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Validation of computer models of an artificial hip joint

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ABSTRACT

Purpose: Problems of the modelling of the surgical cement behaviour during implantation have been presented in the paper. The purpose was to validate the FEM model describing the temperature fields in the bone during the surgery treatment.

Design/methodology/approach: The physical laboratory modelling has been used to perform validation of the model that makes it possible to predict the temperature influence on the bone tissue during polymerization process.

Findings: Due to its non-invasive nature, the computer models' validation method applied in the study seems to be the right solution for the research on surgical procedures of endoprosthesis implantation. However, a particular emphasis should be placed on a correct selection of thermophysical properties of the designed laboratory models. Relying on the calculations and research results, similar local values of maximum temperatures were obtained.

Practical implications: The computer modelling methods presented in the paper together with the analytical approach are of great importance to both forecasting the implants' behaviour during a surgical procedure and in their operational conditions, as well as in the selection and modification process of surgical cements' material properties. The analysis carried out makes it possible to determine the location of zones most threatened with an adverse effect of an elevated temperature. They are located in the vicinity of the top of the endoprosthesis stem.

Originality/value: The work presents the own method of validation of the FEM model used for heat flow modelling.

Keywords: Computer assistance in the engineering tasks and scientific research; Biomaterials; Reliability assessment; Computational material science

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Owing to the specificity of research on the phenomena taking place in human organism during surgical implanting procedures, interpretation of results of tests performed in laboratory conditions and results obtained through the application of analytical methods or computer modelling requires particular caution. In a number of cases, it is not possible to conduct clinical research, therefore, effectiveness of a given method of surgical procedure or introduction of a new biomaterial can be justified only based on in vitro experiments. The possibility of conducting mutually complementary studies, where the results of one study confirm the correctness of another study, becomes an issue of particular importance. This refers in particular to computer modelling methods of the physical phenomena which accompany surgical procedures. Usually, only a laboratory experiment is able to corroborate the correctness of the calculation method assumed in such case. There are frequently no physical quantities enabling the development of correct and accurate analytical or approximated computer models of the phenomena, such as FEM models [1-5]. In many cases, we take advantage of approximations resulting from tests on animals or in-vitro studies, or make an estimation of the necessary physical quantities in an indirect way, based on material properties measurements. Such situation is encountered when investigating the phenomena that take place during implantation of endoprostheses with the use of surgical cement. Aiming at a precise description of the requirements for a successful implantation with the application of surgical cement, while taking into account its material properties and the tissues' properties, the Department of Materials Mechanics' staff, Silesian University of Technology, have developed their own research methodology. The new methodology includes experimental methods of examining the physical properties of such biomaterials as surgical cements, as well as methods of modelling the heat flow phenomena in an analytical approach, and using finite element methods [4-6]. Also, a new method of determining the heat source intensity during surgical cement polymerization has been developed [5]. This methodology is supplemented with computer models' validation methods using laboratory models. The paper presents an example of validation of a computer model applied for an analysis of heat flow phenomena in an artificial hip joint with a cement endoprosthesis.

2. Computer model of a hip joint with an endoprosthetic stem

The aim of the study is experimental verification of the correctness of a computer model applied for the description of heat flow and heat generation phenomena in an artificial hip joint during an endoprosthesis implantation procedure. In the discussed case, the finite element method was applied using ALGOR software and the CAD Alibre Design program, the latter allowing to define the geometric features of the object under consideration. Three areas were distinguished in the model, each corresponding to the properties of the bone tissue, the cement and the endoprosthesis stem. The shape and dimensions of the implant model were assumed based on the properties of the selected cement endoprosthesis. Geometric features of the femoral bone were selected so as to correspond to the endoprosthesis size. The geometric features defined in the Alibre Design program were entered in the FEM program, in which a discrete model was created with the number of nodes equal 48724 (Fig. 1a).

Two types of boundary conditions were assumed. For the bone's outer surface and uncovered parts of the metal stem, a third-type boundary condition was prescribed, corresponding to convective heat exchange with the prescribed respective surface film conductance and ambient temperature. The internal heat source intensity value was determined based on experimental studies published in paper [5]. The thermophysical properties of the bone, cement and metal were prescribed on the basis of literature [7-10]. It was assumed that those properties were not temperature-dependent. An example of the model application for the determination of thermal field in the femoral bone with an endoprosthesis' stem is shown in Fig. 1c.

The described model approach was used to prepare a quantitative description of material requirements for adaptation of implants fixed with the use of surgical cement [5]. In the calculations, different cement amounts around the endoprosthesis' stem were assumed.

