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Modelling and Analysis of the Circumferential Forces and Susceptibility of Vascular Prostheses to Internal Pressure Changes

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Abstract

Based on Laplace's law and the mechanical characteristics of knitted vascular prostheses, mathematical models have been developed enabling one to determine the values of the relative circumferential elongation, circumferential forces and standard circumferential susceptibility of a prosthesis as a function of its diameter and internal pressure. The results obtained refer to the values of the parameters assessed for the initial phase of their exploitation, allow to preliminarily predict the values of these parameters.

Key words: *knitted fabric, vascular prostheses, Laplace's low, pressure, circumferential susceptibility, circumferential forces, standard circumferential susceptibility.*

Introduction

The circumferential susceptibility of vascular prostheses to internal pressure changes is one of their most important parameters [1]. Studies on this subject have been carried out both *in vivo* [2 - 9] and *in vitro* [10 - 12]. From literature data [3] it follows that the circumferential elongation (circumferential susceptibility) of vascular prostheses under the trade name Geseal®, estimated *in vivo* by the technique of computer tomography, shows a value over 30% after two years of its exploitation. On the other hand, the value of circumferential susceptibility of Gelweave® woven prostheses after two years of exploitation was lower by more than four times, which is due, first of all, to the different structures of knitted and woven fabrics. Knitted fabrics are characterized by a higher susceptibility to the action of tensile forces because of higher values of the thread knitting-in coefficients per structure unit [13, 14].

The circumferential elongation tests of Dallton H 8 knitted vascular prostheses *in vitro* [11, 12] showed lower values of this parameter than those reported in papers [3]. This is shown in ***Figure 1***, illustrating test results for a knitted prosthesis with a diameter of D = 0.971 cm, subjected to dynamic changes in internal pressure ranging from 80 to 120 mm Hg at a strain frequency of 50 Hz for a period of 69 days of consecutive hours, which corresponds to about 300 million work cycles. Lower circumferential elongation values *in vitro* result, among others, from the lack of the effects of biochemical processes on the thread matter occurring *in vivo*.

The aim of this study is to model and analyze the circumferential elongation and forces of knitted vascular prostheses depending on the values of their internal pressure and diameter. The results obtained from these analyses refer to the values of the parameters assessed for the initial phase of their exploitation and will allow preliminary prediction of the values of these parameters.

Application of Laplace's law to modelling vascular prostheses

For the considerations Laplace's law was used, which determines the relation between the pressure *P* generated by a fluid flowing through a vessel with a specified radius *R* and circumferential forces *F* per length unit in its walls. This law is shown in ***Figure 2***.

$$P = \frac{F}{s \cdot R} = \frac{2 \cdot F}{s \cdot D} \qquad (1)$$

where:
- *P* - unit pressure in hPa,
- *F* - circumferential force in cN
- *R* - radius of the diameter *D* in cm of the prosthesis subjected to pressure *P*,
- *s* - length of the prosthesis section in cm.

The following assumptions were accepted in the considerations:
- The relation between the unit pressure and circumferential force is described by Laplace's dependence.
- The prosthesis circumference is accepted as circle.
- The effect of the prosthesis wall thickness is omitted in the considerations as its value is several times lower than that of the prosthesis diameter, g << D.

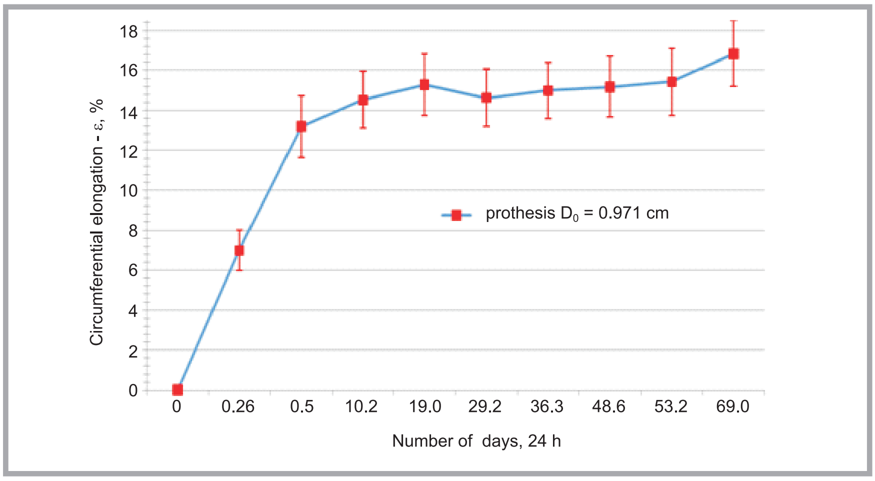

Figure 1. *Value of the circumferential elongation of a Dallon H vascular prosthesis [11, 12].*

