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Experimental and numerical analysis of urological stents

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ABSTRACT

Purpose: In order to evaluate the characteristic changes of the stents' diameters in function of the elongation (during elastic expansion) the biomechanical tests were carried out. The numerical analysis of the selected forms of urological stents was performed. The numerical results were compared with the experimental ones.

Design/methodology/approach: The urethral stent commonly used in clinical practice was analyzed. Two types of research were carried out: experimental – in order to determine the displacement characteristic of the stent, and numerical (by means of the finite element method) – in order to evaluate stresses and strains in the stent.
Findings: The comperative analysis of the obtained experimantal and numerical results showed good correlation, that proves the proper selection of the modeling conditions, and boundary conditions adequate to the real object.
Research limitations/implications: The limitations were connected with the necessity of simplifications applied to the numerical model of the urological stent, and also with the difficulties caused by the established boundary conditions.

Practical implications: The self-expanding stents analyzed in the work are implants for which the change of the diameter causes the significant change of the length. Due to the fact, the very important issue during implantation of this type of stent is the appropriate positioning in the narrowed part of urethra. The worked out characteristics allows to determine the length of the implant for the given diameter.

Originality/value: The work presents the dispacement characteristics of the stent obtained on the basis of the experimental and numerical tests. The correlation of the obtained results is also presented.

Keywords: Numerical techniques; Biomechanical analysis

METHODOLOGY OF RESEARCH AND ANALYSIS AND MODELLING

1. Introduction

In recent years the significant increase in development of treatment with the use of minimally invasive techniques is observed. The development of endoscopic procedures is connected with the development of both laparoscopic tools and new form of implants called stents intended for treatment of strictures in a circulatory, a digestive, an airways and a urogenital system [1-6].

The individual types of stents should have diverse forms and geometrical features as well as elastic properties. Physiochemical properties of stents' surfaces should be characterized by good biocompatibility, i.e. they must be "adjusted" to reactivity of surrounding tissues and physiological fluids [7-12].

Issues of stents usage properties forming should be considered on different levels of structures and processes of biological reality. It enables a detailed selection of mechanical properties of applied biomaterials and stents' forms as well as physiochemical properties of their surfaces. This assures the reconstruction success and postoperational complications [13-15].

Issues of stents usage properties forming are quite complex and should be considered in terms of interdisciplinary research in fields of biomaterials and surface engineering as well as biomechanics and medical physics.

2. Material and methods

In the experimental research the inter-urethral stents (American Medical Systems) were applied. The stents were supplied by the manufacturer in the special implantation tool. The device allow to expand the stent in a narrowed part of a urethra – fig. 1.

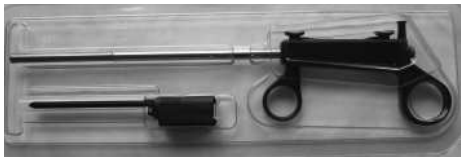

Fig. 1. Stent's delivery tool

The applied releasing mechanism allowed to fully expand the stent (elastic properties of the metallic biomaterial were used). The expansion of the stent was realized by the removal of the clamping sleeve. The initial diameter of the stent was equal to ϕ_0 = 6 mm. After expansion the diameter was ϕ_1 = 14 mm. The length of the stents used in the experimental analysis was equal to l_1 = 40 mm.

The geometrical model of the self-expanding urological stent was analyzed with the use of the finite element method – fig. 2.

- Length of the stent l_s = 40,00 mm,
- Outer diameter of the stent ϕ_{zs} = 14,00 mm,
- Diameter of the wire the stent is made of ϕ_d = 0,15 mm.

The stent consisted of 24 wires: 12 dextrorsal and 12 sinistrorsal, placed alternately with the step 15°.

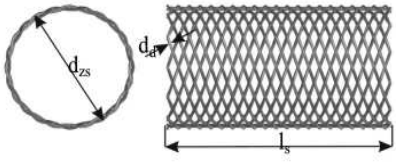

Fig. 2. The model of the urological stent used in the FEM analysis

Mechanical properties of a stainless steel (AISI 316LVM), a cobalt alloy (L605) and a Ni-Ti alloy (superelstic) were assumed in order to carry out the analysis – table 1.

Table 1.
Mechanical properties of biomaterials [16-19]

Biomaterials	Young's modulus E, MPa	Poisson's ratio, ν	UTS, MPa	YS, MPa
Cr-Ni-Mo (AISI 316LVM)	200 000	0,33	860	690
Co-Cu-W-Ni (L605)	221 000	0,33	950	680
Ni-Ti	70 000	0,33	1150	400

On the basis of the geometrical models a finite element mesh was generated. The meshing was realized with the use of theSOLID186 element – fig. 3. This element allows to take into consideration physical nonlinearities and large displacements. Next, boundary conditions were established.

