Finite Element Simulations of Bone Temperature Rise During Bone Drilling Based on a Bone Analog

Yuan-Kun Tu[1,2] Li-Wen Chen[3] Ji-Sih Ciou[3] Chih-Kun Hsiao[2]
Yung-Chuan Chen[3,*]

[1]*Department of Biomedical Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC*
[2]*Department of Orthopedics, E-Da Hospital / I-Shou University, Kaohsiung 824, Taiwan, ROC*
[3]*Department of Vehicle Engineering, National Pingtung University of Science and Technology, Pingtung 912, Taiwan, ROC*

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Abstract

Many researchers have attempted to measure bone temperature using thermocouples; however, the limitations of thermocouples make it difficult to determine the bone temperature in the immediate vicinity of a drilled hole. This study develops a method of analysis that can be used to obtain the bone temperature rise in the immediate vicinity of a drilled hole. A three-dimensional finite element model, based on a bone analog, was used to simulate bone temperature rise during a drilling process. The effect of drilling speed on bone temperature distribution is discussed. The results indicate that, for a constant drill feed rate, the drill bit with a higher rotation speed can cause a noticeable increase in bone temperature as well as the size of the thermally affected zone. Based on the numerical results, an empirical equation is proposed to estimate the peak bone temperature using the value of the rotation drilling speed. The maximum difference between the peak bone temperatures predicted by the proposed equation and those obtained from the numerical model is less than 3.5%.

Keywords: Finite element model (FEM), Temperature distribution, Drill bit, Drilling speed, Thermally affected zone

1. Introduction

The success of osteosynthesis in orthognathic and trauma surgery depends on many factors. While many of these factors are determined by the particular technique used, one practical factor that is commonly underestimated is the possibility of thermally induced bony necrosis at the drill site [1-3]. In orthopedic surgery, heat generation is an important issue during bone drilling since the heat is not easily conducted away from the drill site; thus, the bone is at significant risk of thermal damage. Eriksson and Albrektsson indicated that cortical necrosis occurs in living rabbits when the bone is heated to 47 ℃ for 1 min [2]. Other study showed that if the temperature rises above 55 ℃ for a period longer than 30 s, great damage occurs to the bone [4]. Many researchers have investigated the problem of reducing the heat generated during bone drilling. Studies have shown that drilling at a high rotation speed with a large force might be desirable because it limits the rise in bone temperature [5]. Matthews and Hirsch did not find any significant change in temperature rise with speeds from 350 to 2900 rpm while drilling in human cortical bone [6]. Their studies also indicated that increasing the applied force from 20 to 120 N could decrease the maximum temperature rise. Similarly, other study indicated that a higher applied force led to an effective reduction in maximum cortical bone temperature [7]. The results reported by Augustin *et al*. showed that at a constant drill feed rate, increases in drill diameter and drill speed caused increases in bone temperature [8].

In experimental studies, the temperature rise within the bone is measured using a thermocouple positioned adjacent to the drill site. However, in practice, the thermocouple can be placed no closer than 0.5 mm from the edge of the drilled hole. Since the frictional heat generated by the drilling process is not easily conducted away by the bone, the temperature measurement obtained using a thermocouple does not provide a true indication of the peak temperature in the immediate vicinity of a drilled hole. Therefore, various researchers have suggested the use of finite element (FE) methods for simulating the drilling process [9,10]. However, very few studies have investigated the peak temperature in the immediate vicinity of a drilled hole.

The present study proposes an elastic–plastic FE model (FEM) for simulating the thermal contact behavior between bone and a drill bit during bone drilling. The model allows both the temperature rise and temperature distribution near the

