Numerical thermal study in bone tumor lesion

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Abstract

Research Article

With the evolution of science and new diagnostic technologies, it was possible to observe a continuous improvement in the treatments in general and in the aid of the patients' quality of life. Malignant tumors can be primary or secondary (metastases), with abnormal growth of cells able to invade other types of tissues and organs through systemic dissemination. Sarcomas are rare primary malignancies formed from mesenchymal tissue and often located at the extremities. In this work, the main objective is to evaluate the minimization of the evolution of bone tumor lesion through the injection of bone cement, filling in the space of the lytic tumor lesion. This methodology allows to verify at the adjacent cement – bone tissue interface, an increase in temperature that can control the local growth of bone metastasis. Different computational models, obtained by medical image processing, will be carried out for two analyses (patient younger than 70 years and older than 70 years). The computational model allows a transient thermal analysis using the finite element method. The temperature results may determine the thermal necrosis effect in the bone tumor lesion. Results will be compared using three different bone cements. DOI: https://doi.org/10.24243/JMEB/4.4.234

Keywords: bone tumor; sarcoma; bone cement; numerical model
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1 Introduction

Bone and soft tissue sarcomas are heterogeneous tumors that form from bone tissue, connective tissue, cartilaginous tissue, muscle tissue, adipose tissue, peripheral nerves, and blood vessels, usually at the extremities. These tumors occur at any age and in all anatomical localizations. Until a few decades ago, the surgical treatment of sarcomas passed almost exclusively by amputation of the affected limb. From the 70s and 80s, advances in chemotherapy,

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radiological evaluation, surgical techniques and the reconstructive materials and implant technology have led to advances in the development of limb salvage surgery and consequent improvement of quality of life [1].

Cementation is a technique used for example in percutaneous procedures such as vertebroplasty, kyphoplasty, osteoplasty and sacroplasty [2]. The development of synthetic bone substitutes has gained increasing significance in recent decades. Bone cements are synthetic biomaterials composed of a polymer (powder) and a liquid component (monomer), successfully used in various medical applications, such as in orthopaedic and dental surgery. One of the main applications of bone cements is the fixation of prostheses by filling the free space between the prosthesis and the bone. The introduction of bone cement into the tissue is intended to treat or prevent vertebral and extra-spinal pathological fractures and to reduce pain in patients with osteoporosis and bone metastases [2].

Currently, a wide variety of bone cements are available for use. All professionals should be familiar with differences in chemical synthesis, viscosity, polymerization times, biocompatibility, mechanical strength, radiopacity and rheological properties. The most used bone cements are acrylics, namely PMMA (polymethylmethacrylate), due to their structural and physical properties, excellent biocompatibility, easy handling and low cost. Bone cement develops thermal necrosis in the adjacent tissues during the polymerization process of the cement itself.

PMMA, due to its structural and physical properties, has an exothermic reaction in which the volumetric dimension changes during the polymerization process with the generation of heat [3]. The heat generated can lead to cells thermal necrosis. There are several studies on the exothermic reaction of cement polymerization and predictive results on temperature increase, leading to a time-dependent polymerization process [3], [4]. The polymerization process releases a large amount of heat, and the temperature can reach 90°C inside the body. The polymerization changes the volume of the cement, as the blend initially shrinks, expands in the heat-releasing phase and decreases again when it cools. In theory, the monomer loses 20% of its initial volume. The presentation of the bone cement properties and its handling are essential so that the different phases (mixing, processing and hardening or cure) allow to achieve the expected results.

In this work, the main objective is to evaluate the minimization of the evolution of a bone tumor lesion through PMMA bone cement filling the space of the lytic tumor lesion. The beneficial effect of heat generation on tissues with tumors is presented, using different computational models for transient thermal analysis. Different computational models, obtained by evaluation of medical images, will be carried out for the analysis of two age patients. The computational model incorporates the transient thermal analysis using the finite element method. The properties of the constituent materials (cement, bone) are obtained from values available in the literature. This methodology allows to verify at the adjacent cement – bone tissue interface, an increase of temperature that can minimize the growth of bone metastasis. The main results to be evaluated are temperature fields, in which the effect of the cement cure process may determine the area affected by temperature and consequent necrosis of the bone tumor area. Results will be compared, among the different computational models, using three different bone cements, according their compositions and polymerization process. Results are presented and discussed, in conjunction with CHUP-ICBAS, which allow for a better understanding to the use of bone cement in the tumor lesions treatment.