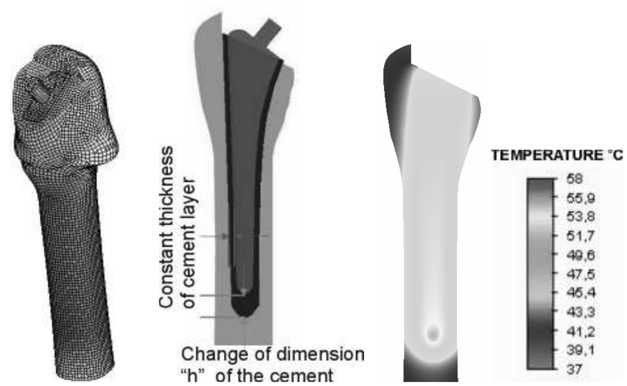

Fig. 1. FEM model of the bone-cement-stem system with a finite elements lattice – (a), its cross-section with shown components – (b) and an example of temperature distribution – (c)

3. Laboratory model

In the attempt to get to know better the bone tissue's thermal properties, a cast made of the Estromal 14LM-01 polyester resin was used, representing the cortical bone (Fig. 2). The cast had an opening for an endoprosthesis along with an allowance for a 3 mm thick cement layer around the endoprosthetic stem. The thermal conductivity coefficient λ for polyester resin amounts to 0.2 – 0.4 W/(m K) and in the bone, it varies between 0.26 and 0.60 W/(m K). The specific heat of polyester resin, c = 1200 – 2400 J/(kg K), is comparable to the bone's specific heat, which amounts to 1260 – 2370 J/(kg K). The resin density is also similar to the bone density: density of the resin fluctuates in the range of 1100 – 1400 kg/m^3, and density of the bone, in the range of 1000 – 2900 kg/m^3.

The cast was cut along the symmetry plane in order to precisely locate thermocouples. The thermocouples were glued in the upper, middle and lower parts of the bone's cast. For this purpose, holes of diameter 0.5 mm were bored, into which *K* type thermocouples with wires of a diameter of 0.22 mm were inserted. The thermocouples' measuring points were located right below the area where the cast and the cement met. In order to provide sufficient stability for the system, the cast was glued to the bottom of a cylindrical glass vessel, which was then filled with 37°C water, whose temperature was maintained by using a suitable thermostat-controlled heating system. After a uniform temperature distribution was achieved, the researchers proceeded to cement preparation. "Palamed" cement was manually stirred for 30 seconds, per manufacturer's instructions. In accordance with the instructions, 40.0g of a PMMA powder were combined with 20ml of a MMA liquid. After achieving a homogeneous substance, the cement was poured into the hole in the cast, then a stem was inserted in a process similar to a surgical implantation procedure, with temperature changes recorded using the Spider 8 computer system.

The courses of temperature changes in time were recorded. One of the temperature measurement point was located near the top where the cement layer was the thickest (Fig. 2a,3) and heat absorption by the metal stem was the least intense. The midpoint was located in an area where the cement layer thickness was uniform, of ca. 3 mm . Surrounding the flange, the cement thickness also was about. 3 mm. However, in that area, heat exchange with the metal endoprosthesis was more intense. The measurement results are presented in Figs 4 and 5. The temperature was recorded immediately after all components were mixed together to the moment when all experimental thermocouples displayed a temperature below 40°C. The measurement results corroborated the data from literature, showing high temperatures at the bone/cement contact surface as high as 57°C.

a) b)

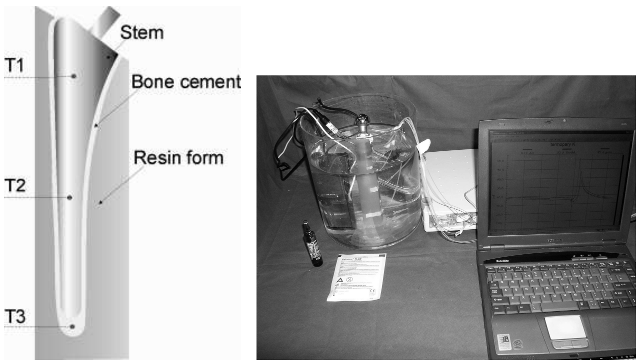

Fig. 2. Lateral cross-section of the laboratory model - (a) and test stand for measuring the surgical cements' polymerization temperature – (b)