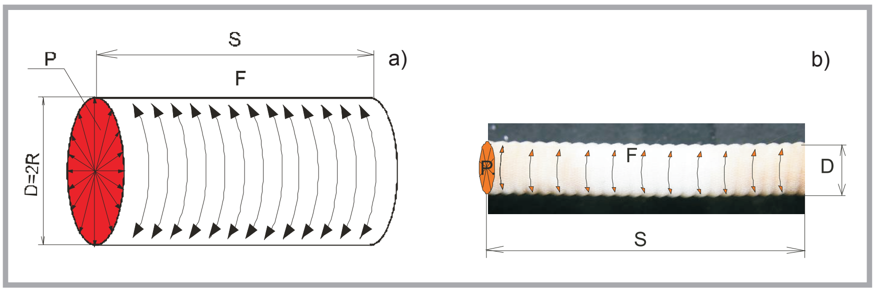

Figure 2. *a) Illustration of Laplace's law b) Photo of vascular prosthesis.*

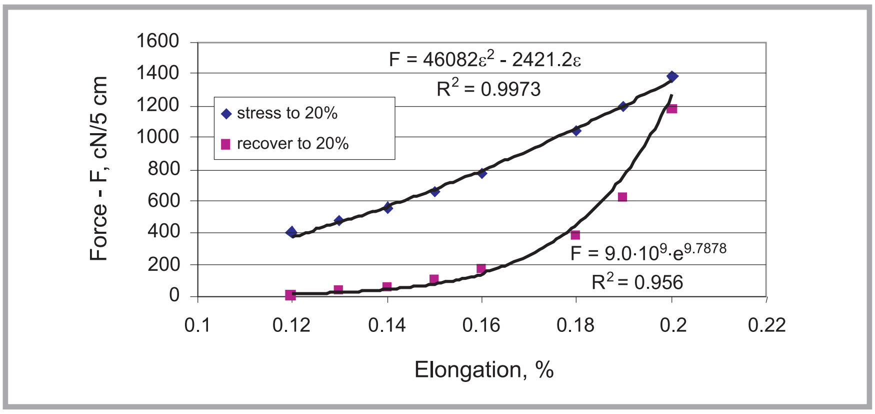

Figure 3. *Example of the relation between the elongation and force in the fifth cycle of hysteresis in the stress and elastic recovery phase at 20% elongation; test conditions: gripping width 5 cm, sample length 4 cm.*

Table 1. *Relationships between the circumferential force and elongation ε of the vascular prosthesis knitted fabric for the phase of stress and elastic recovery.*

Elongation. %	Stress		Elastic recovery	
5	$F = 5411.5\times\varepsilon$	$R^2 = 0.9966$	$F = 140507\times\varepsilon^2 - 3495.9\times\varepsilon$	$R^2 = 0.9736$
10	$F = 8726\times\varepsilon - 260.64$	$R^2 = 0.9970$	$F = 305715\times\varepsilon^2 - 37323\times\varepsilon + + 1171.4$	$R^2 = 0.9844$
20	$F = 46082\times\varepsilon^2 + -2421.2\times\varepsilon$	$R^2 = 0.9973$	$F = 9.0\times10^9\times\varepsilon^{9.7878}$	$R^2 = 0.9560$
30	$F = 1133032\times\varepsilon^2 + - 20651\times\varepsilon$	$R^2 = 0.9918$	$F = 1.0\times10^{11}\times\varepsilon^{14.584}$	$R^2 = 0.9976$

- The relation between the force and elongation of knitted fabric along the prosthesis circumference will be determined on the basis of experimental characteristics for the stress-strain phase of the knitted fabric in 5 hysteresis cycles and different ranges of its tension.

The modelling in question requires knowledge of mechanical characteristics of the knitted fabric used to make vascular prostheses. Mechanical characteristics tests were carried out with the use of unsealed Dallon H prosthesis knitted fabric. Dallon H vascular prostheses are made of a knitted fabric with the same structure for the whole range of their diameters.