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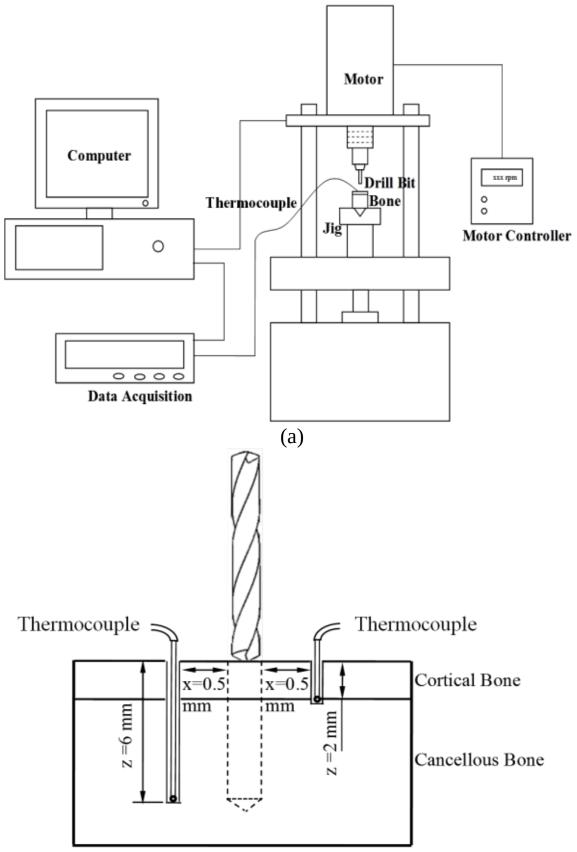
* Corresponding author: Yung-Chuan Chen
Tel: +886-8-7703202 ext. 7460; Fax: +886-8-7740398
E-mail: chuan@mail.npust.edu.tw

drilled hole to be effectively estimated. Utilizing the FEM, a series of simulations were performed to examine the effects of drilling speed on the temperature of the bone during the drilling process.

2. Materials and methods

2.1 Materials and experimental setup

The experimental setup used in this study to measure the temperature rise within the bone during drilling is schematically shown in Fig. 1(a). It includes a drilling machine, a drill bit, a biomechanical test block (a bone analog), an electronic data acquisition system (model 2680A, Fluke Corporation, USA), a computer system, thermocouples (K-type, precision 0.4%, Omega Corporation, USA), a motor controller, and a jig. Biomechanical test blocks, supplied by Sawbones [11], were used as test samples in this study. The Sawbones samples have uniform material properties and are convenient to obtain and preserve. Two test blocks, namely a cortical bone, with a thickness of 2 mm (Model#3401-01), and a cancellous bone, with a thickness of 40 mm (Model#1522-05), were used in the experiments. To verify that the results obtained from biomechanical test blocks are comparable to those obtained from actual bone drilling operations, the experiments were also performed by drilling a pig femur.



(a)

(b)

Figure 1. (a) Experimental setup for bone temperature rise measurement and (b) schematic illustration of the embedded positions of thermocouples.

Signals from thermocouples were transmitted to a computer system via an electronic data acquisition system. The bone temperature rise was monitored by continuous measurement of temperature change during the drilling process. The drill bit used in these experiments was made of stainless steel. The diameter, point angle, and helix angle of the drill bit were 2 mm (D=2.0 mm), 118°, and 23°, respectively. In these drilling experiments, the drilling depth and feed rate of the drill bit were kept constant at 6 mm and 0.9 mm/s, respectively. Figure 1(b) shows two thermocouples placed at position $x = 0.5$ mm from the edge of the drilled hole. The two thermocouples were at depths of $z = 2$ and $z = 6$ mm (where $z = 0$ mm indicates the upper surface of the bone), respectively.

2.2 Finite element model

Many studies [12-14] have observed plastic deformation in human bone. This study utilized a three-dimensional elastic-plastic temperature-displacement coupled FEM to simulate the thermomechanical behavior of the contact region between the drill bit and bone analog. The dynamic simulations were performed using the commercial ABAQUS® /Explicit package [15]. A dynamic failure criterion was applied to control the element removal during the drilling operation. Element deletion and mass scaling were employed to enable convergence of the FEM solution in the friction drilling modeling. Element deletion was also applied to control element removal during the drilling operation. The criterion used to delete an element is based on the value of effective plastic displacement, which was set as 0.1 mm. This option is used to provide material properties that define the evolution of damage leading to eventual failure. During the drilling simulation, bone elements are gradually deformed. When the effective plastic displacement of the elements reaches 0.1 mm, i.e., damage occurrs, the bone elements are removed. In the simulations, the thermal contact behavior between the drill bit and bone was modeled using surface-to-surface contact discretization because it provides more accurate stress and pressure results than node-to-surface discretization. In addition, the contact interaction properties must be defined for the contact pair. In this study, the surface of the drill bit is defined as the master surface. The slave surfaces include all the bone surfaces that will be contacted by the bone surfaces within a diameter of 2 mm. The friction behavior between the drill bit and bone is assumed to be governed by Coulomb's friction law. In accordance with the results presented by Mellal *et al*., the coefficient of friction is assumed to have a value of 0.3 [16].

