Finite element modeling of kirschner pin and bone thermal contact during drilling

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Received November 10, 2009

Abstract The aim of this study is to develop an analysis method which can be applied to simulate the temperature rise during bone drilling. This study uses a dynamic elastic-plastic finite element model to simulate a process of a Kirschner pin drilling through the bone. The results indicate that lowering the initial temperature of Kirschner pin can decrease the temperature rise as well as the thermal affected zone. [Life Science Journal. 2009; 7(4):23 - 27] (ISSN: 1097 – 8135)

Keywords kirschner pin; temperature; bone, thermal contact; finite element analysis

1. Introduction

Kirschner wires or K pins are sharpened, smooth stainless steel pins used for temporary fixation during some operations. Several experiments indicate that the bone drilling may cause thermal necrosis. The pins are often driven into the bone through the skin using a power or hand drill. The heat generated during bone drilling is proportional to the drilling speed. Some of it may be conducted to the bone, which may cause serious damage if the temperature rises higher than 55 ^{o}C [1].

Khanna et al [2] indicated that K-wires had poor drilling qualities because they lacked sharp angled cutting facets and flutes. Eriksson and Albrektsson [3] showed that under certain conditions the temperature of bone during osseous drilling might exceed 70 ^{o}C . Hilly and Shuaib [1] studied the temperature effects on the drilling of human and bovine bone. The results indicated that a drilling speed of 800-1400 rpm was suggested when drilled with a diameter of 3.2mm drill-bit to provide the best cutting condition and to maintain the temperature at a manageable level. Mustafa et al [4] investigated the effect of force on the drilling speed and measured the energy consumed during the drilling process. The results suggested that drilling at high speed with a large force could reduce the bone temperature. Bachus et al [5] studied the drilling force on cortical temperatures. It demonstrated that by applying a larger force to the drill, both the maximum cortical temperature and its duration above 50 ^{o}C might be effectively reduced, decreasing the possibility of thermal necrosis in the cortical bone. Allan et al [6] reported that the temperature rise in bone drilling was related to the amount of drilling wear. In addition, it has been shown that the finite element method is a useful tool to simulation the drilling process [7-8]. Davidson and James [7] developed thermo-mechanical equations to predict the heat generation due to drilling. In simulations, a heat transfer model was coupled with the finite element model to predict the temperature rise during bone drilling.

Although various studies have addressed the influence of drilling in bones, these literatures contain only limited information regarding the temperature rise in K-pin-bone contact problems during drilling. In this study, various initial temperature of K-pin is investigated to explore the effect of parameters on the temperature rise.

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2 Finite element model

In this study, a three-dimensional elastic-plastic dynamic temperature-displacement finite element model is used to simulate the process of a K-pin drilling through the bone. Simulations are performed using a commercial finite element package ABAQUS and a dynamic failure criterion is applied to control the element removal. The K-pin and the bone contact geometry used in this study are shown in Fig. 1.

The region of interest is the immediate surrounding of the drill hole where the temperature is highest. Hence the domain for the numerical simulation is chosen to be a circular disc. The diameter of the K-pin used in this study is taken as 2 mm. The tip radius R, as shown in Fig. 1, is employed to simulate the bluntness of the K-pin. The tip radius of the K-pin is 0.1mm. The point of the drill hole edge, i.e. x=2 and z=0 mm, is taken as the origin of the coordinate system. The corresponding finite element model is shown in Fig. 2. The contact behavior between the K-pin and the bone is modeled using approximately 21859 contact elements in each simulation. The mesh is constructed using eight-node three-dimensional brick elements. The finite element model comprises a total of 41875 elements and 43892 nodes. To explore the effects of initial temperature of K-pin on the temperature distribution, four initial temperatures T_o, i.e. $0\,^{o}\mathrm{C}$, $10\,^{o}\mathrm{C}$, $25\,^{o}\mathrm{C}$ and $37\,^{o}\mathrm{C}$, are simulated. Two applied forces, 20N and 30N, are taken. The drilling speed is taken as 1200 rpm. The initial temperature of bone is assumed as $37\,^{o}\mathrm{C}$. The mechanical properties used in the finite element analysis are summarized in Table 1.

Table 1. Mechanical properties of K-pin and bone used in finite element simulations

	K-pin [9,10]	Bone [10]
Density (Kg/m^3)	7840	2100
Young’s modulus (GPa)	210	17
Yielding strength (MPa)	608	135
Tension strength (MPa)	1000	148
Specific Heat (J/kg℃)	490	1260
Poisson’s ratio	0.3	0.35
Conductivity(Watt/m℃)	16	0.38

3 Results and Discussions

In this research, a dynamic elastic-plastic finite element model is employed to study how lowering Kirschner pins’ temperature can affect the temperature rise in bone during drilling.

