress or strain rate in specific areas of the model).

Numerical investigation of the inflation process of angioplasty balloons and stents in the coronary arteries using FEA were performed on several occasions and it is impossible to include them all in this short paper. Some of them tackle the problem of the stent and balloon interaction [8–10]. There is also a separate group of papers that describe research on stress distribution in the artery tissue caused by the inflating balloons and stent surfaces in the configuration: balloon – coronary stent – coronary artery [11–15].

The literature review carried out by the authors suggests that there are no papers in which the modeling methodology of balloon angioplasty with minimum simplifications is accurately described. Moreover, processes of stent crimping and further inflation are treated separately, which is an essential error in the authors' opinion due to residual stresses and kinematic hardening issues. These insights and the remarks presented earlier were a direct cause to undertake the issue described in the paper. In the work, the authors focused on numerical analysis of the whole stent crimping and implantation process in the coronary artery stenosis with the use of a non-compliant balloon.

It is crucial to conduct extensive numerical studies in the field of biomedical engineering, which may contribute to the development of new medical equipment and technologies. The authors believe that due to complex geometry of studied structures, sophisticated nonlinear material properties of tissues, CAE numerical analyses are often the only way to simulate the behavior of such complex systems.

2. Materials and methods

This chapter is focused on the modeling metodology of the undertaken issue.

2.1. Angioplasty balloon

It was decided to model the high pressure, non-compliant angioplasty balloon geometry in a preliminary compressed form (3-wing configuration) (Fig. 1). Discretization was based on 207,000 4-node 2D elements formulated as fully integrated shell elements, with thickness of 0.02 mm. The following dimensions for the balloon were chosen: body length: 10 mm; total length: 15 mm; inflated balloon diameter: 3 mm; compressed balloon diameter: 1 mm. The balloon material model was based on the Hooke's theory of elasticity, as in many similar works [9,11,14] with the constants listed in Table 1.

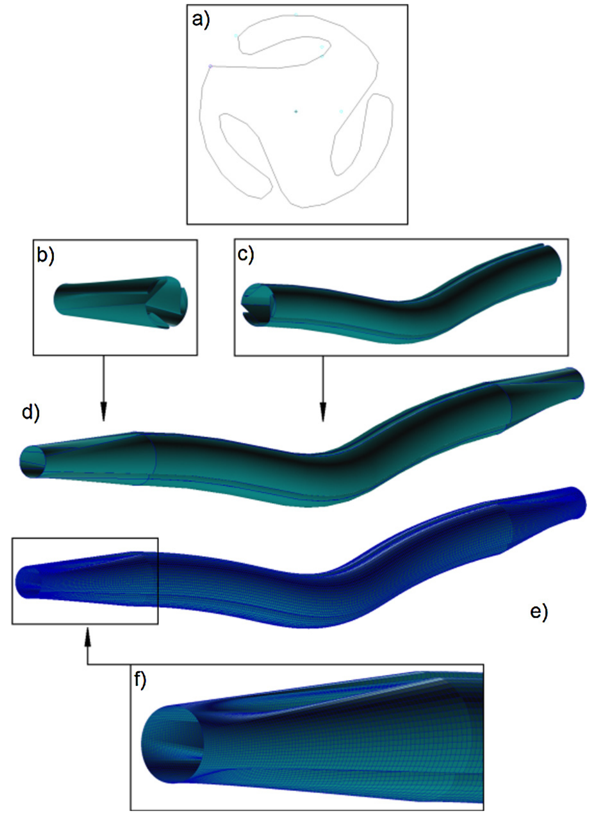

Fig. 1 – Angioplasty non-compliant balloon model (FE).

2.2. Coronary stent

A classic cylindrical stent with 13 repeatable segments (rings) (Fig. 2) was taken into consideration. Dimensions: total length: 8 mm; expanded diameter: 3 mm; compressed diameter: about 1 mm. Discretization was based on 327,520 8-node 3D hexahedron elements. In this case, the elements were formulated as constant stress solid elements (one-point integration).

The constitutive model of the stent material was based on plastic kinematic formulation, with the given constants (Table 2). In the kinematic hardening scheme, the von Mises yield surface does not change in size or shape, however, the center of the yield surface can move in the stress space (the Bauschinger effect).

2.3. Coronary artery fragment

The model of the coronary artery fragment was developed as a composition of the vessel wall and the plaque (in the stenosis