Temperature rise of alveolar bone during dental implant drilling using the finite element simulation

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Abstract: In this study, a three-dimensional elastic-plastic dynamic finite element model is used to simulate the alveolar bone temperature rise during dental implant drilling. An experimental setup was designed to verify the feasibility of the proposed dynamic finite element model. The peak bone temperature within the alveolar bone is investigated through both simulations and experiments. The results indicate that the proposed elastic-plastic dynamic finite element model can provide a good prediction of the alveolar bone temperature rise during the implant drilling. The result also indicated that the peak bone temperature occurs at the interface of cortical bone and cancellous bone for a fixed feeding rate. [Life Science Journal. 2010; 7(1): 68 – 72] (ISSN: 1097 – 8135).

Keywords: dental implant; drill bit; temperature rise; dynamic finite element model

1. Introduction

Dental implant is an artificial dental root used to replace a natural one. It is generally made of pure titanium or titanium alloy. At present, the dental implantology has been considerably matured, but how to improve the success rate of implantation is still the major direction in the relevant research field.

The study by Alberktsson et al [1]indicated that the success of endosteal implants depends on the primary healing capability of alveolar bones. The temperature rise within the alveolar bone during bone drilling is the one critical factor that affects the primary healing capability of alveolar bone. Many researchers [2-5] showed that heat generation is an important problem during bone drilling since the heat is not easily conducted away from the drill site and thus the bone is at significant risk of thermal damage. The literatures indicated that temperatures ranging from 56 ^{o}C to 70 ^{o}C are harmful to bone tissue because alkaline phosphatase (AP) is transformed at that level [5-9]. Eriksson and Albrektsson [10] inferred that temperatures below the transference point of AP (53 ^{o}C) could be considered unfavorable to the reparative capability of bone, as burning and resorption of fat cells together with sluggish blood flow were observed. The above-mentioned phenomena are called osseous necrosis. Eriksson and Albrektsson [10-12] reported in their studies that bone would bear a threshold temperature ranging from 44 ^{o}C to 47 ^{o}C for 1 minute without defective bony regeneration. Finally, Tehemar concluded that heating up to 47 ^{o}C could be considered as the optimal limit that bone can withstand without necrosis [12].

As mentioned above, decreasing the temperature rises caused by surgical drillings can enhance the primary healing capability of alveolar bones and further increase the success rate of implantation. The temperature rise measurement of surgical drilling can be generally divided into two types, infrared rays [13-14] and thermocouples [15-16], both of which have certain limitations. Infrared rays can only be applied to measure the temperature distribution on the bone surface. In experiments, the thermocouple can be placed no closer than 0.5 mm from the edge of the drilled hole to avoid the damage of thermocouple [17]. Since the frictional heat generated by the drilling process is not easily conducted away by the bone, the temperature measurements obtained using the thermocouple are not able to provide a true indication of the peak temperature in the immediate vicinity of the drilled hole. Accordingly, the present study proposes a dynamic finite element model to simulate the thermal contact behavior between the bone and the drill bit during bone drilling. Both the temperature rise and the temperature distribution near the drilled hole to be effectively reproduced through these simulations.

2. Experimental measurement of bone temperature rise

Figure 1 presents a schematic illustration of the experimental setup used to measure the temperature rise within the bone during drilling. As shown, the major components include a drilling machine, a dental drill bit, a biomechanical test block, an electronic data acquisition system (model 2680A, Fluke Corporation), a computer system, thermal couples (K-type), a torque sensor, a load cell, a motor controller, and a jig. Biomechanical test blocks supplied by Sawbones [18] are used to replace human alveolar bone in this study. The mechanical properties of biomechanical test blocks and human bones are similar. The pilot drill bit (Straumann, Swiss) used in experiments is made of stainless steel with a diameter of 2.2 mm. Figure 2 shows two thermocouples placed at positions x=0.5 mm from the edge of the drilled hole. The depths or the vertical positions of the two thermocouples are at z= 1 and z= 6 mm (z= 0 indicates the upper surface of the bone), respectively. The drilling speed and the feeding rate in all the experiments were fixed at 800 rpm and 0.9 mm/s, respectively.