2 Methods and materials

Computational models were obtained through the processing of medical digital X-ray images for two age analysis. Figure 1 a) represents the model of the proximal femur with a lytic metastatic lesion in a female patient less than 70 years old, with a measured average of the cortical external diameter De=32.9mm and cortical internal diameter Di=20.6mm. Figure 1 b) represents a patient female with age higher than 70 years old, with a measured average of the cortical external diameter De=38.3mm and internal diameter Di=17.5mm.

Two computational models were reproduced with the measured dimensions. Bone cement was introduced in the middle of the model to fill a metastatic lytic lesion area, with dimensions L=20mm in depth and width H=48.5mm. The metastatic lytic lesion was measured from different digital X-ray images. Figure 2 a) represents the geometrical model with the main dimensions and identification of materials. Figure 2 b) represents the mesh and materials used to study the

numerical model, where blue zone represents the cortical tissue, violet is the spongy bone and the red colour is the bone cement.

a)   b)

Fig. 1 Metastatic lytic lesion of the proximal femur obtained by digital X-ray for: a) patient younger than 70 years, b) patient greater than 70 years.

a)   b)
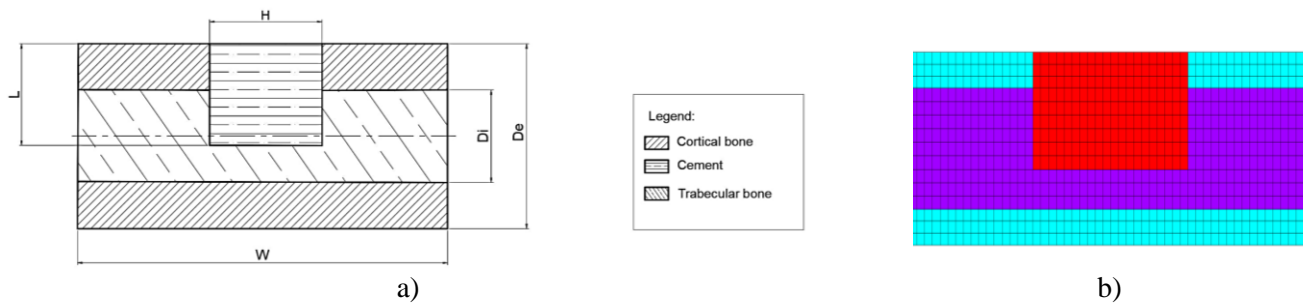
Fig. 2 a) Representative drawing of the model; b) Numerical model.

The numerical simulations were performed using the finite element method with ANSYS software. The geometric model was meshed with a 2D thermal solid element (PLANE 77) with 8 nodes and a single degree of freedom, temperature, at each node. All material properties (cortical, spongy bone and bone cement) are in accordance with the literature [3], [7] represented in Table 1.

Table 1 Thermal material properties, [3], [7].

Material	Density, kg/m^3	Thermal conductivity, W/K.m	Specific heat, J/kgK
Cortical Bone	2100	0.38	1260
Spongy Bone	620	0.39	4926
Bone cement A, B or C	1100	0.20	2000

A perfect contact model was prepared between the cortical, spongy and cement bone, where the heat transfer is carried out by heat conduction. The initial temperature in the model was assumed equal to 37ºC. Three different bone cements were used in the numerical simulations. The time-dependent effect of each bone cement was introduced in the numerical model according to the experimental results collected in the literature [5], [6] represented in figure 3. The maximum heat peak appears in cement type A with a value of 103ºC. Bone cement represented by curve C has the smallest peak temperature value, 52ºC. According to the cement polymerization process, a total simulation time of 1800 seconds was established in all simulations, with an incremental time step equal to 5 seconds.