Figure 2 illustrates the drill bit and bone contact geometry reflected in the simulated model. The region of particular interest is located in the immediate vicinity of the drilled hole, and thus, the domain for numerical simulations is specified as a cylinder with 10 mm in diameter and 8 mm in height. In this study, the thicknesses of the cortical bone and cancellous bone are set at 2 and 6 mm, respectively. In addition, the diameter, point angle, and helix angle of the drill bit are specified as the values used in the drilling experiments. The origin of the coordinate system (x,z) is set to correspond to the surface of the bone at a distance of 1 mm from the center of the drill bit.

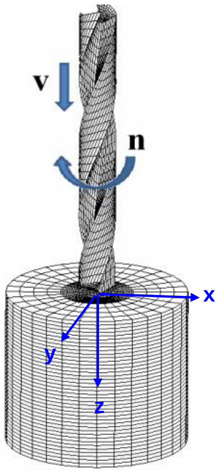


Figure 2. Finite element model of drill bit and bone.

In the FE model (shown in Fig. 2), the mesh is constructed using eight-node three-dimensional brick elements with a total of 21,415 elements and 31,483 nodes used in each simulation. Contact elements are used to simulate the contact behavior at the interface between the drill bit and bone. The bone and drill bit are assumed to have the same initial temperature of 25 ℃. The values used for drilling depth and the feed rate of the drill bit are those used in the drilling experiments. The region on the outer surface of bone, i.e., the surface at a radius of 5 mm, is assumed to be fixed during the simulations. The drill bit is modeled as a rigid body. The mechanical properties of the cortical and cancellous bones used in the FE simulations are provided by Sawbones and summarized in Table 1.

Table 1. Mechanical properties of sawbones used in FE simulations.

Property	Cortical bone	Cancellous bone
Density (kg/m^3)	1640	640
Young's modulus (MPa)	16700	1000
Yield strength (MPa)	105	19
Tensile strength (MPa)	106	19.1
Specific heat (J·kg^{-1}·℃$^{-1}$)	1640	1477
Poisson's ratio [18]	0.3	0.055
Conductivity (W/K·m)	0.452	0.087

3. Experimental results and verification of the FEM

This study measured the temperature rise in a pig femur and in a biomechanical test block (provided by Sawbones) to compare the temperature differences during the drilling process. The pig femur was obtained from a fresh pig in the local area. The cortical bone thickness of the pig femur used in this experiment was 2.08 mm. Figure 3 plots the bone temperature distributions with drilling time for the samples from Sawbones and for the porcine femur. The feed rate and drilling speed of the drill bit were v = 0.9 mm/s and n = 800 rpm, respectively. The peak temperatures obtained from the Sawbones test blocks and the pig femurs were measured as 51 ℃ and 49.8 ℃, respectively. The corresponding drilling time required to reach the peak temperature was 7.8 s and 7.7 s, respectively. The results indicate that the biomechanical test blocks used in this study are comparable to pig bone with respect to providing comparative accuracy in predicting bone drilling temperature rise.

