Three Dimensional Simulation of Heat Transfer Problem after Cemented Hip Replacement

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Abstract: Total hip replacement involves cement flow interacting with other variables causing heat in the femoral canal. Understanding of heat transfer during cooling after cemented hip replacement is very essential for the surgery. Therefore, this research presents mathematical model and numerical simulation of heat transfer during cooling after cemented hip replacement. The artificial domain is constructed based on real domain using a set of CT scan data of the 65 years old patient. The governing equations are the classical heat transfer equations. The model is solved by finite element method. The temperature across multi-layers of the right artificial domain with implant was carried out.

Key–Words: Femur, Hip replacement, Implant, Finite element method, Mathematical modeling, Heat transfer.

1 Introduction

The hip joint damage and arthritis cause pain and loss of movement. Hip replacement surgery will replace the damaged hip joint configuration with artificial parts to release pain and improve the mobility. In the surgery, the hip joint is replaced by a stem implant. The polymethylmethacrylate (PMMA) bone cement is used to affix implants and to remodel lost bone. Ice pack is applied for 20 minutes to reduce irritation and inflammation in the hip area. A main surgery problem is the aseptic loosening. It is known that this problem is based on incomplete heat transfer in the bone-cement-prosthesis system. It is also believed that mechanical properties of the cement and thermal and chemical injuries of the bone tissue in the bone-cement interface are two main factors that affect the heat transfer process in the system [10, 14, 20]. Thus, it is important to understand the heat transfer phenomena in the system. Over the last 10 years, many researches have been studied heat transfer on the top part of the femur using mathematical model [1, 7, 6, 16]. Effects of the mechanical properties of the cement have been investigated [2, 5, 9, 12, 17, 21]. In 2003, Chandi et al. [11] developed a phenomenological kinetic model with specified parameters determined by an optimization technique in order to model the bone polymerization procedure. In 2004, Walsh et al. [21] presented the fixation properties of the implant-cement interface and the mechanical properties of the cement using polymethylmethcrylate (PMMA) and a Bisphenol-aglycidylmethacyrlate resin-hydroxyapatite cement (CAP). Stańczyk [19] proposed a kinetic model of chemical reactions to predict temperature field in the cement mantle during polymerization. The results indicate that the polymerization was isothermal at the temperature of 27 $^\circ C$. Recently, many researches have been proposed. Hansen [6] used an arbitrary bone cement consisting of an initiator and monomer to study heat transfer in a bone-cement-prosthesis system around a hip with a femoral stem. The three-dimensional geometry was used in this model.

In this paper, we study heat transfer on the full part of the femur bone with implant is inserted. Moreover, we focus on heat transfer phenomenon during cooling after surgery in the hip replacement region where PMMA cement is occupied in the top 17 cm of top part of the femoral canal having the implant in the middle. The rest of the paper is organized as follows. Section 2 describes the governing equations of the heat transfer problem in the hip replacement procedure. Section 3 presents the numerical results. Finally, conclusions are given in section 4.

2 Mathematical Model

In this study we focus on heat transfer in the cemented hip replacement using the metal and metal implant with no cup. Essential region of the cemented hip replacement is shown in Figure 2 consisting of a femur region, an implant region and a femoral region. On the top part of femoral region is occupied by the cement and the bottom part is occupied by the ambient air. The governing equations to describe the heat transfer problem in each region are the set of partial differential equations as follows [6]:

$$\rho_i C_p^i \frac{\partial T_i}{\partial t} + \nabla \cdot (-k_i \nabla T_i) = 0, \; i = 1, 2, 3, 4 \qquad (1)$$

where ρ_i is the density (kg/m^3), C_p^i is the heat capacity at constant pressure $(J/(kg \cdot K))$, k_i is the thermal conductivity $(W/(m \cdot K))$ and the index i refers to the i^{th} region where $i = 1, 2, 3$ and 4 for the femur region (Ω_{fem}), the implant region (Ω_{imp}), the cement region (Ω_{cem}) and the ambient region (Ω_{air}), respectively.

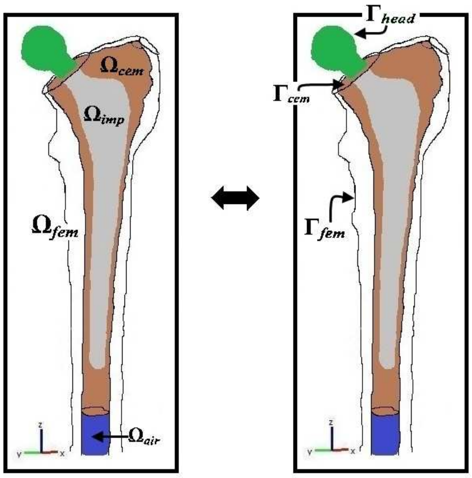

Figure 1: Four subdomains and boundaries.