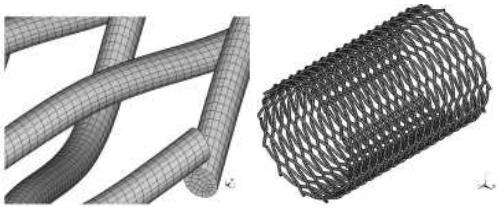

Fig. 3. Discrete model of the urological stent used in the FEM analysis

3. Results

3.1. Results of experimental analysis

The biomechanical tests were carried out in order to determine the characteristic changes of the stents' diameters versus the elongation during elastic expansion. The fig. 4 presents stages of the expansion. 9 stages of the expansion were set (displacement step of the sleeve was equal to 10 mm).

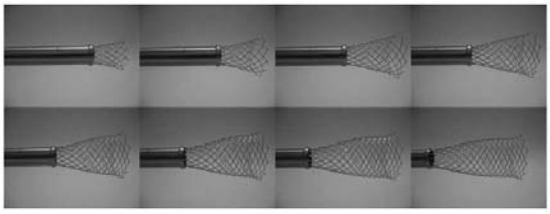

Fig. 4. Stages of stent expansion

The analysis of the free expansion revealed that the stents reach the nominal diameter ϕ = 14 mm gradually. It was also observed that the shortening of the stent in the first stage of the expansion was lower. The high shortening was observed after the full expansion. The obtained results were presented in table 2.

In the case the stent was expanded on the whole length simultaneously, the shortening would be proportional to the reached diameter. Therefore, the obtained characteristics was considered as linear. The nonlinear change of the geometrical features during the expansion was connected with the construction of the analyzed implant.

The change of the diameter versus the elongation was presented in fig. 5.

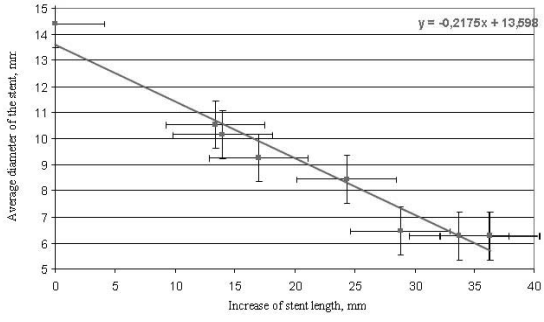

Fig. 5. Changes of stents diameter in function of increase of stent length

Table 2.
Results of experimental analysis

Stage of expansion	Stent length, l_n, mm	Increase of stent length, Δl_n, mm	Stent diameter ϕ_n, mm	Length of expanded end of the stent, $l_{max\ exp\ n}$, mm	% of length for max diameter of stent = 14 mm, $l_{\phi max\ n}$ %	% of length for max diameter of stent = 6 mm, $l_{\phi minx\ n}$ %	Avarage diameter of stent $\phi_{śr\ n}$, mm
1	76,30	36,30	6,26	-	0,00	100,00	6,26
2	76,28	36,28	6,72	-	0,00	100,00	6,26
3	73,70	33,70	11,92	-	0,00	100,00	6,26
4	68,80	28,80	14,40	1,00	2,50	97,50	6,46
5	64,33	24,33	14,40	10,96	27,00	73,00	8,45
6	57,00	17,00	14,40	15,05	37,00	63,00	9,27
7	54,00	14,00	14,40	19,56	48,00	52,00	10,16
8	53,40	13,40	14,40	21,41	53,00	47,00	10,54
9	40,00	0,00	14,40	40,00	100,00	0,00	14,40

3.2. Results of FEM analysis

The obtained displacements, strains and stresses are the reduced values according to the Huber-Mises-Henck hypothesis. The obtained results were presented in tables as well as in the graphic form.

Table 3.
Results of FRM analysis

Established radial displacement Δr, mm	Diameter after compression d, mm	Increase of stent length Δl, mm	Strain $\varepsilon_{r\ red}$, %
-0,50	13,00	8,08	0,47 ÷ 1,03
-1,00	12,00	14,64	0,87 ÷ 1,98
-1,50	11,00	20,03	1,20 ÷ 2,85
-2,00	10,00	24,55	1,51 ÷ 3,67
-2,50	9,00	28,35	1,80 ÷ 4,46
-3,00	8,00	31,56	2,07 ÷ 5,22
-3,50	7,00	34,25	2,33 ÷ 5,96
-4,00	6,00	36,47	2,59 ÷ 6,67

Camping of the stent from the diameter $\phi_0 = 14{,}0$ mm up to $\phi_1 = 6{,}0$ mm, enabling the insertion to the implantation device, was the first stage of the analysis. The calculation were realized in the displacement manner (change of the stent radius from $r_0 = 7{,}0$ mm to $r_1 = 3{,}0$ mm. The change of the radius was realized by displacement in the x direction equal to -4 mm in the cylindrical coordination system.

