Medical Engineering & Physics xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Experimental investigations and finite element simulation of cutting heat in vibrational and conventional drilling of cortical bone

Yu Wang [a,b], Meng Cao [a], Xiangrui Zhao [a], Gang Zhu [a], Colin McClean [c], Yuanyuan Zhao [a], Yubo Fan [a,b,*]

[a] Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China
[b] Research Institute of Beihang University in Shenzhen, Shenzhen 518057, China
[c] Institute of Biomedical Engineering, National Yang-Ming University, Taipei, Taiwan

ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form 30 March 2014
Accepted 27 April 2014

Keywords:
Cutting heat
Vibrational drilling
Bone drilling
FEM
Simulation

ABSTRACT

Heat generated during bone drilling could cause irreversible thermal damage, which can lead to bone necrosis or even osteomyelitis. In this study, vibrational drilling was applied to fresh bovine bones to investigate the cutting heat in comparison with conventional drilling through experimental investigation and finite element analysis (FEA). The influence of vibrational frequency and amplitude on cutting heat generation and conduction were studied. The experimental results showed that, compared with the conventional drilling, vibrational drilling could significantly reduce the cutting temperature in drilling of cortical bone ($P < 0.05$): the cutting temperature tended to decrease with increasing vibrational frequency and amplitude. The FEA results also showed that the vibrational amplitude holds a significant effect on the cutting heat conduction.

1. Introduction

Bone drilling is a fundamental operation of orthopedic surgery, but inevitably generates a lot of heat, which may cause irreversible bone damage. Thermal bone damage can lead to bone necrosis or even osteomyelitis [1], which will reduce bone strength and causing loosening of internal fixation. So cutting heat will not only affect the post-operational recovery but also adversely influence the operation itself [2,3]. Hence, there is great significance to seeking an effective method of reducing the cutting heat in bone drilling.

Karmani proposed several important factors that contribute to cutting heat in the bone drilling and summarized the influence of drill force, speed, drill condition, coolants and other factors [4]. Augustin et al. [5] studied the effect of drill bit diameter, rotation speed, feed speed, drill bit helix angle and external cooling measures on the cutting heat. Allan et al. [6] presented a relationship between the level of drill bit wear and the temperature of the bone being drilled. Seze et al. [7] established a finite element model of the drill bit and bone to analyze the temperature distribution in different drilling depth. Alam et al. [8] proposed a finite element model of bone drilling, in which the drill was considered as a heat source contacted with the bone continuously.

In the 1960s, Kumabe first proposed vibrational drilling, which adds vibration along the axis of the drill bit [9]. Since then, extensive use of this method has proven its effectiveness over conventional drilling, particularly in reducing cutting heat [10–14]. But it is only in recent years that vibrational drilling had been applied to bones. Alam et al. [15] compared the drilling forces and torques during conventional and ultrasonically-assisted drilling. It was revealed that the ultrasonically-assisted drilling reduced trust force and torque compared to conventional drilling. Khademi et al. [16] also proved that a vibration frequency of 16 Hz and amplitude of 2–30 μm can reduce the feed force by 42%. But there is no attention has been paid to its potential ability of reducing the cutting heat in bone drilling.

In this study, vibrational drilling was applied to fresh bovine bones to research the effects of vibration drilling on cutting heat through experimental investigation and finite element analysis. In the experimental investigation, vibrational drilling of cortical bone was compared with conventional drilling to verify the effectiveness of this new drilling method in reducing the cutting heat. The influence of frequency and amplitude on cutting temperature was also studied. Finally a finite element model was established to simulate

* Corresponding author at: Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China. Tel.: +86 13691114411.
E-mail address: yubofan@buaa.edu.cn (Y. Fan).

http://dx.doi.org/10.1016/j.medengphy.2014.04.007
1350-4533/

the cutting heat conduction during vibrational and conventional bone drilling.

2. Materials and methods

2.1. Specimen preparation

Studies have shown that bovine bones, which are widely used in bone cutting heat research, have the similar thermal properties to human bones [17]. So in this study, cortical bone specimens were cut from the mid-diaphysis of bovine femurs which were obtained from a local butcher and were stored frozen at −10 °C before the experiment. Firstly, the epiphysis of bovine femurs were cut off, and the mid-diaphysis were cut into 10 mm thick slices by a precision cutting machine (KJ type SYJ-200, China; Fig. 1a). Then the thickness of the thickest part of each slice were measured. The thicknesses were in the range of 8–10 mm. So in the experiment the drilling depth was fixed at 8 mm to ensure the drill would not penetrate. As shown in Fig. 1b, the bone marrow was removed and the point to be drilled was marked on each slice of bones. Prior to drilling, the specimens were completely thawed for 1 h in a thermostat-controlled water bath which was adjusted to room temperature to guarantee that each specimen was at the same temperature at the beginning of drilling experiments.