Procedure of determining the mechanical characteristics of knitted fabric

It is a commonly known fact that textiles, including knitted fabrics, belong to bodies with visco-elastic properties. The value of the force as a function of the elongation in such a case depends on the force action time. Moreover, vascular prostheses are subjected to variable values of pressure, i.e. the upper and lower pressure values. Therefore, in tests, one should take into account the specificity of prosthesis exploitation conditions. The knitted fabric was subjected to mechanical conditioning in 5 cycles of tension and elastic recovery. Samples 5 cm in width and 4 cm in length were tested by means of an INSTRON tensile testing machine for a wide range of unit elongations, from 5 to 30% in separate tension cycles to 5, 10, 20 and 30% of elongation (***Figure 3***). Then for the stress and elastic recovery phase in the fifth cycle of the hysteresis loop, the force values measured and corresponding elongation values were used to determine the mechanical characteristics of the knitted fabric under investigation.

The relations between the force and elongation for the above-mentioned elongation ranges, 5 ÷ 30%, for the stress and elastic recovery phase are presented in ***Table 1***.

Moreover, the vascular prosthesis knitted fabric was characterised by the following mechanical parameters:

Tensile strength along courses (34.7 ± 6.9) N, determined according to our own test procedure, tensile strength along wales of a Dallon H prosthesis with a diameter of 0.971 cm (269 ± 10) N, determined according to PN-87/P-04884.04, pin disruptive strength (310 ± 20) N, determined according to ISO 7198:1998.

Model for the determination of circumferential elongations depending on the values of the prosthesis pressure and diameter

From the analysis of the mechanical characteristics of vascular prosthesis knitted fabric, it follows that, depending on the range of elongation, the relation between the force and elongation can be described with the following functions:

Linear function: $F = a\cdot\varepsilon + b$ (2)

Square function: $F = a\cdot\varepsilon^2 + b\varepsilon + c$ (3)

Power function: $F = a\cdot\varepsilon^b$ (4)

Solution for the linear function:

Substituting function (2) and dependence (5) of the prosthesis diameter (D) into ***Equation 1***:

$$D = D_0\cdot(\varepsilon + 1) \qquad (5)$$

we obtain ***Equation 6*** of the circumferential prosthesis elongation ε as a function of its diameter in a free state D_0, pressure P and mechanical characteristics of the knitted fabric (regression coefficients a and b).

$$\varepsilon = \frac{2\cdot b - P\cdot s\cdot D_0}{P\cdot s\cdot D_0 - 2\cdot a} \qquad (6)$$

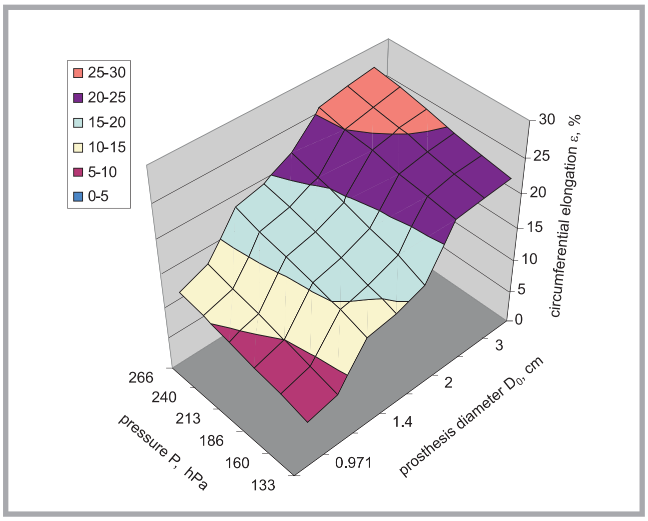

Figure 4. Effect of the prosthesis diameter D_0 and pressure P on the circumferential elongation ε.