Figure 3 shows the variation of bone temperature along the radial direction of the bone for various initial temperature T_o with drilling time T_{sec} =1 sec. The results shown in this figure are taken from the bone

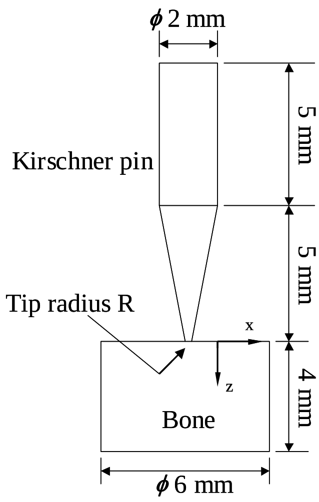

Figure 1. Geometry of Kirschner pin and bone

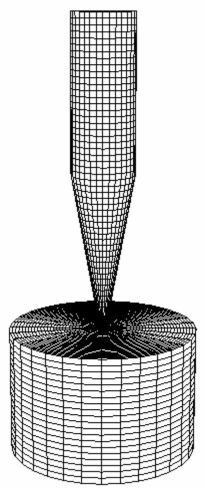

Figure 2. Finite element model of Kirschner pin and bone

surface, i.e. z= 0 mm. The applied force is F= 20 N. The results indicate that the bone temperature increases as the initial temperature of the k-pin increases. Hence, the bone temperature can be reduced as the K-pin has a lower initial temperature. In Fig. 3, the peak bone temperatures are $40.1\,^{o}\mathrm{C}$ and $38.4\,^{o}\mathrm{C}$ for the K-pin with an initial temperature of $37\,^{o}\mathrm{C}$ and $0\,^{o}\mathrm{C}$, respectively. All the temperatures shown in Fig. 3 are under $55\,^{o}\mathrm{C}$. Figure 4 plots the variation in the bone temperature for four different initial temperatures of K-pin with drilling time of 3 sec. Compared with Fig. 3, it shows that as the drilling time increases, the bone temperature increases. It can be seen that the temperature distributions on the bone surface increase rapidly when the drilling time is 3 sec. Also, the peak temperature changes apparently as the initial temperature of the K-pin

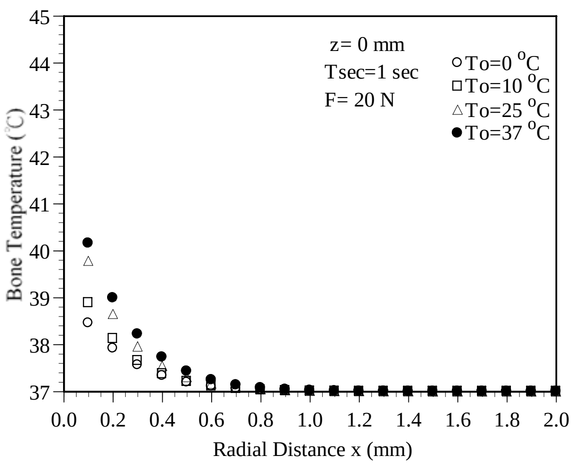

Figure 3. Variation of bone temperature along the radial direction as a function of initial temperature T_o with drilling time of 1 sec

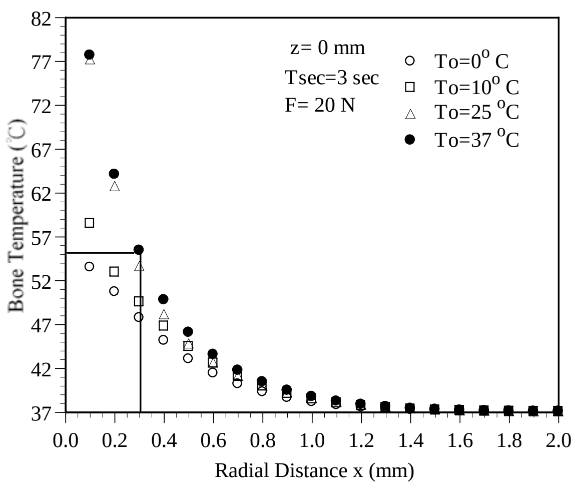

Figure 4. Variation of bone temperature along the radial direction as a function of initial temperature T_o with drilling time of 3 sec