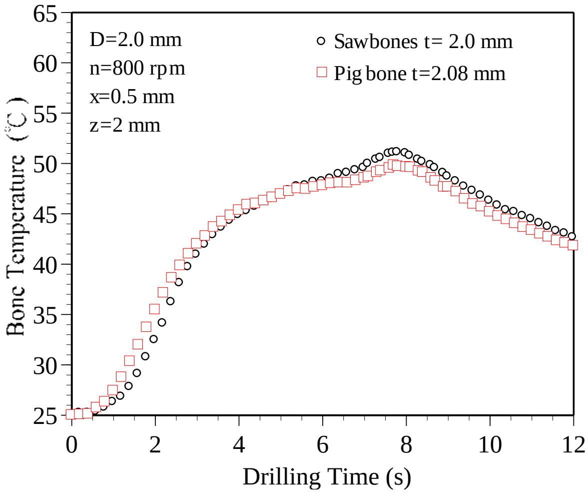
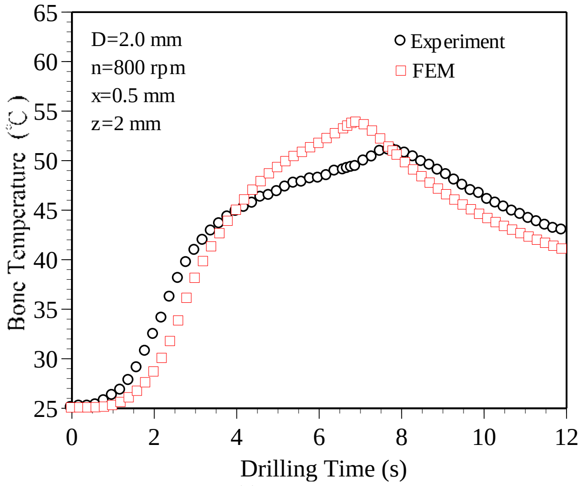
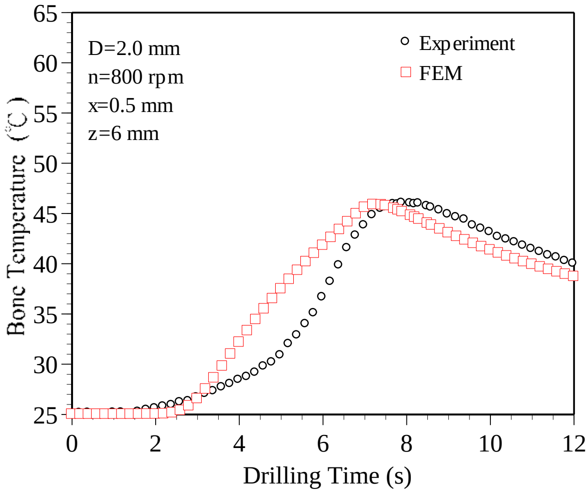


Figure 3. Comparison of bone temperature distributions obtained from Sawbones samples and pig bone.



(a) z = 2 mm



(b) z = 6 mm

Figure 4. Comparison of numerical and experimental results for variation of bone temperature with drilling time. (a) z = 2 mm and (b) z = 6 mm.

To compare the variations of numerical and experimental results in bone temperature and drilling time, the drill feed rate and drilling speed of the drill bit were v = 0.9 mm/s and n = 800 rpm. The results shown in Fig. 4 are taken from the measurement positions located at a distance of x = 0.5 mm from the edge of the drilled hole and at depths of z = 2 mm and z = 6 mm, respectively. In general, both figures show that good agreement exists between the simulation results experimental values. In Fig. 4(a), the peak temperature obtained in the numerical simulations is 54 ℃, while that observed experimentally is 51 ℃. The corresponding drilling times required to reach these peak temperatures are 6.9 and 7.8 s, respectively. In Fig. 4(b), the peak temperature in numerical simulations is found to be 45.9 ℃, while that observed experimentally is 46.1 ℃. The difference in the drilling times required for achieving the peak temperatures is about 0.7 s.

Figure 5 presents the variation of bone temperature along the radial direction x for various drilling speeds. The measurement depth is z = 2 mm. The experimental measurements obtained for a drilling speed of n = 1200 rpm are indicated by the solid symbols. It can be seen that the decreasing trend of bone temperature along the radial direction x is similar to an exponential function. Figure 5 also shows that the sizes of the thermally affected zone (TAZ) obtained for drilling speeds of n = 600, 800, and 1200 rpm are 0.35, 0.7, and 1.38 mm, respectively. Applying the nonlinear least squares fitting process described by Ridders [17] to the simulation data in Fig. 5 (indicated by the empty symbols), it can be shown that the peak bone temperature T induced at each drilling speed n is related to the distance from the edge of the drilled hole x via the expressions:

