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Computer modelling of the heat flow in surgical cement during endoprosthesoplasty

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Methodology of research

ABSTRACT

Purpose: The problem of the modelling of the surgical cement behaviour during implantation has been presented in the paper. The purpose was to find the proper model describing the temperature fields in the bone during the surgery treatment.

Design/methodology/approach: Computer modelling has been used to predict the temperature influence on the bone tissue during polymerization process.

Findings: During orthopaedic surgical procedures with the use of methyl polymethacrylate surgical cements, the temperature sometimes reaches 80°, which causes atrophy of the bone tissue. The process occurs locally, since it depends on both the amount of polymerization heat generated during the reaction and on the heat exchange conditions at cement-bone tissue and bone cement – implant boundaries. Striving to better understand the above-mentioned phenomena through a model approach, models were developed under the study to calculate temperature distributions in the bone and in implant components during the procedure of endoprosthesis stem implantation. Calculations were made for different cement layer thickness variants and for different amount of cement concentrated around the top of the stem. The characteristics of temperature changes with time in different points of the bone and cement have been determined and temperature distributions in bone and cement for selected instants of time have been worked out.

Practical implications: The analysis carried out makes it possible to determine the location of areas most threatened with an adverse effect of an elevated temperature. In each case, they are located in the vicinity of the top of the endoprosthesis stem. These conclusion together with obtained data should be important for the surgeons during surgical operation..

Originality/value: The work presents the own method of heat flow modelling during the polymerization of surgical cements. The results of the own method of the heat source characteristic description has been shown as well.

Keywords: Computer assistance in the engineering tasks and scientific research; Biomaterials; Reliability assessment; Toxicity

1. Introduction

The surgical procedure called endoprosthesoplasty or alloplasty of the hip joint is one of the most frequently performed surgical procedures, where sick elements of the human organism are replaced with implants. The procedure consists in placing an implanted element, i.e. an endoprosthesis called “the stem”, inside the femoral bone. An element in the form of a cup is inserted in the pelvis so as to cooperate with the stem. Both parts of an implant require firm fixing in the bone. Currently, many solutions of endoprosthesis are applied, where different methods of their permanent fixing in the femoral bone and in the pelvis have been adopted. One of the original methods of fixing the discussed implants was the so-called “anchoring” by means of surgical cement. This solution is still applied and, as clinical research shows, the "anchoring" of a stem and cup has a number of advantages of a biological and mechanical nature, ensuring permanent and reliable functionality of endoprosthesis' elements. Like in every case of replacing parts of an organism with artificial elements, such as implants, this solution is not perfect, either. Its most important disadvantages include the short-term adverse effect of high temperature on the tissues in the vicinity of an implant during a surgical procedure [1-8].

Hip joint alloplasty is a procedure of exceptional responsibility and an exceptional scale of technical problems. What is important, is the appropriate preoperative choice of the type and size of an implant, and of a suitable operative technique. The surgeon's ability to predict the future effects of a surgical procedure in the light of the compromise, which sometimes in necessary, between the theoretically most favourable and the practically possible matching of an endoprosthesis to individual qualities of the patient, is of equal importance [4]. During orthopaedic surgical procedures with the use of methyl polymethacrylate surgical cements, the temperature sometimes reaches 80^{o}, which causes atrophy of the bone tissue and its replacement with connective tissue, the latter being too weak to correctly transfer loads between a prosthesis and the bone.

2. Modelling of heat transfer during a surgical procedure

The problem of an adverse effect of surgical cement on the human organism during a surgical procedure has not been solved so far. In spite of a number of studies concerning the problem of designing new polymer materials for medical needs, with better strength and of a lower polymerization temperature, the value of temperature at which human tissues undergo destruction as a result of protein coagulation, is constantly exceeded during chemical reactions. The process occurs locally, since it depends on both the amount of polymerization heat generated during the reaction and on the heat exchange conditions at cement-bone tissue and bone cement – implant borders. Understanding of this phenomenon from the point of view of thermodynamics would form the right basis for forecasting places, where living tissue may undergo destruction, as well as the range of the destructive effect of temperature. In this case, the effect of the source field of temperature should be taken into consideration. A solution to the problem of determining the temperature distribution in implant components and in the bone, requires solving a number of partial tasks. One of them is to determine the heat source efficiency. The efficiency depends on the course of the polymerization process and is variable in time. In authors' previous papers, the heat source efficiency was determined for surgical cement based on tests made in a vacuum [4]. Fig. 1 presents the heat source efficiency as a function of time during Palamed cement polymerization. In further calculations, it was assumed that the course of the reaction and the related efficiency do not depend on external conditions, such as ambient temperature or heat exchange conditions, which have an effect on the temperature of components participating in the reaction. The making of such assumptions allowed the elaboration of appropriate models to calculate temperature distributions in the bone and in implant components during the procedure of endoprosthesis stem implantation. The finite element method was used to this end.