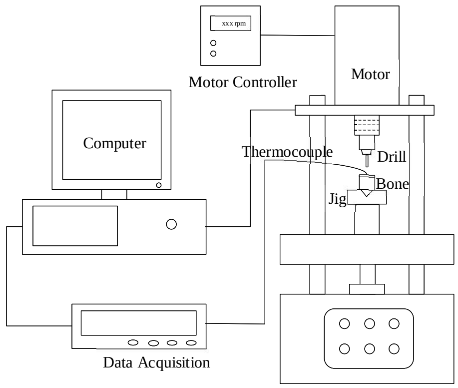

Figure 1. Experimental setup for bone temperature rise measurement

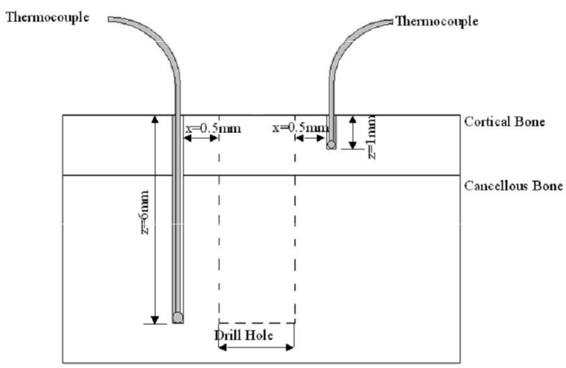

Figure 2. Schematic illustration of thermocouple embedded positions

3. Finite Element Model

A three-dimensional elastic-plastic dynamic temperature-displacement coupled finite element model (FEM) is used to simulate the thermo-mechanical behavior of the contact region between the drill bit and the alveolar bone during drilling. The simulations are performed using the commercial ABAQUS/Explict package (2008), and a dynamic failure criterion is applied to control the element removal during the drilling operation. In performing the simulations, the thermal contact behavior between the drill bit and the alveolar bone is modeled using contact elements.

The shape of alveolar bone is extremely complicated, but the region of particular interest is in the immediate vicinity of the drilled hole for a single implantation. Thus, without loss of generality, the domain for the numerical simulations is simplified as a circular disc. The alveolar bone model used in this study is 10 mm in diameter and 20 mm in height. As shown in Fig. 3, the thicknesses of cortical bone and cancellous bone are taken as 2 mm and 18 mm, respectively. These dimensions are taken according to the maximum width of the single edentulous zone as well as the relevant dimensions of human alveolar bone. The drill bit and bone contact geometry considered in this study is shown in Fig. 4. The finite element model comprises a total of 241,296 eight-node hexagonal elements and 250,975 nodes. The contact behavior between the drill bit and the bone is simulated using 25,800 contact elements. According to the previous study [19], the coefficient of friction is taken as 0.3. Figure 4 shows the enlarged view of the drill bit and bone contact finite element model.

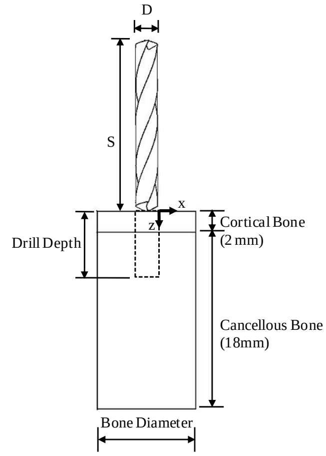

Figure 3. Configuration of a drill bit and bone contact model

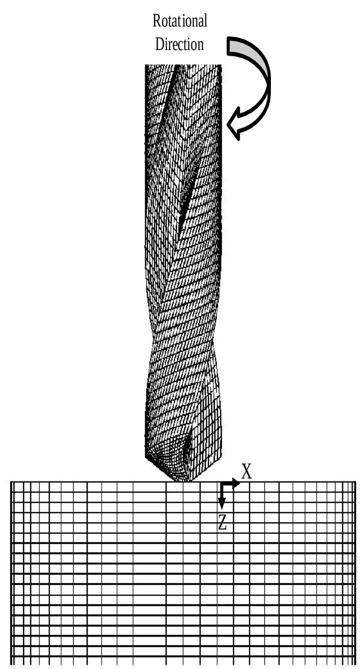

Figure 4. A enlarge view of the drill bit and bone contact finite element model

The alveolar bone used in this study is a biomechanical test block supplied by Sawbones [18] according to the testing standards of ASTM D-1621, D-1623, and D-273. The material of drill bit is SUS420 stainless steel. The mechanical properties of the drill bit and bone used in finite element simulations are summarized in Table 1. The initial temperatures of the drill bit and the bone in simulations are both taken as 25 °C

Table 1. Mechanical properties of the drill bit and bone used in FE simulations

Material properties	Biomechanical test blocks [18]		Drill bit [20]
	Cortical	Cancellous	
Density(kg / m^3)	1640	320	7800
Young's Modulus(MPa)	16000	2840	200000
Poisson's Ratio	0.30	0.06	0.24
Yielding Stress(MPa)	106.99	5.69	585.00
Tensile Stress(MPa)	107.00	5.70	760.00
Specific Heat (J /kg-℃)	1640	1570	460
Thermal Conductivity (W / m-k)	0.45	0.05	24.90
Thermal Expansion (k^{-1})	6.30×10^{-5}	6.30×10^{-5}	1.03×10^{-5}

4. Results and Discussions

The feasibility of the proposed dynamic FEM model was confirmed by comparing the numerical solutions for the variations of bone temperature with the experimental results. Figure 5 and 6 present the simulation and experiment results of the temperature variation during drilling at the positions of x=0.5, z=1.0 mm and x=0.5, z=6.0 mm, respectively. The I-bars represent the temperature range of experimental results and the empty symbols are the corresponding mean values. The solid symbols indicate the numerical results obtained from the proposed dynamic finite element model. Both figures show good agreements exist between the simulation results and the experimental mean values. The largest deviation between the simulation and experimental results is less than 2 °C . Thus, the validity of the proposed dynamic FEM model is confirmed.