$$T(^oC)=25.81+37.29exp(-1.44x) \quad \text{at } n = 600 \text{ rpm} \tag{1}$$

$$T(^oC)=26.19+54.72exp(-1.39x) \quad \text{at } n = 800 \text{ rpm} \tag{2}$$

$$T(^oC)=27.01+125.47exp(-1.30x) \quad \text{at } n = 1200 \text{ rpm} \tag{3}$$

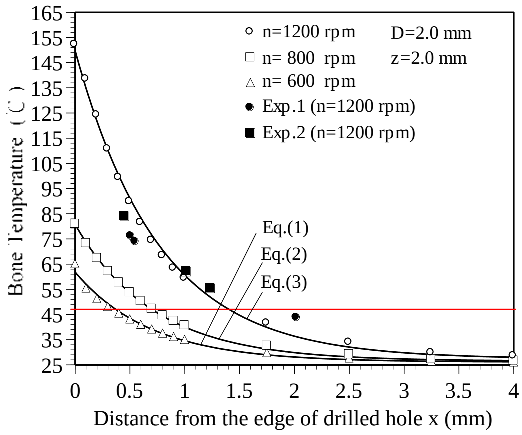


Figure 5. Variation of bone temperature along the radial direction for various drilling speeds.

The feasibility of the proposed dynamic FEM was confirmed by comparing numerical solutions for variations in bone temperature with experimental results obtained from the biomechanical test blocks.

The thermocouples used in practical bone drilling experiments can be positioned no closer than 0.5 mm from the edge of a drilled hole. However, this problem can be effectively resolved using the dynamic FEM proposed in this study. The simulations were performed at three drilling speeds, i.e., n = 600, 800, and 1200 rpm. Figure 6 presents the variation of bone temperature with the drilling time at depths of z = 2, 3, 5, and 6 mm. The drilling speed and temperature measurement position are n = 800 rpm and x = 0.5 mm, respectively, in all four cases. The bone temperature distributions vary noticeably with measurement depth. The peak bone temperature occurs after approximately 7 s in all cases. The difference between the peak bone temperatures obtained at different measurement depths reaches 8 ℃. The maximum value for the peak bone temperature was about 54 ℃, occurring at depth z = 2 mm. This depth corresponds to the interface between the cortical bone and the cancellous bone. Thus, in the following discussions, all the bone temperatures are taken at depth z = 2 mm.

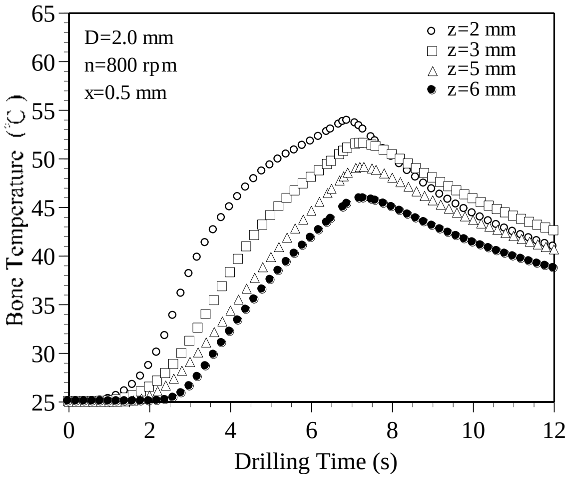


Figure 6. Variation of bone temperature and drilling time at various depths.

4. Discussion

Since the frictional heat generated by the drilling process is not easily conducted away by the bone, the information about temperature distribution at positions in the immediate vicinity of the drilled hole is important. Figure 7 shows the simulation