changes. This shows that lowering the initial K-pin temperature can reduce the temperature rise in bone during bone drilling. However, the bone temperatures at some regions are higher than $55\,^{o}\mathrm{C}$. In this study, the region that bone temperature exceeds $55\,^{o}\mathrm{C}$ is defined as the thermal affected zone (TAZ). The TAZ can be used as an index to adjudge the damage zone of the bone. For example, as the solid line shown in Fig. 4, the TAZ is about 0.35 mm for the case of a K-pin with an initial temperature of $37\,^{o}\mathrm{C}$. However, the TAZ is 0 mm for a K-pin with an initial temperature of $0\,^{o}\mathrm{C}$. From Fig. 4, a simulation result shows that the bone temperature will not exceed $55\,^{o}\mathrm{C}$ if the initial K-pin temperature is $0\,^{o}\mathrm{C}$. In addition, the TAZs can be determined as 0.33 mm and

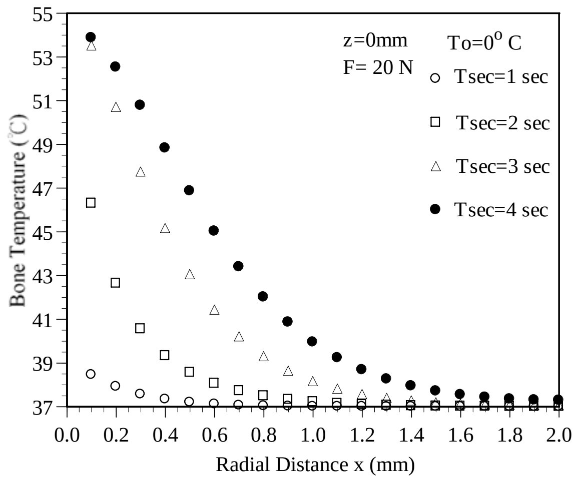

Figure 5. Variation of bone temperature along the radial direction as a function of drilling time

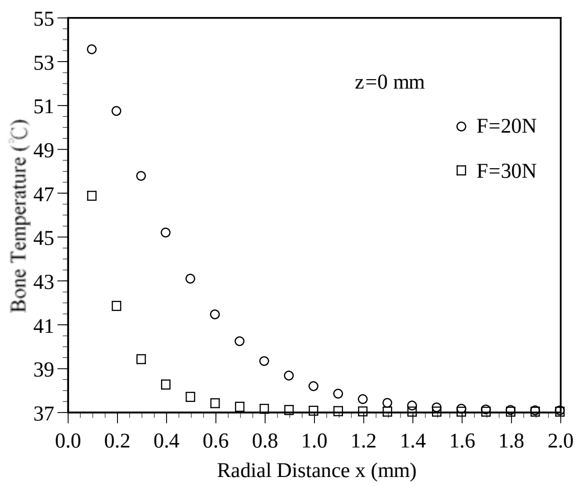

Figure 6. Variation of bone temperature along the radial direction as a function of applied force

be varied along the radial direction at the distance of 0.16 mm for a K-pin with initial temperatures of $25\,^{o}\mathrm{C}$ and $10\,^{o}\mathrm{C}$, respectively. The results indicate that a K-pin with low initial temperature can reduce bone temperature rise during drilling. The results also indicate that the cortical bone is a poor conductor because the TAZ is not obvious. The effect of drilling time on the bone temperature distribution is shown in Fig. 5. The initial K-pin temperature is $0\,^{o}\mathrm{C}$. It is obvious that the bone temperature increases with the drilling time. This can be attributed to that more friction heat is created as the drilling time increases. It is clear that all the temperatures on the bone surface are under 55 °C . Figure 6 shows the variation of bone temperature along the radial direction for two applied forces. The drilling times shown in Fig. 6

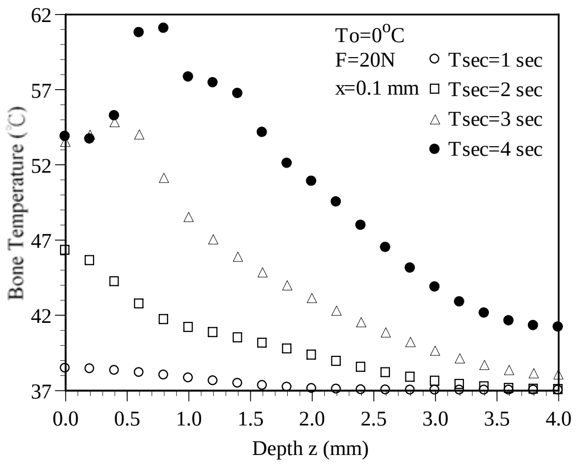

Figure. 7. Variation of bone temperature along the depth as a function of drilling time for the applied force of 20N

are 3 seconds and 1.3 seconds for the applied forces of 20N and 30N, respectively.