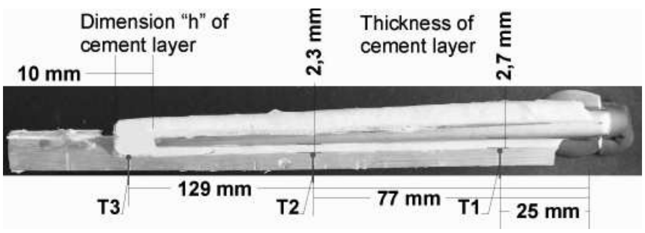

Fig. 3. Method of thermocouples arrangement in the laboratory model

Near the top, a maximum local temperature of 56°C was reached after 470 seconds from the stem implantation moment. After another 70 seconds, a maximum temperature of 48,7°C was reached in the middle part of the cortical bone model, where the cement layer thickness was 2.3 mm. 75 seconds later, in a measuring point near the flange, the temperature reached its maximum value of 42,4°C where the cement layer thickness was 2,7mm. Research shows that the nature of heating the laboratory model of bone tissue was similar to the course of projected temperature changes based on calculations made utilizing the finite element method (Fig. 5a). Figure 5b presents a comparison of maximum temperatures determined experimentally and calculated using the above-described laboratory model.

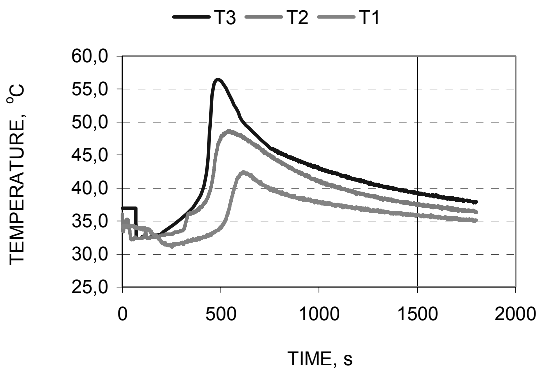

Fig. 4. Dependence of temperature on surgical cement polymerization time in the laboratory model

a) b)

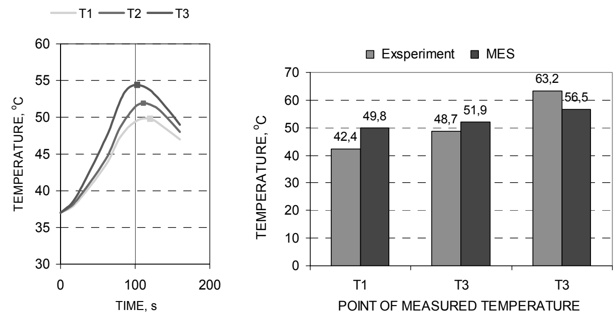

Fig. 5. Temperature dependence on the surgical cement polymerization time determined in a numerical model - (a); a comparison of maximum temperatures determined experimentally and calculated – (b)

The maximum temperatures were locally reached at varying times. Reaching maximum temperature took much longer for the laboratory model when compared to the time calculated using the computer model. The cause of these discrepancies could be find in the heat absorption coefficient values assumed for the calculations.

4. Conclusions

Due to its non-invasive nature, the computer models' validation method applied in the study seems to be the right solution for the research on surgical procedures of endoprosthesis implantation. However, a particular emphasis should be placed on a correct selection of thermophysical properties of the designed laboratory models. Relying on the calculations and research results, similar local values of maximum temperatures were obtained. The laboratory model applied for this study may constitute a proper basis for further approximations in the computer model. In any case, the physical constants assumed will be another estimate only, whose complete verification is not possible because of the object under consideration, where not only the tissues' properties, but also the flow of bodily fluids (including blood), and the metabolic processes in the tissues, determine the heat flow.

Despite its imperfection, the computer model developed and the investigations conducted in laboratory conditions enable the formulation of a number of conclusions which are of practical importance for surgeons performing procedures of endoprosthesis stem implantation with the use of cement. As results from the calculations made, one of the most important factors conducive to bone tissue destruction is the heating process concentration in some regions.

The surroundings of the endoprosthesis stem top should be regarded as a region particularly exposed to the destructive influence of an elevated temperature. In this region, the protein coagulation temperature is frequently exceeded. The size of the area where the bone tissue destruction takes place depends on the amount of cement located below the stem top. It would be therefore advisable that particular attention be paid during a surgical procedure to precise making of a hole for the stem to be implanted. A too deep hole may result in the bone tissue destruction throughout the femoral bone cross-section near the endoprosthesis stem. Before the tissue reconstruction takes place in that region, loading of the tissue may lead to mechanical injuries whose effects will add up to the long-term effects of the surgical procedure. The region under discussion is also a region under the highest effort, which results from the stresses distribution in the endoprosthesis' surroundings. Thus, the biological effects of excess temperature increase will overlap in that place during the implant's operation with the overload caused by stress concentration, the latter being induced by inhomogeneity of the mechanical properties and local pressures of a rigid stem top on the weakened bone tissue.