3 Results and Discussion

Figure 4 represents the temperature variation, depending on the distance between the tumor region, characterized by the cement, and the cortical bone tissue, for each female age. The maximum temperature occurs in the neighbour region to the cement-spongy bone interface, with highest value for cement type A in both models. Cement type C

produces a smaller value for temperature increase in bone tissue. For this type of cement only 2.5mm of bone spongy tissue is affected by temperature higher than 45ºC.
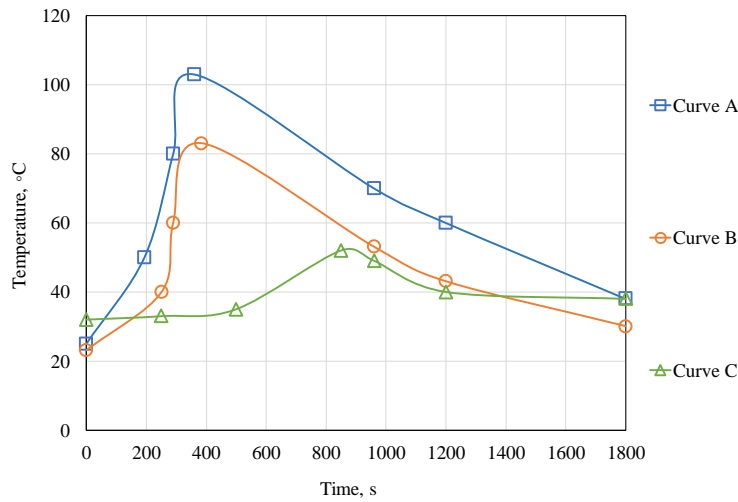

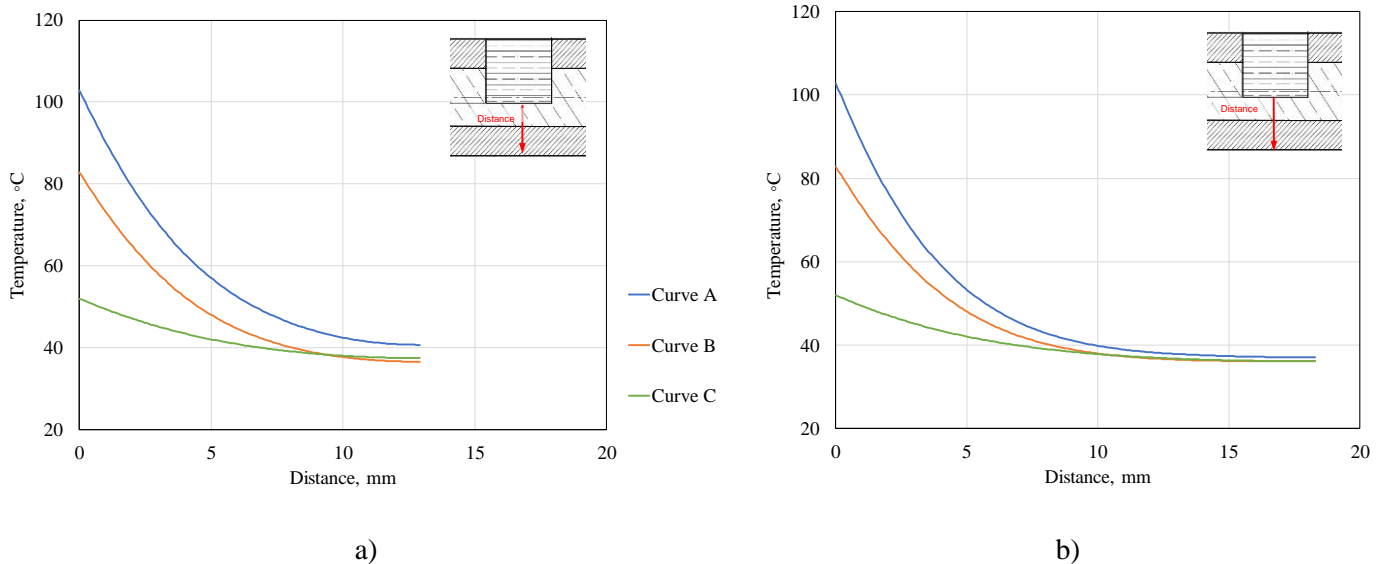***Fig. 3 Time-temperature curing effect of three bone cements.***

a)

b)