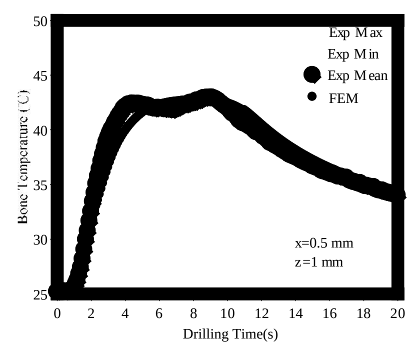

Figure 5. Comparison of experimental and numerical results for variation of bone temperature with drilling time at depth z=1 mm

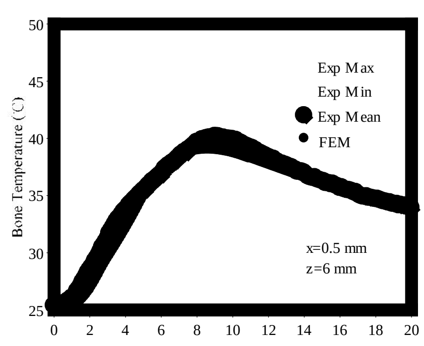

Figure 6. Comparison of experimental and numerical results for variation of bone temperature with drilling time at depth z=6 mm

It is important to decide what the peak temperature is and where it is occurred during dental implant surgical drilling. However, because of the technical reason, the thermocouple can be placed no closer than 0.5 mm from the edge of the drilled hole. In the following, the proposed dynamic finite element is used to investigate the peak bone temperature during drilling. The drilling speed and the feeding rate in all the finite element simulations were fixed at 800 rpm and 0.9 mm/s. Figure 7 shows that the bone temperature distribution at five different distances from the edge of the drilled hole, i.e. x=0.1 ~0.5 mm. The measurement depth in Fig. 7 is at z= 1 mm. The results show that the bone temperature increases rapidly in the region adjacent to the drilled hole (i.e. x=0.1 mm). It can be observed that the peak temperatures at measurement positions x = 0.1, 0.2 and 0.5 mm are found to be 55.3, 54.3 and 50.3 °C , respectively. The peak temperature varies by as much as 5 °C within a distance of 0.5 mm from the drilled hole. It also can be found that the drilling time taken to have the peak temperature occurred is different for different measurement positions.

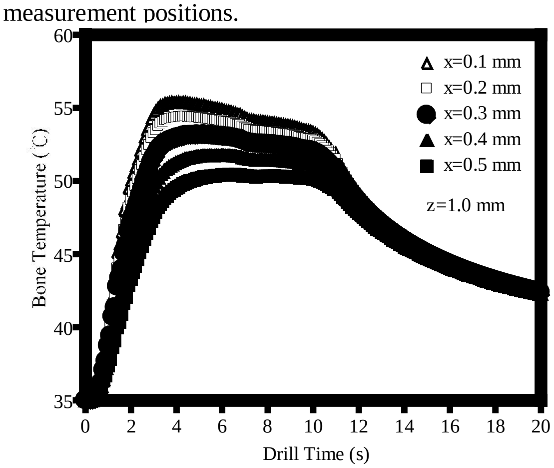

Figure. 7. Variation of bone temperature with drilling time at different measurement distances from the drill hole with a depth of z=1 mm

In the following, the bone temperature distribution along the drilling depth is explored by finite element simulations. The drilling depth of the drill bit is taken as 6 mm. The measurement distance from the drill hole is taken as x = 0.1 mm. Firstly, the variation of bone temperature within the cortical bone is discussed. The thickness of the cortical bone used in this study is 2.0 mm. Figure 8 shows the variation of bone temperature with drilling time at four different measurement depths, i.e. z= 0.2, 0.4, 0.6, 1.0 mm. The bone temperature rise at various depths of z= 1.2 to 2.0 mm is shown in Fig. 9. These two figures show that the bone temperature increases as the depth increases. The peak bone temperature within the cortical bone is 63.5 °C occurred at the depth of z=2.0 mm.