Where the surgeon is concerned about a too large amount of cement around the implant top, attention should be paid after the surgical procedure to the possible consequences of overloading the endoprosthesis shortly after the procedure and appropriate recommendations should be formulated for the patient regarding the method of imposing load on the treated joint and physical exercises. Thus, the computer modelling methods presented in the paper together with the analytical approach are of great importance to both forecasting the implants' behaviour during a surgical procedure and in their operational conditions, as well as in the selection and modification process of surgical cements' material properties. The physical laboratory models should constitute the main validation method for computer models.

The work presents only one of many aspect [11-15] of the biomaterials' influence on the phenomena taking place in organs with implants i.e. heat flow in the artificial hip joint with cements' fixation of the stem. In feature it will be necessary, for instance, take into account the interface layer properties and mechanical features of cement as the polymer with its typical creep behaviour [6, 11] or shrinkage of the material during the polymerisation process.

References

[1] C. Li, S. Kotha, C. Huang, J. Mason, D. Yakimicki, M. Hawkins, Finite element thermal analysis of bone cement for joint replacements, Journal of Biomechanical Engineering 125 (2003) 315-322.

[2] E. Hansen, Modelling heat transfer in a bone-cement-prosthesis system, Journal of Biomechanical Engineering 36 (2003) 787-795.

[3] M. Stańczyk, J.J. Telega, Modelling of heat transfer in biomechanics – a review. Part II. Orthopaedics, Acta of Bioengineering and Biomechanics 4/2 (2002) 3-31.

[4] J. Okrajni, S. Ziemba, J. Stumpf, Description of heat flow in a surgical cement layer, Acta of Bioengineering and Biomechanics 8/2 (2006) 135-142.

[5] J. Okrajni, M. Plaza, S. Ziemba, Computer modelling of heat flow in surgical cement during endoprosthesoplasty, Journal of Achievements in Materials and Manufacture Engineering 20 (2007) 313-314.

[6] A. Balin, G. Junak, Low-cycle fatigue of surgical cements, Journal of Achievements in Materials and Manufacture Engineering 20 (2007) 211-214.

[7] K. Iesaka, W.L. Jaffe, F.J. Kummer, Effects of preheating of hip prostheses on the stem-cement interface, Journal of Bone and Joint Surgery, 85-A/3 (2003) 421-427.

[8] C. Li, S. Schmidt, Effects of pre-cooling and pre-heating procedures on cement polymerization and thermal osteonecrosis in cemented hip replacements, Medical Engineering and Physics 25 (2003) 559-564.

[9] O. Rodop, et al., Effects of steam design and pre-cooling prostheses on the heat generated by bone cement in an in vitro model, The Journal of International Medical Research 30 (2002) 265-270.

[10] I. Knets, V. Krilova, R. Cimdins, L. Berzina, V. Vitins, Stiffness and strength of composite acrylic bone cements, Journal of Achievements in Materials and Manufacturing Engineering. 20 (2007) 135-138.

[11] D.W.A. Rees, Nutting creep in polymer composites, Journal of Materials Processing Technology 143-144 (2003) 164-170.

[12] P.J. Prendergast, S.A. Maher, Issues in pre-clinical testing of implants, Journal of Material Processing Technology 118/1-3 (2001) 337-342.

[13] M. Kaczmarek, Z. Paszenda, B. Duda, J. Marciniak, Influence of the nanocrystalline carbon layer on the blood coagulation, Proceedings of the 7th International Scientific Conference on the Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAMS'98, Gliwice-Zakopane, 1998, 263-266 (in Polish).

[14] P. Niedzielski, S. Mitura, Z. Paszenda, J. Marciniak, Diamond coated implants for medicine, Proceedings of the 8th International Scientific Conference on Achievements in Mechanical and Materials Engineering, AMME'1999, Rydzyna, 1999, 569-574.

[15] W. Chrzanowski, J. Marciniak, Biomechanics' and bio-material conditions of intermedullary osteosynthesis, Proceedings of 3rd Scientific Conference on Materials, Mechanical and Manufacturing Engineering, M^{3}E'2005 Gliwice-Wisła, 2005, 319-324 (in Polish).