The results for the given boundary conditions were presented in table 3 and fig. 6 and 7.

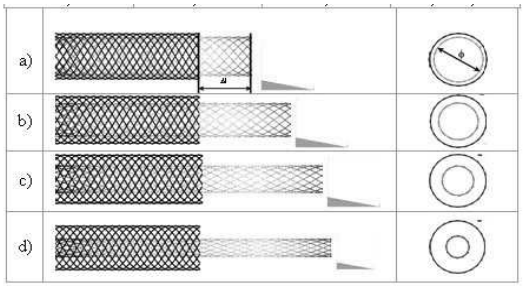

Fig. 6. Increase of stent length: a) ϕ = 12 mm, Δl = 14,46 mm , b) ϕ = 10 mm, Δl = 24,55 mm, c) ϕ = 8 mm, Δl = 31,56 mm, d) ϕ = 6 mm, Δl = 36,47 mm

The maximum reduced strains were observed for the maximum clamping of the stent and were the same for all the selected biomaterials and were equal to $\varepsilon_{red\ max} = 6{,}67\%$ – fig. 7.

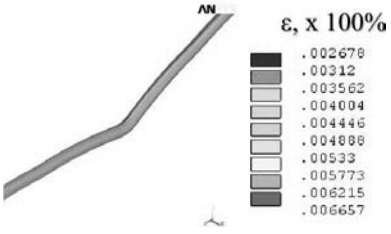

Fig. 7. Strains distribution in the wire of the stent

3.3. Comparison of experimental and FEM analsis results

The biomechanical characteristics of the urological stents obtained with the use of the finite element method showed good correlation with the experimental results – fig. 8. The obtained results were approximated by linear equations to ensure the proportional increase of the length (during clamping) with respect to the final diameter. For the numerical model, both the design of the model reflecting the real object and the appropriate boundary conditions, allowed to simulate the phenomena that occur during implantation, ei. increase of the diameter in function of the shortening of the stent.

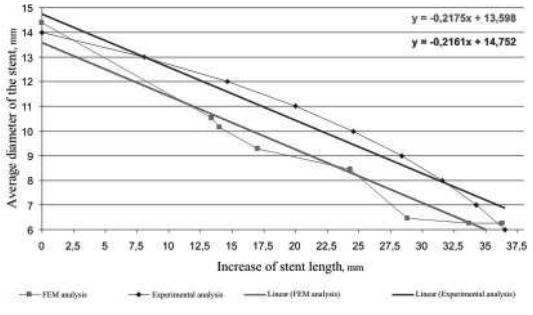

Fig. 8. Comparison of experimental and FEM analysis results

4. Conclusions

The commonly used geometrical form of the urethral stent was applied in the biomechanical analysis. This type of stent is a self-expanding implant. A self-expansion of the stent is realized by appropriate mechanical properties of the metallic biomaterial. This biomaterial should show good elastic properties.

The biomechanical characteristics was determined in order to calculate the diameter of the stent in function of the shortening during expansion. For this type of implant the change of the diameter is correlated with the significant change of the length. Due to this fact, the appropriate positioning of the stent in the narrowed part of urethra seems to be very important. The obtained characteristics allowed to determine the length of the stent for the given diameter (other than the final diameter). The obtained characteristics was approximated with the linear equation. Nonlinearities in the diameter range 14 mm to 6 mm are caused by the geometry of the stent.

The next stage of research was the numerical analysis with the use of the finite element method by means of the ANSYS. For the given geometry of the urethral stent, the strain and stress state was calculated with the use of the Huber-Mises-Henck hypothesis.

Furthermore, the comparative analysis of the results obtained from the numerical model and the real object was carried out. The aim of the comparative analysis was the verification of the established geometrical model and boundary conditions. In spite of the applied simplifications it seems that the numerical analysis with the use of the finite element method was purposeful. It is shown by the good correlation of the displacement results obtained from the experimental and the numerical analysis.

The obtained results are preliminary and constitute the initial stage for the numerical analysis of a stent – urethra cooperation. In this analysis displacements, strains and reduced stresses will be calculated.

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