To completely define the problem, boundary conditions need to be specify. On the surface of the head of the implant Γ_{head}, the outer surface of the femur Γ_{fem} and the inlet surface of cement Γ_{cem}, Newton boundary condition [15] is applied, i.e.,

$$-k_i \frac{\partial T_i}{\partial \mathbf{n_i}} = h_\infty^i (T_i - T_{ext}), \; i = 1, 2, 3 \qquad (2)$$

where T_i denotes an unknown surface temperature, h_∞^i denotes heat transfer coefficient for each materials, $\mathbf{n_i}$ denotes the outward unit normal to Γ_i and the index i refers to the i^{th} region where $i = 1, 2$ and 3 for the femur surface (Γ_{fem}), the head of implant surface (Γ_{head}) and the cement surface (Γ_{cem}).

On the interfaces between any two regions, we impose the continuity of the heat flux across the contact surface, i.e.,

$$k_i \frac{\partial T_i}{\partial \mathbf{n_i}} - k_j \frac{\partial T_j}{\partial \mathbf{n_j}} = 0. \qquad (3)$$

In summary, heat transfer process after the cemented hip replacement is governed by boundary value problem (BVP):

BVP : Find $T^{cem}, T^{imp}, T^{fem}, T^{air}$ such that the system of partial differential equations (1) and boundary conditions (2) and (3) are satisfied.

3 Numerical results

The example under consideration is a right artificial femur bone which has a length $50\,cm$, implant which has a length $15\,cm$ and PMMA cement which is assumed to be in between the implant and the femur bone and covers the top $17\,cm$ of the femoral canal. Moreover, ice pack covering the leg is used to increase the temperature gradient needed for the decreasing of heat. Three dimensional model of the right artificial femur was constructed based on real domain using a set of CT scan data and Mimics software. The artificial domain as shown in Figure 2 consists of four parts including femur region (Ω_{fem}), the implant region (Ω_{imp}), the cement region (Ω_{cem}) and the ambient region (Ω_{air}). The implant was assumed to be fixed inside femoral canal and was surrounded with cement. Figure 1 shows the complete geometry of the right artificial femur bone with implant.

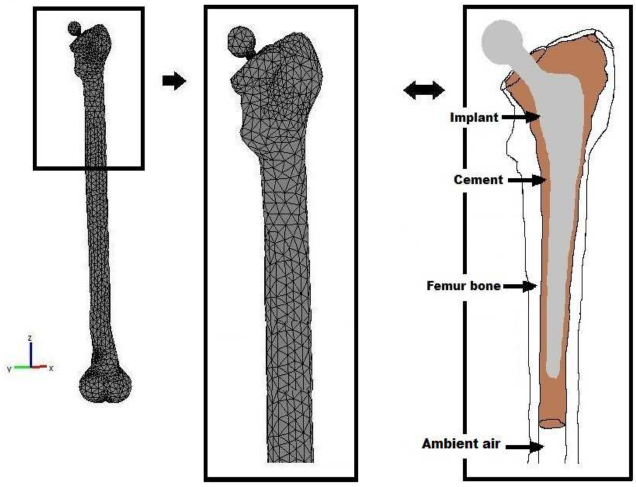

Figure 2: The finite element mesh ambient air and the top part of computational domain.

Table 1: The Experiment Parameters used in the numerical simulation of artificial domain.

Parameters	**Femur**	**Ambient air**	**Cement**	**Implant**	**Units**
Density (ρ)	1000	1.8677	1100	7800	kg/m^3
Thermal conductivity (k)	0.26	0.0398	0.17	14	$W/(m \cdot K)$
Heat capacity (C_p)	1260	1557.75	1460	460	$J/(kg \cdot K)$

The computational domain as shown in Figure 2 is separable in space into 86,493 tetrahedral elements and 126,809 degrees of freedom. Values used in the simulation collected from the literature are shown in Table 1 and Table 2 [1, 3, 4, 8, 13, 18]. In the numerical simulation, the initial temperatures of femur bone, bone tissue, ambient air, cement and implant were set to be 37 $^\circ C$, 38 $^\circ C$, 35 $^\circ C$, 100 $^\circ C$ and 23 $^\circ C$, respectively.

Table 2: Values of heat transfer coefficients for each materials, h_∞, $W/(m^2K)$ [18].

	Cement	Ambient
Metal stem	1,000 - 10,000	50 - 100
Femur bone	100 - 1,000	500 - 10,000

In this study, we focused on the temperature distribution during cooling in the cemented hip replacement procedure. All temperature values in the computation regions have been computed. The heat transfer from the cement through the implant and from the cement through the bone layers have been investigated. Figure 3 represents the temperature distribution on a vertical cross section along the axial femur bone with implant at time = 360 sec. It is founded that in cement region temperature at the bottom of the implant and above the cement plug is about 37 $^\circ C$. In the top part of the cement region, maximum temperature is 62 $^\circ C$. This show that the higher temperature region is presented only in the upper regions of the femur.