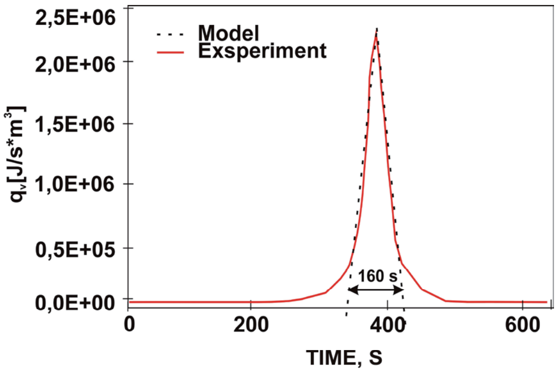

Fig. 1. Heat source characteristics with a marked, assumed for calculations

The geometric features of the model were defined based on measurements of a preparation of a real femoral bone. Three zones were defined in the model, corresponding to the properties of bone tissue, cement and endoprosthesis. The shape and dimensions of the implant model were the same as for a cement KERAMED endoprosthesis, the size of which was selected adequately to the preparation features. The so-built model was then introduced in the MES program, where a discrete model was created, with the number of nodes equal 48724 (Fig. 2).

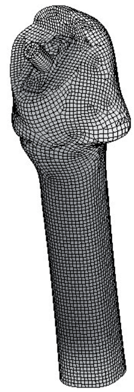

Fig. 2. Model of the bone-cement-stem system with mesh

Two types of boundary conditions were assumed in the modelling process. On the outer bone surface and uncovered parts of the metal stem, a 3rd type boundary condition was imposed, corresponding to convective heat exchange, with a defined, relevant heat transfer coefficient and ambient temperature. The inner heat source value was determined based on experimental research, the results of which are published in paper [4]. The thermophysical properties of the bone, cement and metal, were assumed based on literature data [5]. It was assumed that thickness of the surgical cement layer fixing the endoprosthesis stem should range between 2 mm and 5 mm. At the same time, it is desirable that a constant thickness of the cement layer be obtained throughout the surface of its contact with the femoral bone. The condition of constant thickness of the cement layer is hardly ever met in practice.

This results mainly from individual qualities of the femoral bone tissue in the patient. The differing values of bone cement layer thickness and different amounts of cement in the area of endoprosthesis top have a significant influence on the localization of bone tissue destruction processes under the effect of temperature. When striving to better understand the above-mentioned phenomena through a model approach, calculations were made for seven variant of the cement layer thickness, ranging from 1 mm to 7 mm and for different amounts of cement in the area of endoprosthesis top. A time of the temperature increase polymerization duration was assumed to equal 160s (Fig. 1). Some examples of the determined temperature distributions are presented in Fig. 3,4.

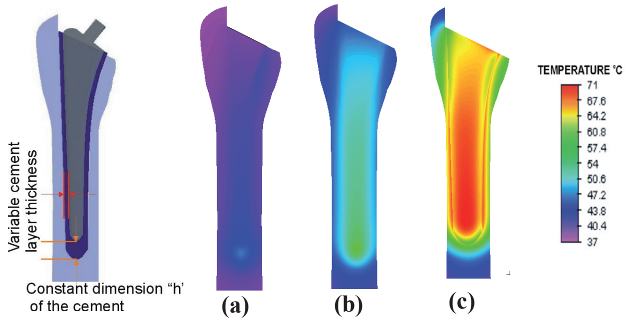

Fig. 3. Temperature distributions on a section of the model, for different values of the surgical cement layer thickness: (a) 1 mm, (b) 3 mm, (c) 7 mm

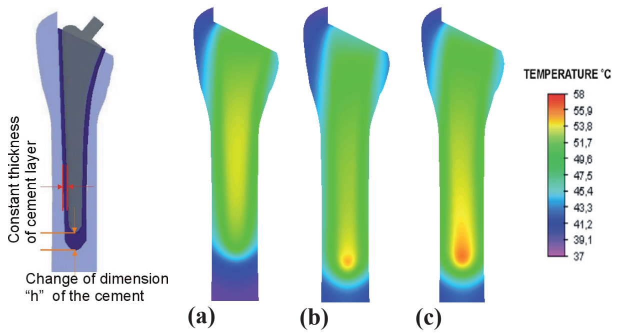

Fig. 4. Temperature distributions on the model section for different values of parameter h, which defines the surgical cement amount in the area in the vicinity of the stem top: (a) h = 3 mm, (c) h = 10 mm, (d) h = 13.5 mm

The analysis carried out makes it possible to determine the location of areas most threatened with an adverse effect of an elevated temperature. In each case, they are located in the vicinity of the top of the endoprosthesis stem. Based on the temperature distributions, local characteristics of temperature changes in time were then developed for the determined model points. Fig. 5 shows the changes of the bone tissue temperature in time, on the border between the tissue and cement. The temperature in this point depends on the cement layer thickness and shows the highest value after ca. 110 s from the moment assumed to be the beginning of the process.

