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Physicochemical properties of fixation plates used in funnel chest treatment

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Materials

ABSTRACT

Purpose: The paper presents physicochemical properties and biomechanical analysis of fixation plates made of Cr-Ni-Mo stainless steel used in the funnel chest treatment.

Design/methodology/approach: The corrosion tests were realized by recording of anodic polarization curves with the use of the potentiodynamic method. The VoltaLab® PGP 201 system for electrochemical tests was applied. The numerical analysis was performed for: the stabilizer of 460 mm length, 16 mm width and 4.5 mm thickness, the stabilizer of 460 mm length, 16 mm width and 3.5 mm thickness, the stabilizer of 460 mm length, 16 mm width and 2.5 mm thickness.

Findings: The tests showed that structure of the steel the plates were made of, met the PN-ISO 5832-1 standard. The surface damage is induced in the given deformation regions and is a potential reason of corrosion. The numerical analysis shows that stresses in plates didn't exceed the yield point: for the stainless steel $Rp_{0,2min}$ = 590 MPa. Values of maximum displacements occuring in the stabilizing bar in the range of clinically acceptable displacements.

Research limitations/implications: The obtained results are the basis for the optimization of physicochemical and mechanical properties of the metallic biomaterial.

Practical implications: On the basis of the obtained results it can be stated that that stainless steel can be applied in the funnel chest treatment.

Originality/value: The paper presents the influence of surface damage and stresses and displacement of plates used in the funnel chest treatment on the corrosion resistance.

Keywords: Metallic alloys; Biomaterials; Corrosion; Numerical techniques

1. Introduction

Funnel chest (pectus excavatum) is backwards deformation of a corpus of sternum and forward deformation of an ensiform process – fig. 1. Costicartilages are deformed and too long. Occurrence of this defect is about 2% but surgical treatment is necessary for about 25% of patients. This type of deformation is almost 2 times frequent in boys than girls [1÷3].

In 1998 Donald Nuss introduced a new, minimally invasive technique of funnel chest treatment. A gist of the method is based on the assumption that for adults with chronic pulmonary emphysema, chest is barrel-shape deformed.

In the Nuss'es method, before operation a chest between midaxillary lines must be measured in order to select an appropriate implantation plate. The technique consists of the following operations [2÷5]:

- general anaesthesia with endotracheal intubation and epidural anaesthesia,
- administration of an antibiotic while anaesthesia with 48 hours continuation after operation,
- placement of patient with hand abduced on the shoulder line,
- selection of the proper length of the fixation plate and appropriate bent,
- determination of auxiliary points on chest,
- incision of skin,
- insertion of thoracoscope,
- insertion of clamp,
- insertion of bent plate,
- reversion of the plate (180˚) and correction of deformation.


a) b)

Fig. 1. Pectus excavatum: a) front view, b) side view [3]

Short hospitalization time and good temporary cosmetic result are doubtless advantages of this minimally invasive treatment of funnel chest.

In the Nuss's method bones are not resected or intersected. Correction of deformation is realized by the growth of ribs along the fixation plate. It concerns especially small children (3-8 years). For adults the better cosmetic result can be obtained but there are serious difficulties in deformation of chest (costochondral hardening). Antalgic administration (up to 5 days after operation) is required for patients due to severe pain.

The most popular metallic biomaterial used for this type of implants is austenitic Cr-Ni-Mo stainless steel. These steels are also used in orthopaedic surgery, stomatology (fixation plates, spinal implants, intramedullary nails, maxillofacial plates) [6÷8], operative cardiology (coronary and vascular stents), urology (urethral and ureteral stents) [9÷12].

The aim of this work were both a physiochemical characteristic of plates fixating funnel chest after implantation and analysis of stress and displacement distribution in the plates while their anatomical loading.

2. Materials and methods

The first stage of research was a biomechanical analysis of the fixation plates in conditions of anatomical loading.