Figure 4 shows the geometry of the top part of implant stem (P_1), the bottom of implant stem, (P_2) and the cement plug, (P_3). Figure 5–7 show the temperature distribution on three different horizontal cross section on the top 17 cm of the computational domain. The results indicate the heat is generated by the hardening of cement. Heat from the cement transfers to the implant, thereby increases the temperature. This show up by the red color of the whole region at 900 $sec.$. When the time pass through 1230 $sec.$, heat is then lost by the implant first. Heat lost by the cement is lower. That cause the temperature of the cement to be higher than the temperature of the implant seen at 1230 $sec.$

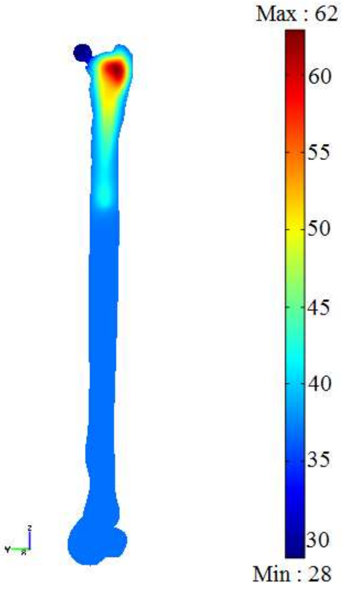

Figure 3: Temperature distribution on a vertical cross section along the axial artificial domain at t = 360 sec.

Figure 8 shows the temperature profile at three different points at the interface between the cement and bone. The blue line with triangle reflects that the cooling is from the greater amount of the cement present. The red line with square shows that the cooling is from the less amount of cement there. Finally, the green line with cross shows the effect of a greater surface area for the heat to left. Heat can also go directly to the bone at the end of the cement.

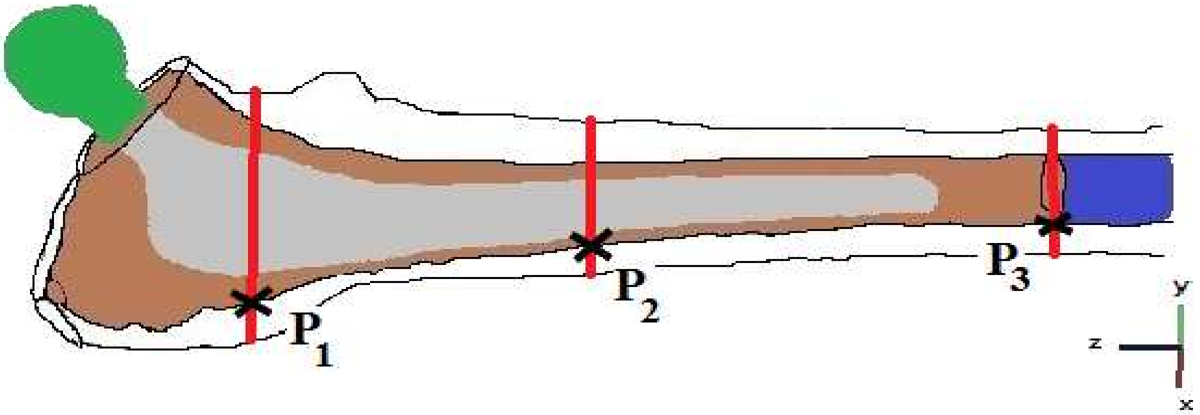

Figure 4: The geometry of the top part of implant stem (P_1), the bottom of implant stem, (P_2) and the cement plug, (P_3).

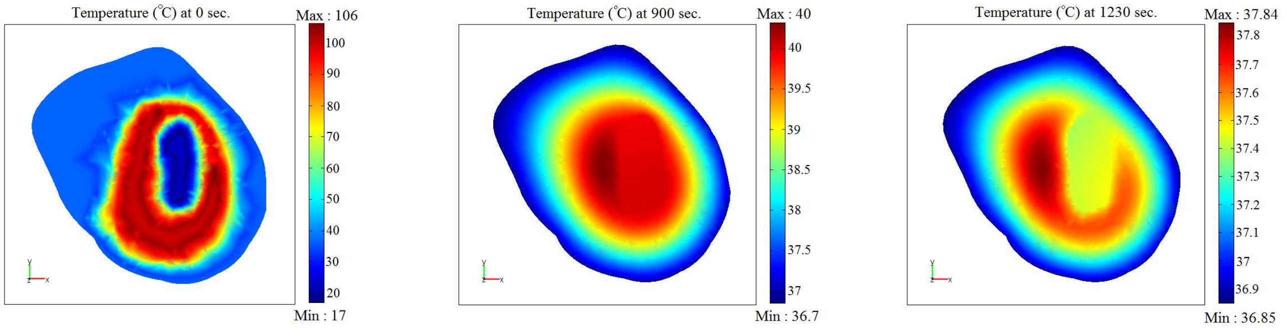

Figure 5: Temperature distribution at the top part of implant stem, (P_1).