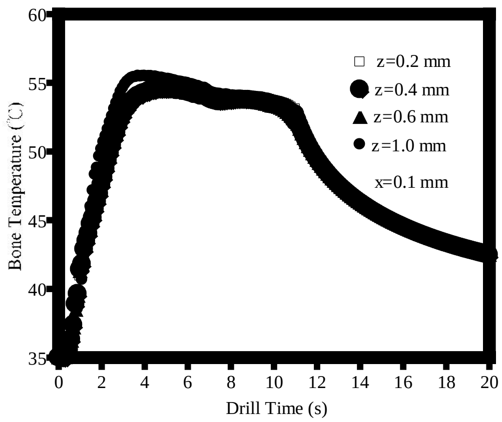

Figure 8. Variation of bone temperature with drilling time at measurement depths of z= 0~ 1.0 mm

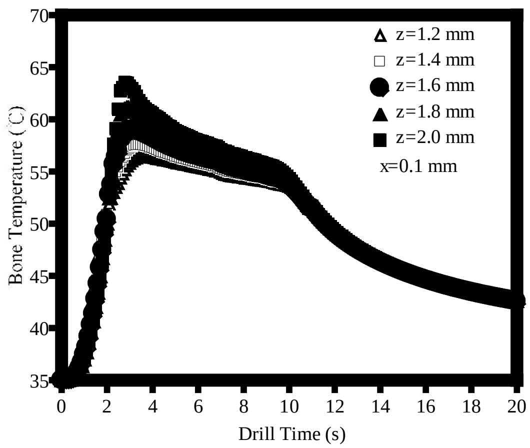

Figure 9. Variation of bone temperature with drilling time at measurement depths of z= 1.2~ 2.0 mm

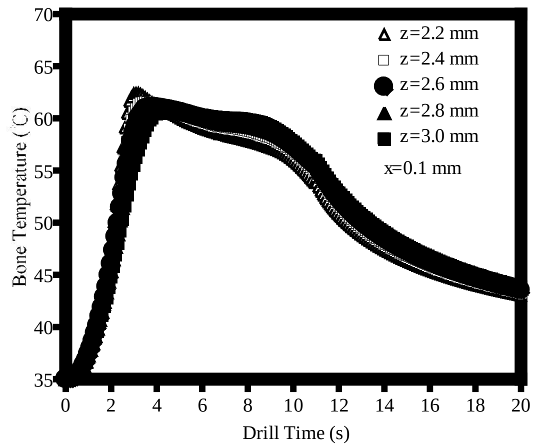

Figure 10. Variation of bone temperature with drilling time at measurement depths of z= 2.2~ 3.0 mm

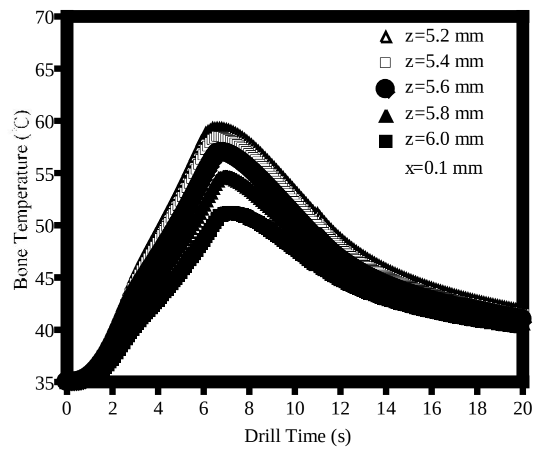

Figure 11. Variation of bone temperature with drilling time at measurement depths of z= 5.2~ 6.0 mm

However, the profile of bone temperature distribution within the cancellous bone is different to the one in the cortical bone. Figures 10 and 11 present the variation of bone temperature within the cancellous bone for depths of z=2.2 ~ 3.0 mm and z=5.2 ~6.0 mm, respectively. It can be found in Figs. 10 and 11 that the peak bone temperature decreases as the depth increases. The peak bone temperature is found to be 62.3 and 51.2 °C in Figs. 10 and 11, respectively. To summarize the results shown in Figs. 8 to 11, it can be found that the peak bone temperature occurs at the interface of cortical bone and cancellous bone for a constant feeding rate. According to the simulation data, the peak bone temperature is 63.5 °C occurred at drilling time of 3 seconds in this study.

5. Conclusion

In this study a 3D elastic-plastic dynamic finite element model is proposed to simulate the bone temperature rise during a dental implant drilling process. An experimental setup was designed to verify the feasibility of the proposed dynamic FEM model. The numerical results support the following major conclusions:

1. The proposed elastic-plastic dynamic FEM model can provide a good prediction of the alveolar bone temperature rise in the implant drilling process.
2. Because of the technical reason, the thermocouple is not able to detect the peak temperature in the immediate vicinity of the drilled hole. This problem is effectively resolved in the elastic-plastic dynamic FE model proposed in this study.
3. The temperature rise within the cortical bone is higher than what within the cancellous bone.
4. The peak bone temperature occurs at the interface of cortical bone and cancellous bone for a fixed feeding rate.

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