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Numerical evaluation of sequential bone drilling strategies based on thermal damage

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ABSTRACT

Sequentially drilling multiple holes in bone is used clinically for surface preparation to aid in fusion of a joint, typically under non-irrigated conditions. Drilling induces a significant amount of heat and accumulates after multiple passes, which can result in thermal osteonecrosis and various complications. To understand the heat propagation over time, a 3D finite element model was developed to simulate sequential bone drilling. By incorporating proper material properties and a modified bone necrosis criteria, this model can visualize the propagation of damaged areas. For this study, comparisons between a 2.0 mm Kirschner wire and 2.0 mm twist drill were conducted with their heat sources determined using an inverse method and experimentally measured bone temperatures. Three clinically viable solutions to reduce thermally-induced bone damage were evaluated using finite element analysis, including tool selection, time interval between passes, and different drilling sequences. Results show that the ideal solution would be using twist drills rather than Kirschner wires if the situation allows. A shorter time interval between passes was also found to be beneficial as it reduces the total heat exposure time. Lastly, optimizing the drilling sequence reduced the thermal damage of bone, but the effect may be limited. This study demonstrates the feasibility of using the proposed model to study clinical issues and find potential solutions prior to clinical trials.

1. Introduction

Bone drilling is common in many orthopaedic procedures, including predrilling for screw placement, temporary bony fixation, and surface preparation for joint fusion. Significant heat is produced during drilling due to material removal and frictional resistance between the cortical bone and the drill [1]. This heat dissipated from the drilling site can cause damage to the surrounding bone through thermal osteonecrosis, which is the result of the temporary or permanent loss of blood supplied to the bone that consequently leads to osteocyte and bone death [2–6]. To suppress the heat, studies have shown that drill size, cutting speed, and irrigation have significant effects on bone temperature [7,8]. In particular, irrigation has been shown to significantly decrease drilling temperatures even under intermittent supply [4,5]. However, irrigation is not appropriate for some clinical situations. For example, bone drilling to aid in fusion of a joint would be negatively impacted by irrigation because it washes away the cells one is trying to access by drilling into the the subchondral bone. Furthermore, these cases often require repeated sequential passes within a finite region to encourage increased blood flow to aid in healing. Depending on the operating location or simply preference, a surgeon can choose either a twist drill or a Kirschner wire (K-wire) for sequential drilling. As K-wires are known to produce more heat than twist drills due to lack of flutes [9,10], the risk of thermal damage under near-dry, sequential drilling using them is potentially dangerously high.

Both temperature and exposure time are critical factors in determining bone thermal damage. A thermal dose measurement, defined by a cumulative equivalent exposure time at 43 °C (CEM_{43}), is often adopted to predict the onset of bone necrosis [11,12]. Its ultimate validity as a metric is still debatable since it was initially created for cancer therapy. Experimentally, temperatures above 70 °C have been seen to result in immediate bone death [6,13], whereas irreversible cell death of osteocytes occurs after 30 s at a temperature of 55 °C and after 60 s at 47 °C [7,8]. These three conditions, in fact, produce significantly different CEM_{43}. The threshold of 47 °C is typically used as an indicator instead of 43 °C when tissues are on the brink of destruction.

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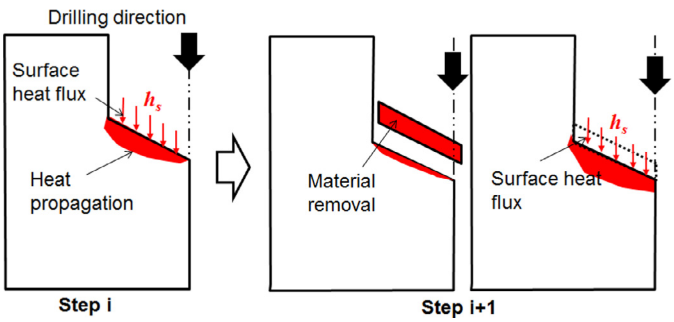

Fig. 1. Schematic drawing of the advection model for drilling heat transfer FEA.

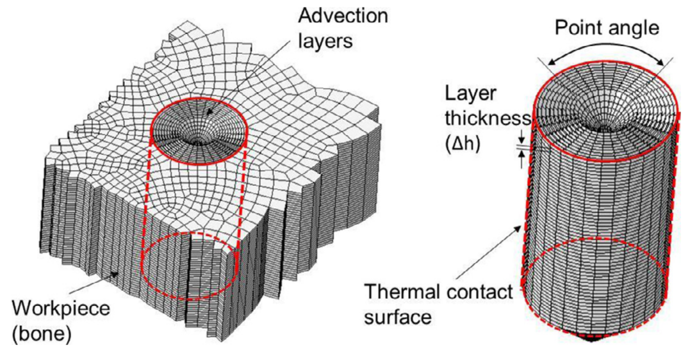

Fig. 2. Model configurations of the 3D heat transfer FEA for bone drilling.