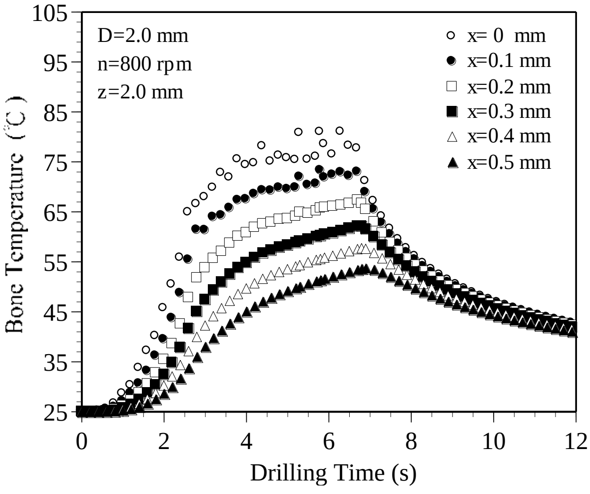


Figure 7. Variation of bone temperature with drilling time at various locations from the edge of the drilled hole.

results for the variation of bone temperature with drilling time at six distances from the edge of the drilled hole, i.e., x = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5 mm. Note that in the simulations, the drilling speed was given as n = 800 rpm. The results show that the temperature increases rapidly in the region of the bone located immediately adjacent to the drilled hole. This result is expected since bone is a poor thermal conductor, and thus, the frictional heat generated during the drilling operation is not easily conducted away from the drill site. From inspection, the peak temperatures derived for measurement positions x = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5 mm are 80, 73, 67, 62, 58, and 53 ℃, respectively. The peak temperature varies by as much as 27 ℃ within a distance of 0.5 mm from the drilled hole. The corresponding drilling times required to achieve the peak temperature at measurement positions x = 0 and 0.5 mm are 6.3 and 6.9 s, respectively. Thus, the thermal conduction causes a lag of approximately 0.6 s before the region of the bone located at a distance of 0.5 mm from the drilled hole reaches its peak temperature. The simulation results confirm that the frictional heat generated by the drilling process is not easily conducted away by the bone. Since the maximum temperature occurs at a distance of 0 mm from the edge of the drilled hole, all the remaining simulations only consider the measurement position x = 0.0 mm.

A further series of simulations was performed to investigate the effect of drilling speed on the temperature rise induced within the bone. In these simulations, the measurement position was located at x = 0.0 mm and z = 2.0 mm. Drilling speeds of n = 600, 800, and 1200 rpm were used. Figure 8 indicates that a higher drilling speed leads to an obvious increase in bone temperature. From inspection, the peak temperatures are 59.5, 80.9, and 152.0 ℃ for drilling speeds of 600, 800, and 1200 rpm, respectively. The peak temperature increases by approximately 92 ℃ as the drilling speed is increased from 600 to 1200 rpm. The peak temperatures for drilling speeds of 600, 800, and 1200 rpm occur after 4.3, 5.8, and 6.6 s, respectively. Thus, a higher drilling speed increases both the peak bone temperature and the drilling time required to reach the peak temperature. According to the results reported by Eriksson and Albrektsson [1,2], a temperature of 47 ℃ is the limit that bone can withstand without undergoing necrosis. In this study, the region in which bone temperatures exceed 47 ℃ is defined as the TAZ. The TAZ can be used as an index to estimate the potentially damaged zone in the bone. The results confirm that the proposed dynamic FEM can be applied to obtain the bone temperature rise in the vicinity of the drilled hole. The TAZ increases with increasing drilling speed. This can be attributed to increases in the accumulated frictional energy from the drilling operation with increasing drilling speed. This increase in frictional energy, in turn, results in a higher bone temperature and a larger TAZ. Figure 9 presents the temperature distribution contours within the bone for each drilling speeds of 600, 800, and 1200 rpm and corresponding drilling times of 2.2, 3.8, 5.4, and 6.6 s. Note that the contours correspond to a measurement depth of z = 2 mm in every case. The gray-colored areas shown in Fig. 9 represent the TAZ region. The size of the TAZ increases with increasing drilling speed and drilling time.

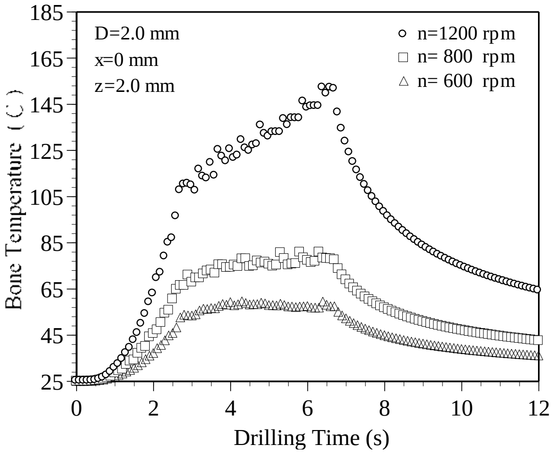


Figure 8. Variation of bone temperature with drilling time for various drilling speeds.