2.2. Experimental equipment

The experimental setup was shown in Fig. 2. Conventional and vibrational drillings were performed on a dynamic material testing machine (Instron E10000, USA), which can provide adjustable vibration with uniform feed speed. Bone samples were clamped in a vise which is fixed on the platform of the testing machine. A regular hand drill, connected with a flexible drive rod, was used to transfer the rotational torque to a drill bit holder. The drill bit holder was mounted to the testing head of the machine. During experiments, the feed rate was fixed at 40 mm/min, and the rotation speed was fixed at 8000 rpm (revolutions per minute). The standard carbide twist drill bits with a 4 mm diameter were used. The helix angle of this bit is 28°, and the chisel edge angle is 55°. A BP-7033 platinum resistor module with a temperature measurement accuracy of ±0.1% was chosen to measure the temperature of the drilling holes.

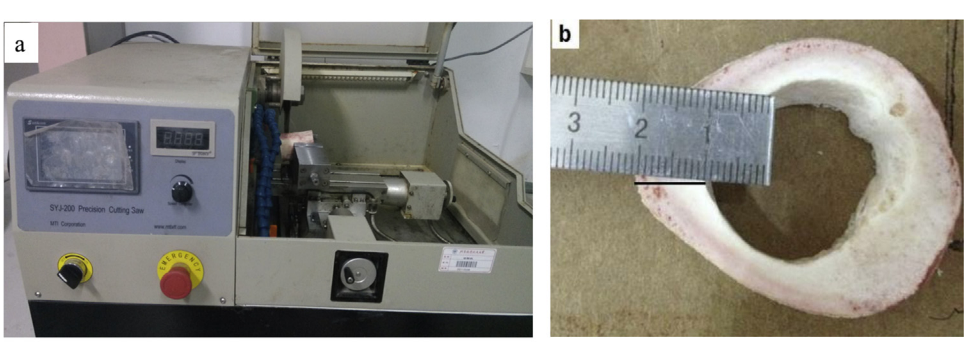
The motion of the testing head of the dynamic material testing machine was pre-programed in the WaveMatrix software to realize the feed motion of conventional and vibrational drilling with a fixed frequency and amplitude. Before drilling started, the drill bit was adjusted to just touch the bone surface by manual control. Then the hand drill was turned on, and the testing head would drop 8 mm according to the pre-programmed trajectory to realize the feed motion. When the feed motion was finished the testing head would quickly return to the starting position, so the drill bit was pulled out of the drilling hold immediately. Then the platinum resistor was quickly inserted to the bottom of the drill hole to measure the temperature. We continuously recorded the measured temperature until the temperature began to drop, so the highest temperature was chosen as the result.

During the vibrational drilling, the amplitude and frequency were adjusted orthogonally, in which amplitude was within the range of 100–500 μm and increased in steps of 100 μm, and the frequency was within 5–20 Hz and stepped up by 5 Hz. Therefore, 20 vibrational drilling groups (experimental groups) and 1 conventional drilling group (control group) were used. And 10 drillings were finished within each group. Totally 210 holes were drilled. In order to avoid excessive friction heat produced by drill bit wear, the drill bit was changed after 10 drillings. The mean temperatures of the drill holes in each group were calculated. The unpaired *t*-test method was used to evaluate the influence of vibration.

2.3. FEM modeling

During bone drilling there were two reasons why the temperature of bone would rise. One was that the friction between bone and drill bit and the internal structure damage would generate heat. The other reason was that due to the different thermal properties the temperature of drill bit would rise much faster than bone and was always much higher, so the drill bit would conduct heat to the bone. In this study, only the heat conduction between drill bit and the bone were simulated by FEA. A two-dimensional finite element model (FEM), which was generated by the pre-processing software package GAMBIT, was used to simulate the cutting heat conduction. Fig. 3 showed the geometrical configuration of the cutting heat conduction models for both conventional and vibrational drilling.

In order to achieve dynamic analysis of cutting heat conduction in vibrational drilling, the drill bit was constructed to a simple model, in which the screw thread was ignored. And since the temperature distribution in the bone was the research objectives, so the drill bit was constructed as a hollow wireframe model, of which the initial temperature was assigned to the boundary. The diameter of the drill bit was 4 mm, which was consistent with the drill bit used in the experiment. The diameter and the thickness of the bone were 8 mm and 9 mm. In order to consider the impact of air flow on the thermal conduction, an air layer which was 0.1 mm thick was constructed between the drill bit and the bone. There was an air region about 1.5 mm in height above the drill bit to provide the space for the drill bit vibration. The margin of this region was set as the exit of pressure, in which the air could flow freely. The initial position of the drill bit in the vibrational drilling was located at the upper limit position of the vibration, which was associated



(a) The precision cutting machine (b) specimen for drilling

Fig. 1. Specimen preparation. (a) The precision cutting machine (b) specimen for drilling.

Please cite this article in press as: Wang Y, et al. Experimental investigations and finite element simulation of cutting heat in vibrational and conventional drilling of cortical bone. Med Eng Phys (2014), http://dx.doi.org/10.1016/j.medengphy.2014.04.007