The finite element method was applied to calculate stresses and displacements in the stabilizing bar. The analyses were performed for:

- the stabilizer of 460 mm length, 16 mm width and 4.5 mm thickness,
- the stabilizer of 460 mm length, 16 mm width and 3.5 mm thickness,
- the stabilizer of 460 mm length, 16 mm width and 2.5 mm thickness.

Bone screws were used to fix the stabilizer to the ribs.

The first part of the work was the creation of physical models of the stabilizing bar. On the basis of this a computational models were determined – fig. 2. The meshing was performed with the use of SOLID 45 finite elements. This type of element is used for the three-dimensional modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions [13]. The following boundary conditions were set:

- the outer plane of the bar was loaded with the force directed inward – the sternum reaction,
- forces which were directed towards the bar didn't cause its displacements while changes of the air pressure in lungs,
- the degrees of freedom were taken away in the way reflecting the displacement of the real object,
- the bar was loaded with the maximum force which didn't cause the exceeding of the metallic biomaterial yield stress ($R_{p0,2} = 590$ MPa).

The following material properties were set:

- Young modulus $E = 2.355 \cdot 10^5$ MPa,
- Poisson's ratio $\nu = 0.3$.

All calculations were performed with the use of the finite element method in the ANSYS 5.7 program.

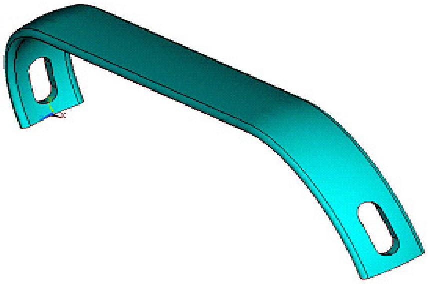

Fig. 2. The geometrical model of the bar used for the chest stabilization

In the second stage of the research 50 plates after implantation were selected. All the plates were made of the AISI 316 LVM stainless steel. The chemical composition meets the PN ISO 5832-1 standard [14]. In order to check the amount of non-metallic inclusions and grain size, additional metallographic and microscopic tests were carried out.

Another stage of the research was the evaluation of mechanical damage caused by bending of the plate to the anatomical curvature of chest. Reactivity of implants in body environment is generally determined by corrosion resistance of metallic biomaterial. Corrosion resistance is correlated with a biocompatibility. Good biocompatibility is observed for metals and alloys with high anodic potentials [15]. Therefore, for the selected plates, pitting corrosion tests were carried out.

The corrosion resistance tests of the samples were performed with the use of the potentiodynamic tests (VoltaLab, type PGP 201). Anodic polarization curves were registred with the use of measuring set consisting of:

- potentiostat with generator,
- reference electrode – saturated calomel electrode (SCE),
- auxiliary electrode – platinum electrode,
- working electrode – speciment tested,
- PC computer with special software.

The test consisted in the recording of the anodic polarization curves. Before the tests the samples were cleaned with the ethyl alcohol in the ultrasound washer. The tests were performed in the Tyrode's physiological solution [16], at the temperature of 37±1ºC and pH = 6.8 ÷ 7.4. Measurements started after the corrosive potential had been established, which took place after about 60 minutes. The change of the potential rate was equal to 1 mV/s.

3. Results

3.1. Results of biomechanical analysis

The stress analysis has shown that maximum stresses are located in the place where the bar sticks to the sternum. The stresses reached the permissible value 590 MPa. The maximum forces affecting the bar depending on its thickness are presented in the table 1.

Table 1.
The maximum forces affecting the bar depending on its thickness

No	Bar thickness, mm	Force, N	Stress, MPa	Displacement, mm
1	4.5	1025	590	1.06
2	3.5	870	590	1.4
3	2.5	340	590	2.2

A sample stress distribution for the bar of 4.5 mm thickness is presented in (applied force 1025 N).

For the bar model of 2.5 mm thickness maximum displacements (2.2 mm) were located in the place where the bar sticks to the sternum. However the minimum displacements were present in the bar of 4.5 mm thickness and were equal to 1.07 mm – fig. 3, table 1.