Fig. 4 Temperature function of bone distance, for high peak of bone polymerization: a) Age lower than 70 years, b) Age higher than 70 years

Figure 5 represents the temperature field in the models, with and without the identification of the necrosis effect, defined for the time corresponding to the peak of heat release. The results show that the temperature in the cement zone reaches the maximum value of 103ºC when using cement type A, 83ºC when using cement of curve B and 52ºC when using cement type C, respectively. The effect of thermal necrosis on bone tissue is shown in grey colour. When using cement type B or C the region of thermal necrosis is reduced.
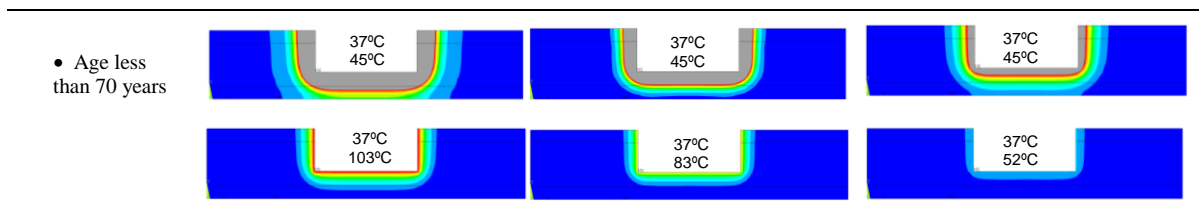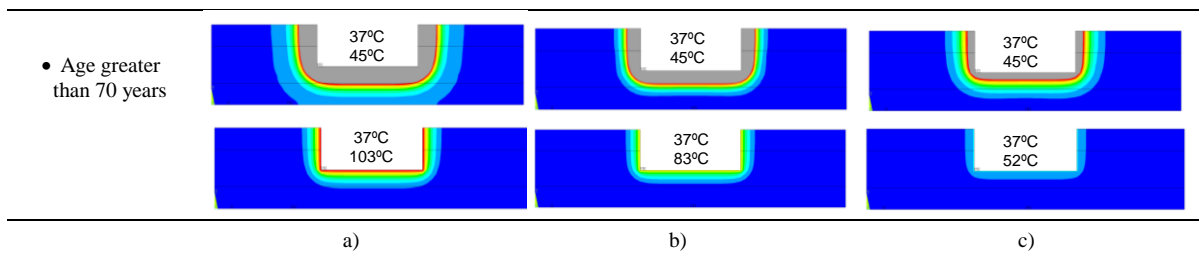
Fig. 5 Thermal analysis for each age patient in function of: a) Curve A, b) Curve B, c) Curve C.

Many studies propose a temperature of 47ºC for 1 min to allow the thermal necrosis in cortical bone [8], [9]. In other investigation, the cement showed maximum temperature approximately 45ºC [10]. In the present study and for all the simulations, the threshold value for bone thermal necrosis was 45ºC. As verified in figure 5, it is possible to conclude that using cement type C leads to a smaller thermal necrosis (approximately 2.5mm). The necrotic area when using cement type B is about 6mm and 7.5mm for cement type A. The comparison between the female age not allow significant differences, when comparing the thermal necrosis effect in bone tissue. The main difference is the dimension of the bone geometry, which allows to conduct the heat to distant locations.

4 Conclusions

The results obtained from a numerical analysis using the finite element method allow to conclude about the propagation of the temperature in the bone material. The zones adjacent to the PMMA reach values of high temperature, being the Curve C representative from the material of the lowest peak temperature. Consequently, the higher the polymerization peak is, the greater is the tissue necrosis area. For each PMMA composition, in the female patient age in this study, the area of necrosis extension is similar. It is important to apply the specific PMMA composition, depending on the necessary effect to minimise the evolution of bone tumor. The temperature effect, time, initiator concentration, curing environment, water bath, pressure, and monomer mixing ratio, allow to obtain a different cement characteristic, that may influence the polymerization curve.

In order to compare the obtained temperature field in all computational models with perfect contact, and as a future work, the effect of thermal contact conductance may be analysed. A low value means less heat will flow across the boundary between the materials, while a high value means more heat will flow. These results could help to understand the thermal resistance to heat flow across the contact boundaries.

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