Similar characteristics were developed for points located in the stem's upper part, near the implant's flange, and below its top. On that basis, the maximum temperatures were determined which, in accordance with the model, may be reached locally by the bone tissue. The values of these temperatures depending on the cement layer thickness and on the different “h” dimension characterizing the amount of cement in the area of endoprosthesis top are shown on Fig. 6,7. Assuming 56°C as a limit temperature, in terms of the possibility of the living cells' survival in the organism one may notice that already when the cement layer is 5 mm thick, areas may occur in the bone where the bone tissue undergoes destruction.

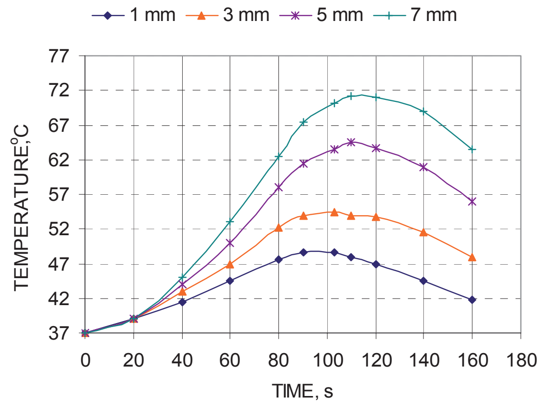

Fig. 5. Diagrams of the bone tissue temperature dependence on time, determined for different cement layer thickness values

Fig. 6. Influence of the cement layer thickness on the bone tissue temperature at half of the stem height

In the presented calculations, an assumption was made that the cement layer has a uniform thickness throughout the implant surface, obtaining an approximation for the relation between the thickness and maximum temperature reached locally. The largest local cement concentration occurs in the vicinity of the implant's top. It is in this place, that the highest temperature during polymerization should be expected (Fig. 3,4). The value of the temperature to be reached by bone tissue will depend here on the distance of the stem top from the element closing the bone marrow canal, i.e. the "plug". The area in the vicinity of the stem top is the most exposed to the adverse effect of temperature during polymerization. In addition, taking into account the stress concentration, it seems reasonable to assume that the place in the neighbourhood of the stem top is characterized by particularly adverse conditions due to the eventuality of losing a permanent connection between the implant and human organism tissues.

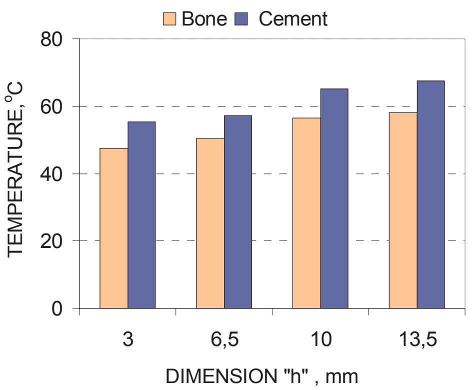

Fig. 7. Influence of "h" dimension of cement on maximum temperatures (bone cement layer thickness: 3 mm)

The work presents only one aspect of the permanent fixation of the stem, i.e. the polymerization temperature influence. In feature it will be necessary take into account the interface layer properties [9-14] and mechanical properties of cement as the polymer with its typical creep behaviour [15].

3. Conclusions

The most important conclusions is that one of the significant factors that determine the bone tissue destruction is the localization of the heating process. The environment of the endoprosthesis stem top should be regarded as an area particularly threatened with a destructive influence of elevated temperatures, since it is in this place where the protein coagulation temperature is very often exceeded. The size of the area where the bone tissue destruction takes place depends on the amount of cement located below the stem top. Therefore, during a surgical procedure, particular attention should be paid to precise making of a hole for the stem to be implanted. A too deep hole may cause destruction of the bone tissue throughout the femoral bone section, near the stem. Before tissue reconstruction takes place in this area, the imposed load may lead to mechanical damage, which will have effects in the future, even a long time after the surgical procedure. The discussed area is also a place of the highest effort resulting from the distribution of stresses in the vicinity of the endoprosthesis. Thus, the biological effects of an excessive increase in temperature will overlap in this place during the implant's work with overload caused by stress concentration induced by inhomogeneity of mechanical properties and local pressure of the stiff top of the stem on weakened bone tissue.

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