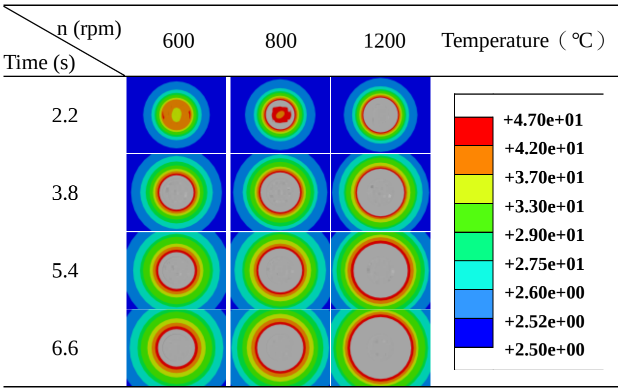


Figure 9. Bone temperature contours for various drilling speeds and drilling times.

Equations (1)-(3) predict the peak bone temperatures with distance x from the drilled hole for various drilling speeds. By comparing the simulation results, the maximum difference between the predicted and the simulated results is less than 5% in all cases. In other words, the proposed equations give a good approximation of the simulation results and, therefore, provide a convenient means of predicting the peak bone temperature during bone drilling.

In experimental bone-drilling studies, the thermocouple used to measure the drilling-induced temperature rise can be positioned no closer than 0.5 mm from the drilled hole. As a result, it is impossible to obtain the true value of bone temperature in the immediate vicinity of the drilled hole. In this study, a FEM was proposed to solve this problem. The drilling operation was simulated using an elastic-plastic FEM of the bone analog and drill bit. The validity of the FEM was confirmed by comparing the simulation results with the experimental results. Simulations were then performed to clarify the effect of the drilling speed on the temperature rise induced within the bone in the immediate vicinity of the drilled hole.

Previous study showed that the temperature increased with increasing depth of the hole in a human bone specimen [14]. The drill speed was varied from 400 to 2000 rpm and the drill diameter was 3.2 mm. Other study recorded temperatures of over 100 ℃ at a distance of 0.5 mm with low drill speeds and a drill diameter of 3.2 mm [6]. In the experiments, thermocouples were used to measure the temperature rise in a femoral specimen. The simulation results reported by Davidson and James [9] also showed that the maximum temperature increased with increasing rotational speed of the drill bit. Their simulation results indicated that the maximum temperature varied from 60 ℃ to 140 ℃ at a distance of 0.5 mm from the drill hole with the drill speed varied from 100 to 200,000 rpm and a drill diameter of 2.5 mm. The model proposed here predicts a maximum temperature of between 45 ℃ and 90 ℃ at that location.

The limitation of this study is that the diameter of a drill bit was 2 mm with a helix angle of 23 °. The drilling depth and feed rate of the drill bit were 6 mm and 0.9 mm/s, respectively. The drilling rotational speed was less than 1200 rpm. However, the drilling speed and diameter of the drill bit could also affect the maximum temperature and temperature distribution in human bones, more researches on these parameters should be considered in the future study.

5. Conclusion

This study investigated the bone temperature rise during bone drilling. The numerical results indicate that the peak temperature increases more than 27 ℃ within a distance of 0-0.5 mm from the drilled hole. The peak bone temperature and the size of the TAZ increase with increasing drilling speed. The FEM was verified by experiments and can be used to predict the peak value of the bone temperature during drilling with speeds of 600, 800, and 1200 rpm. The peak temperature difference obtained from the proposed FE model and the experiment is no more than 3 ℃. The sizes of the TAZ obtained from drilling speeds at n = 600, 800, and 1200 rpm are 0.35, 0.7, and 1.38 mm, respectively.

Acknowledgments

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