In these two cases, the K-pins have the same drilling depth. It is observed that the bone temperature can be reduced effectively as the applied force is increased form 20 N to 30 N. The results shown above are taken from the bone surface. The temperature distributions in bone during drilling along longitudinal direction (the z-axis) are shown in Figs. 7 and 8. These two figures show the bone temperature distributions for various drilling time with applied forces of 20N and 30N, respectively. In these cases, the K-pin has an initial temperature of 0 °C . Although, the drilling time shown in Figs. 7 and 8 are different, the drilling depths represented by the same symbols in these two figures are the same. It is clear that the bone temperature increases with the drilling time. The peak temperature can reach as high as 61 °C when the drilling time is 4 seconds for the applied force of 20N, as shown in Fig. 7. Accordingly, a larger applied force is proposed to reduce the peak temperature in bone, as shown in Fig. 8. The peak temperature is reduced to 52 °C as the applied force is increased to 30N. From the discussion above, the K-pin with a lower initial temperature or a larger applied force can reduce the bone temperature rise easily in surgical operation.

4. Conclusion

This study has performed numerical investigations into the temperature rise distribution in bone during drilling. The numerical analysis has been conducted using an

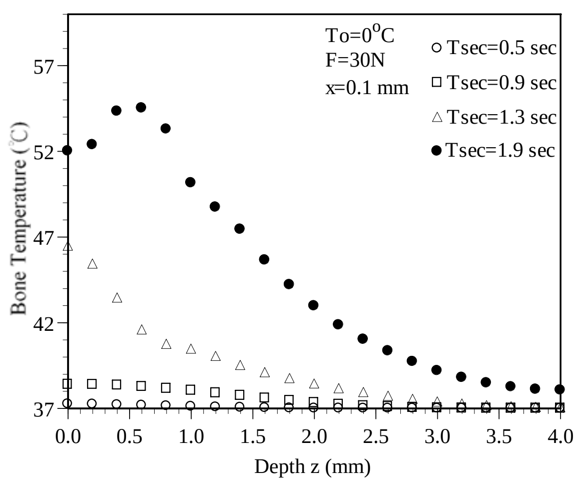

Figure 8. Variation of bone temperature along the depth as a function of drilling time for the applied force of 30N

elastic-plastic dynamic temperature-displacement finite element model. The effect of initial temperature of K-pin and applied force on the temperature rise has been examined. Based upon the numerical results, the following conclusions can be drawn:

1. The proposed dynamic elastic-plastic finite element model can be used to simulate the temperature rise for a K-pin drilling through the bone.
2. A K-pin with a lower initial temperature can reduce the temperature rise in bone during drilling.
3. The size of the thermal affected zone can be reduced for a K-pin with a lower initial temperature.
4. A larger applied force can reduce temperature rise effectively.

References

1. Hillery MT, and Shuaib I. Temperature effects in the drilling of human and bovine bone. Journal of Materials Processing Technology, 1999, 92-93: 302-308.
2. Khanna A, Plessas SJ, Barrett P, and Bainbridge LC. The Thermal Effects of Kirschner Wire Fixation on Small Bones. Journal of Hand Surgery, 1999, 24: 355-357.
3. Eriksson A, Albrektsson T. Temperature threshold

levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. Journal of Prosthetic Dentistry 1983, 50: 101-107.

4. Abouzgia MB, James DF. Measurements of shaft speed while drilling through bone. Journal of Oral and Maxillofacial Surgery, 1995, 53:1308-1315.
5. Bachus KN, Rondina MT, Hutchinson DT. The effects of drilling force on cortical temperatures and their duration: An in vitro study. Journal of Medical Physics and Engineering 2000, 22: 685-691.
6. Allan W, Williams ED, Kerawala CJ. Effects of repeated drill use on temperature of bone during preparation for osteosynthesis self-tapping screws. Journal of Oral and Maxillofacial Surger , 2005, 43: 314-319.
7. Davidson SRH, James DF. Drilling in bone: modeling heat generation and temperature distribution. Journal of Biomechanical Engineering, 2003, 125: 305-314.
8. Guo YB, Dornfeld DA. Finite element modeling of burr formation process in drilling 304 stainless steel. Journal of Manufacturing Science and Engineering, 2000, 122: 612-619.
9. Borzacchiello A, Ambrosio L, Nicolai, L, Harper EJ, Tanner KE, Bonfield W. Comparison between the polymerization behavior of a new bone cement and a commercial one: modeling and in vitro analysis. Journal of Materials Science, 1998, 9: 835-838.
10. http://www.matwed.com