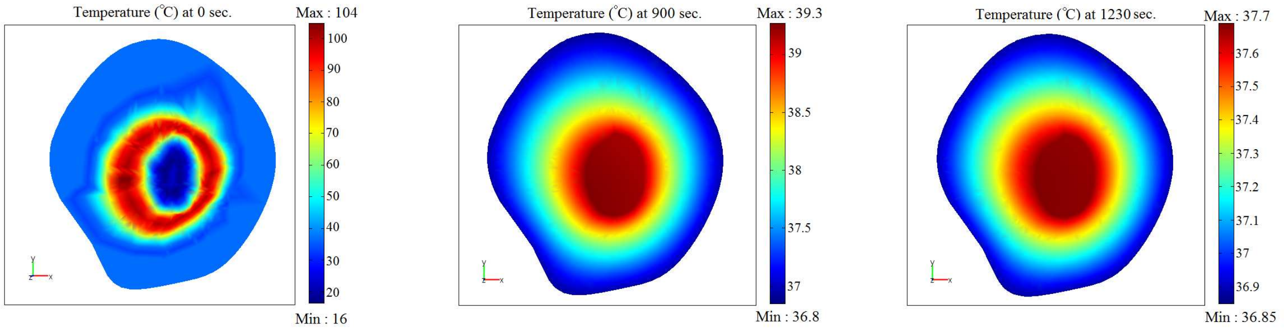

Figure 6: Temperature distribution at the bottom of implant stem, (P_2).

4 Conclusion

In this paper, a mathematical model of heat transfer in the femur bone with femoral implant was developed to describe the thermal behavior of curing PMMA cement in hip replacement procedure. Computational domain consists of femur bone, femoral canal, cement and implant regions. Finite element method was used for the solution of the mathematical model. Temperature distribution in the bone-cement-implant system was computed. The results shown that high temperature presented on the top part of femur bone. It decreases along the axial femur bone.

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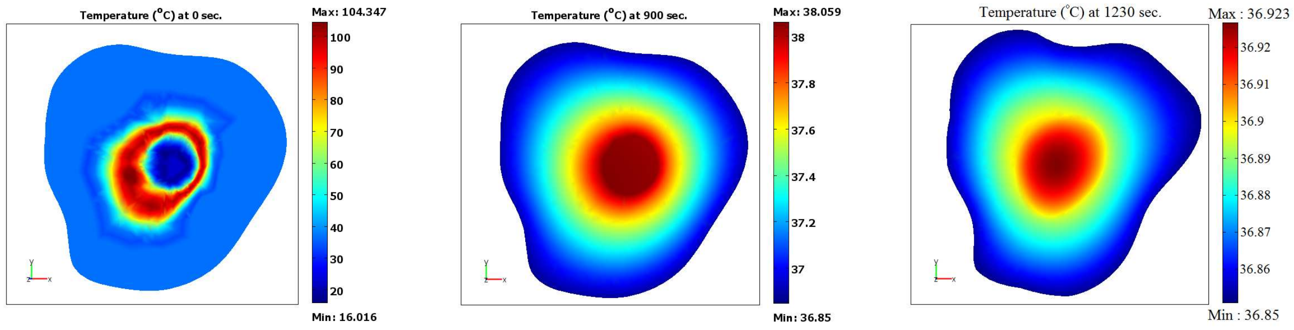

Figure 7: Temperature distribution at the cement plug, (P_3).

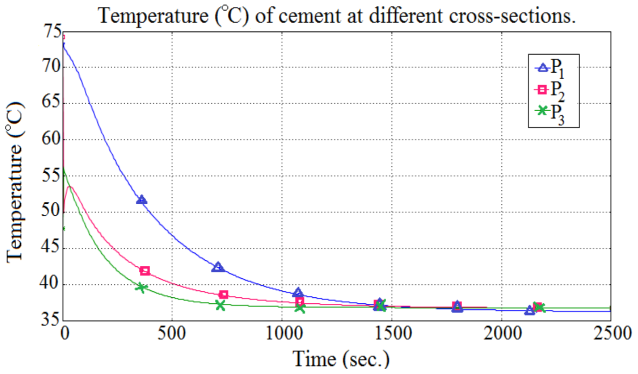

Figure 8: Temperature profile at three different points(P_1, P_2 and P_3 as shown in Figure 4) on the cement-femur interface of three horizontal cross sections.

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