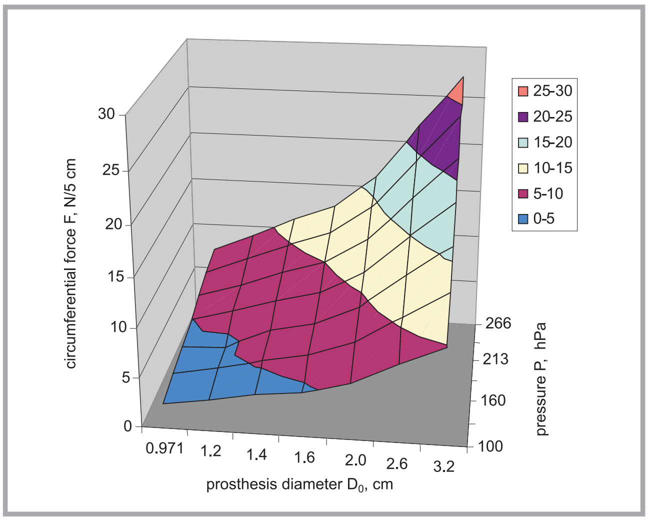

Figure 5. Effect of the prosthesis diameter D_0 and pressure P on the circumferential force F.

Solution for the square function:

Substituting function (3) and dependence (5) into ***Equation 1***, we obtain the following square equation:

$$2 \cdot a \cdot \varepsilon^2 + (2 \cdot b - P \cdot D_0 \cdot s) \cdot \varepsilon + \\ + 2 \cdot c - P \cdot D_0 \cdot s = 0 \qquad (7)$$

Calculation of the circumferential elongation as a function of parameters P and D_0 was made with the use of the computational tools of the Microsoft Office Excel program.

Solution for the power function:

Substituting function (4) and dependence (5) into ***Equation 1***, we obtain the following equation:

$$P = \frac{2 \cdot (a \cdot \varepsilon^b)}{D_0 \cdot s \cdot (\varepsilon + 1)} \qquad (8)$$

Calculation of the circumferential elongation as a function of parameters *P* and D_0 was made with the use of the Solver computational tools of the Microsoft Office Excel program.

Model for determination of circumferential longitudinal forces depending on the prosthesis pressure and diameter

After the transformation of ***Equation 1*** with respect to *F* and after taking into account dependence (5), we will obtain ***Equation 9***:

$$F = \frac{P \cdot D_0 \cdot s \cdot (\varepsilon + 1)}{2} \qquad (9)$$

The above dependences were used to determine the values of the circumferential elongation ε.

Model for determination of the standard circumferential susceptibility depending on the prosthesis pressure and diameter

According to ISO 7198, the circumferential susceptibility of the prosthesis can be calculated from the following formula:

$$\varepsilon_p = \frac{R_{P2} - R_{P1}}{R_{P1} \cdot (P_2 - P_1)} \cdot 10^4 \qquad (10)$$

where:

R_{P1} - radius of the prosthesis diameter under the lower pressure,
R_{P2} - radius of the prosthesis diameter under the upper pressure,
P_1 - lower pressure in mm Hg,
P_2 - upper pressure in mm Hg.

The circumferential susceptibility, calculated as above, is expressed as a percentage change in the diameter per 100 mm Hg.

The circumferential elongation ε_2 of the prosthesis under the upper pressure P_2 will be:

$$\varepsilon_2 = \frac{R_{P2} - R_0}{R_0} \qquad (11)$$

The circumferential elongation ε_1 of the prosthesis under the lower pressure P_1 will be:

$$\varepsilon_1 = \frac{R_{P1} - R_0}{R_0} \qquad (12)$$

After the transformation of ***Equations 11*** and ***12*** in relation to R_{P1} and R_{P2}, respectively, and substitution in ***Equations 10***, we will obtain:

$$\varepsilon_P = \frac{\varepsilon_2 - \varepsilon_1}{(\varepsilon_1 + 1) \cdot (P_2 - P_1)} \cdot 10^4 \qquad (13)$$

The values of circumferential elongations ε_1 and ε_2 were determined on the basis of the dependence derived above.

Analysis of modelling results of circumferential elongations of vascular prostheses depending on their pressure and diameter

As expected, the values of circumferential elongations of vascular prostheses increase with an increase in their pressure. The values of circumferential elongations shown in ***Figure 4*** were calculated by means of the dependences derived and experimental functions of the mechanical characteristics of the knitted fabric determined for the stress phase. For the pressure range used for calculations, *P* = 80 ÷ 200 mm Hg, i.e. (106.4 ÷ 266 hPa), the circumferential elongation of the prosthesis of diameter D_0 = 0.971 was increased by 54.6%, while that of the prosthesis of D_0 = 3.2 cm increased by 18.1%. The circumferential elongation values of the prosthesis of diameter D_0 = 3.2 cm are more than twice as high as those of the prosthesis of D_0 = 0.971 cm.