3.2. Results of non-metallic inclusions test

Non-metallic inclusions didn't exceed the pattern number equal to 1.5 which according to the ISO 4967-1997 (E) standard [17] is the limit value.

3.3. Results of structure analysis

Structure of the tested stainless steel consisted of deformed austenite with numerous slip bands. The grain size met the PN – ISO 5832-1 standard and was equal to the pattern number G=11.

3.4. Analyses of surface damage

Microscopic observations of implant surfaces showed mechanical damage. Numerous, deep scratches appeared as the result of fitting of the plates to the anatomical curvature of chest with the use of the surgical tool.

The most damaged surface was observed in the middle part of the plates (outer side) as well as at the ends (holes) – fig. 3. The damage were similar for all the plates. These regions are the most subjected to interference of surgical tools damaging the passive layer that cause the decrease of the corrosion resistance of implants. These regions were selected for corrosion tests. Obtained results were compared with non-damaged surfaces.

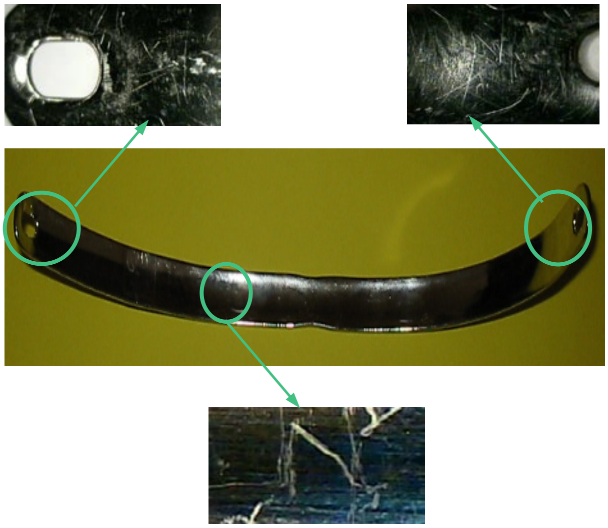

Fig. 3. Plate with the surface damage

3.5. Results of pitting corrosion resistance

The corrosion tests revealed no significant differences in breakdown potentials for the selected plates. Anodic polarization curves, corrosion potentials, breakdown and repassivation potentials, polarization resistance and the degree of rusting were presented in the table 2. The highest mass losses were measured for the plate with the highest value of the breakdown potential. Comparison tests of the plates in the initial state showed that breakdown potentials were in the range E_B = +1180 ÷ +1220 mV, that indicated on the wide passive range. The plates after implantation were characterized by lower breakdown potentials E_B = +464 ÷ +579 mV, that indicated the presence of the pitting corrosion.

Table 2.
Results of research on the pitting corrosion resistance

Material	Sample	Corrosion potential E_{corr}, mV	Breakdown potential $E_{B,}$ mV	Repassivation potential E_{cp},mV	Average polarization resistance $R_{p\ av}$, kΩcm^2	Degree of rusting C, mm/year
Cr-Ni-Mo type D	electropolished and passivated	-85 ÷ +21	+1180 ÷ +1220	0 ÷ +75	837	-
	1	+ 6	+464	-20	702	335
	2	+26	+579	-	909	400
	3	+13	+547	-97	1370	232

4. Conclusions

On the basis of the performed stress and displacement analyses of the stabilizing bar it can be stated that:

- maximum stresses occuring in the bar can not exceed 590 MPa, which is equal to the force affecting the bar in the place where it sticks to the sternum – 1025 N for the bar of 4.5 mm thickness, 840 N for the bar of 3.5 mm thickness and 340 N (bar thickness 2.5 mm),
- values of maximum displacements occuring in the stabilizing bar are the range of clinically acceptable displacements.

The tests showed that the structure of the steel the plates were made of, met the PN-ISO 5832-1 standard. The surface damage is mostly mechanical. The damage is induced in the given deformation regions and is a potential reason of corrosion. Corrosion products can cause immuno- and allergic reactions. The mechanical damage causes the decrease of the corrosion potentials of the metallic biomaterial that causes the increase of metalosis risk of.

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