To analyze bone drilling temperature, Davidson and James [14] have developed thermo-mechanical equations from machining theory coupled with a heat transfer finite element analysis (FEA) to predict heat generation and temperature distribution in bone. Lee et al. [15] used a finite difference method and machining theory to establish a model to predict temperature during bone drilling. In essence, these models are directly translated from traditional, well-developed metal drilling concepts [14–16]. However, most of the literature to this point focuses on the temperature field in single-pass drilling and the maximum temperature adjacent to the drill tip. These models are also two-dimensional (2D), which cannot be expanded to analyze thermal interactions between passes and global heat accumulation. Furthermore, the heat generation calculated based on the drilling force model contains inherent uncertainty in the heat partition – the fraction of total heat that goes into the bone, the drill bit, and the bone debris. Lee et al. [15] directly used Boothroyd's equation derived from metal cutting to establish the heat partition whereas Davidson and James [14] assumed a constant fraction. Selection of this fraction can be critical as it is proportional to the temperature ouput. An alternative way to avoid the use of a heat partition is via the inverse heat transfer method (IHTM) [17]. IHTM finds the resultant heat source based on the best-fitted overall temperature field despite small errors existing in measurements, thermal properties, or geometrical settings. We have previously used this method to quantify a complex heat flux profile for deep-hole drilling under minimum quantity lubrication and to study the temperature distribution around diamond burrs used in neurosurgical bone grinding [18,19].

The objective of this paper is to establish a methodology with the aim to compare different drilling strategies without going through extensive drilling experiments and clinical trials. In this paper, a 3D FEA is first presented along with IHTM to determine the heat source. Then, a modified thermal dose model is introduced and incorporated into the 3D FEA model for bone damage prediction. Three clinical solutions are evaluated, including tool selection, the time interval between passes, and hole sequencing for minimal heat accumulation. It is important to note that, because clinically available tools are given and controlled manually in the operating rooms, optimizations of drilling rotational speed, feed rate, cutting edge geometry, and irrigation, as stated in other literature, are not covered in this paper.

2. FEA thermal model for sequential drilling

2.1. Model setup

The drilling thermal model was adopted and modified from the advection model invented by Bono and Ni [20]. Fig. 1 shows the concept in a 2D axisymmetric configuration. The heat flux is applied on the hole bottom surface at step *i*. Then, a layer of material (elements) is removed at step *i*+1 and the heat is simultaneously applied on the following new surface. The same cycle is repeated throughout the entire drilling process. The advantage of this model is considering material removal which carries away a portion of the heat, thus automatically accounting for heat partition.

This 3D advection model was a moving heat source problem considering the speed, location, and trajectory of the drill tip. Our technique was to model the workpiece and the region to be drilled as two separate parts, as shown in Fig. 2. The drilled region was defined as advection layers, where the sequential removal of elements took place in this part. Thermal contact between these two parts was defined to have zero resistance to ensure continuous heat flow across the boundary. Two reasons for this two-part modeling are that (1) a complex 3D geometry can be meshed using tetrahedrons without being constrained by the arrangement of advection layers and (2) the advection layers can be placed at different locations and orientations to increase the model flexibility.

The advection layers were formed with an exact drill point angle and diameter (2 mm in this case). The thickness of each layer was set to be 0.1 mm, which was equivalent to a 0.1 s time duration under 1 mm/s feed rate used for these experiments. This feed rate was selected in our prior study on drilling tool comparison based on the motion detected during hand-held drilling [21]. Resolution and accuracy of the temperature field next to the heat source are significantly affected by the layer thickness: finer advection layers create a more continuous movement for the heat source, but also significantly increases the number of elements and steps, resulting in a heavy computational load. Numerical convergence testing was carried out to ensure a result could be obtained. At 0.1 mm layer thickness, a reasonable computational load, there was less than 1% difference in temperature, compared to a continuous case.

There were assumptions made for this model. First, the material properties were constant. The bone density around hole margins might change after drilling, consequently affecting the heat transfer, but the affected area was small compared to the entire operating region. Second, the heat flux was uniformly distributed on the hole bottom surface. The detailed spatial distribution might be generated based on the cutting edge geometry [18], but the impact on the overall temperature of the operating area is limited. Lastly, the heat flux was independent of time since tool wear and chip build-up issues were found to be insignificant under proper operating conditions [21].

The material properties were set within the ranges of human cortical bone [22–24], where the density was 2 g/cm^3, the thermal conductivity was 0.5 W/m °C, and the specific heat was 1290 J/kg °C. Cancellous bone and marrow were not considered in the model since the majority of the heat was expected in the cortical bone, provided a higher density and larger drilling forces. The boundary condition was set as adiabatic given that free convection between bone and air is low and has limited effect on the temperature inside the bone. The material of each hole was removed along with the drill pass, and all newly-created surfaces were adiabatic. Fig. 3(a) shows a clinical