The results shown in ***Figure 4*** indicate that under conditions of statistically acting pressure inside the prosthesis, the greater the diameter of the prosthesis , the greater its circumferential elongation, indicating the higher circumferential susceptibility of prostheses with greater diameters. In order to maintain the circumferential susceptibility values of all the prosthesis diameters at a constant level within a constant internal pressure range, the prostheses should be characterised by increasing longitudinal rigidity with an

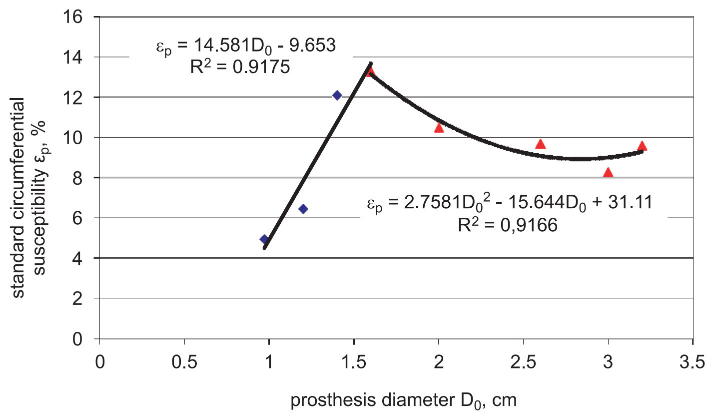

Figure 6. *Effect of the vascular prosthesis diameter on the standard circumferential susceptibility for the pressure range of P = 80 ÷ 120 mm Hg.*

increase in their diameters, which can be obtained by changing the type of stitches in the knitted fabrics used to make vascular prostheses.

Analysis of modelling results of circumferential longitudinal forces depending on the prosthesis pressure and diameter

In accordance with dependence (9), the value of circumferential force F increases linearly with an increase in pressure P. ***Figure 5*** (see page 89) shows the effect of pressure P and the vascular prosthesis diameter on the value of circumferential longitudinal forces. Within the pressure range of 100 ÷ 266 hPa, i.e. (80 ÷ 200 mm Hg), force F increases from 2.55 N to 7.17 N for the diameter D_0 = 0.971 cm.

For the prosthesis diameter D_0 = 3.2 cm, we obtained force F values ranging from 13.1 to 27.0 *N,* which means that they are higher than the computational values for the prosthesis of diameter D_0 = 0.971 cm and extreme values of pressure.

Similar qualitative dependences were observed for the effect of the prosthesis diameter D_0 on the value of the circumferential force under a higher pressure P.

The maximum values of the circumferential force F = 27 N/5 cm determined for the prosthesis diameter D_0 = 3.2 cm and pressure P = 266 hPa are almost 10 times lower than the tensile strength values of knitted fabrics.

Assessment of the standard circumferential susceptibility of vascular prostheses

The circumferential susceptibility calculated according to the ISO 7198 standard is expressed as the percentage of diameter change per 100 mm Hg. The calculation was carried out according to dependence (13) for the pressure range of 80 ÷ 120 mm Hg and prosthesis diameter range of 0.971 ÷ 3.2 cm. The results of the calculations are shown in ***Figure 6***. Within the diameter range D_0 = 0.971 ÷ 1.6 cm, the circumferential standard susceptibility increases from 4.97 % to 13.3 %, while within the diameter range D_0 = 1.6 ÷ 3.2 cm the value of circumferential susceptibility decreases to ε_p = 9.6%, which results from the mechanical characteristics of knitted fabric. The increasing value of pressure is accompanied by the knitted fabric's stressing phase, while during the cycle of decreasing pressure, the knitted fabric's destressing phase occurs. In the destressing phase, the great decreases in circumferential forces are accompanied by small changes in the values of circumferential elongation, which are greater, the larger the circumferential elongation is for the stressing phase. Therefore the values of circumferential susceptibility calculated per pressure unit and recalculated per 100 mm Hg decrease within a range of relatively higher values of vascular prosthesis diameters. Here it should be emphasised that the values of the standard circumferential susceptibility of vascular prostheses determined on the basis of Laplace's law and mechanical characteristics of knitted fabrics approximately refer to the conditions of the initial phase of prosthesis exploitation.

Summary and conclusions

Based on Laplace's law and the mechanical characteristics of vascular prosthesis knitted fabric, mathematical models have been developed enabling the determination of the circumferential elongation, circumferential forces and standard circumferential susceptibility of vascular prostheses as a function of their diameter and internal pressure. The analyses of the results obtained allow us to draw the following conclusions:

1. Values of the circumferential elongation of the vascular prosthesis increase with an increase in its diameter and internal pressure. For extreme values of the prosthesis diameter and pressure, the circumferential elongation reaches values close to 30%.
2. The value of the circumferential force F in the prosthesis walls increases linearly with an increase in pressure P. For the prosthesis diameter D_0 = 3.2 cm, the values of forces F range from 13.1 to 27.0 N/5 cm, being 5.13 to 3.8 times higher than computational values for the prosthesis with a diameter D_0 = 0.971 cm and extreme pressure values.
3. The maximum values of circumferential force F = 27 N/5 cm determined for the prosthesis diameter D_0 = 3.2 cm and pressure P = 200 mm Hg are almost 10 times lower than those of the prosthesis knitted fabric tensile strength determined.
4. In order to maintain the value of circumferential susceptibility at a constant level for all the prosthesis diameters within a constant range of internal pressure, the prostheses should be characterised by increasing the longitudinal rigidity with an increase in their diameter. This is feasible by changing the type of stitches of the knitted fabrics used to make vascular prostheses.

Acknowledgment

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CLO-2IN-TEX
Conference Summarising the Project

On the 5th March 2012, the Faculty of Material Technologies and Textile Design of the Technical University of Łódź held a conference on the topic of: DEVELOPMENT OF A RESEARCH INFRASTRUCTURE FOR INNOVATIVE TECHNIQUES AND TECHNOLOGIES OF THE TEXTILE-CLOTHING INDUSTRY. The Project was implemented from the resources of the Operational Programme Innovative Economy 2007-2013, within the framework of 2nd priority: R&D Infrastructure Development of Facilities with High Research Potential. (‘*Donations for Innovations*’).

The aim of the project was to create a research infrastructure that helps the Polish textile & clothing industry to support the development of innovative technologies. Thanks to the project realisation, modern technological and metrological laboratories were built. The development of metrological laboratories allowed to initiate a procedure of accreditation. Within the framework of the project, the laboratories of the following three departments were modernised: the Department of Knitting, the Department of Clothing Technology and Textronics, and the Department of Material and Commodity Science and Textile Metrology.

The effect of the Project was the introduction of radical innovations and a breakthrough in the Polish textile-clothing industry, transforming it from a traditional branch of the economy into an industry based on knowledge and modern technological solutions, as well as a move from mass production to individual, personalised multifunctional products of high quality and human-friendliness, protecting both health and life . Thanks to the project, the will be the possibility of tightening cooperation between science and industry, which should bring about an increase in the competitiveness of Polish companies, a rise in the number of new workplaces in the industry, and an improvement in the quality of life, health and human safety.

During the Conference, Prof. Ryszard Korycki, the Project’s Coordinator, summarised the achievements related to the development of laboratories. Afterwards the representatives of the Project’s Controlling Community – Professors Iwona Frydrych, Krzysztof Kowalski, Krzysztof Gniotek and Izabella Krucińska presented the achievement of their teams. Among the 80 guests who attended the Conference were representatives of provincial authorities, partner universities, sector institutes, high schools with a clothing profile and representatives of the textile & clothing industry. In the subsequent part of the ceremony, guests visited the modern laboratories developed.

Some of the equipment and apparatuses which the visitors could observe in action are listed below:

technological lines for processing different kinds of ready-made clothing, modelling systems with a 3D scanning camera for designing clothing, computer programmable flat weft knitting machines working with a CAD/CAM designing system for knitted products, thermal movable manikins with climatic chambers and equipment for testing comfort and radiation protection, metrological and physical property measuring apparatuses as tensile testers, Kawabata system, SEM and AFM microscopes, WAXC and SAX difractometers, among others.

The Total cost of the project amounted to 20,684,783.63 PLN, from which 85% was covered by the European Regional Development and 15% by National Public Funds. Funds assigned for buying and launching the apparatus and equipment amounted to 18,052,611.46 PLN.

On behalf of the team for promotion of the project

S. Sztajnowski Ph.D, Eng.

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