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Thermal Model to Investigate the Temperature in Bone Grinding for Skull Base Neurosurgery

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Abstract

This study develops a thermal model utilizing the inverse heat transfer method (IHTM) to investigate the bone grinding temperature created by a spherical diamond tool used for skull base neurosurgery. Bone grinding is a critical procedure in the expanded endonasal approach to remove the cranial bone and access to the skull base tumor via nasal corridor. The heat is generated during grinding and could damage the nerve or coagulate the blood in the carotid artery adjacent to the bone. The finite element analysis is adopted to investigate the grinding-induced bone temperature rise. The heat source distribution is defined by the thermal model, and the temperature distribution is solved using the IHTM with experimental inputs. Grinding experiments were conducted on a bovine cortical bone with embedded thermocouples. Results show significant temperature rise in bone grinding. Using 50°C as the threshold, the thermal injury can propagate about 3 mm in the traverse direction, and 3 mm below the ground surface under the dry grinding condition. The presented methodology demonstrated the capability of being a thermal analysis tool for bone grinding study.

Keywords

Skull base neurosurgery; Grinding; Bone Temperature; Modeling

1. Introduction

Bone grinding using the spherical diamond tool is a key procedure in the expanded endonasal approach, which is a neurosurgical operation, for cancer treatment in the skull base. This approach utilizes the endoscopic technology to access the skull base from the

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nasal cavity. Neurosurgeons use the miniature spherical diamond grinding tool, called bur, to remove the bone in order to provide exposure for tumor removal, and meanwhile to identify and protect the important cranial nerves during the operation. Heat is generated during bone grinding and propagates through the bone to the adjacent nerves and blood vessels. The rising temperature of the bone, nerve, and artery can cause three types of thermal related injury [1–4]. First, bone necrosis typically starts when the temperature rises over a critical value of 50°C [5]. Second, nerve is vulnerable to the elevated temperature. Depending on the type of nerve, the critical temperature for starting the thermal injury could start at 43°C [6]. Third, coagulation of blood in the carotid artery due to the temperature rise caused by bone grinding is a major reason for stroke during this neurosurgical procedure. Better understanding the bone temperature rise caused by grinding using the spherical diamond tool is a key step to prevent the thermal related injury in the skull base neurosurgery.

Studies have been conducted to investigate the temperature in bone machining [7–9] on orthopedic procedures. Shin et al. [7] has quantified that the highest temperature varied from 49 to 115°C under various cutting conditions in round bur bone milling. Hosono et al. [8] suggested that tissues neighboring the drilled bone, especially nerve roots, can be damaged by the heat generated by bone drilling. Temperature up to 140°C was measured by Matthews et al. [9] in drilling the human cortical bone. However, no research has been found to quantitatively report the bone temperature rise for the spherical grinding tool, though the related concerns have been raised in the neurosurgery community [10]. This research aims to fulfill this gap by advancing the thermal model to the spherical shaped tool for bone grinding.

Grinding is an energy intensive process. Virtually all the grinding power is converted into heat. The heat generated in grinding is transported away from the grinding zone to the bone, tool, and debris [11]. The ratio of energy partitioned to the bone is of particular interest in this research. In surgery, the real-time measurement of the temperature in the bone and surrounding tissue is almost impossible due to the narrow nasal cavity fully occupied by the endoscopic surgical tools. However, knowing the heat generation can enable the estimation of bone temperature and, therefore, provides better selection of tool and operating settings. Determining the heat generation in bone grinding can be achieved using an inverse heat transfer method (IHTM), a method incorporating both modeling and experimental measurements. Applications of IHTM in grinding have been reported. For example, Hong and Lo [12] constructed a linear inverse model to identify the temperature distribution and heat flux along the cutting path. Kim et al. [13] applied sequential inverse heat transfer algorithm to determine workpiece temperature in creep feed grinding. Brosse et al. [14] combined an inverse method and thermography-based temperature measurement method to investigate the heat flux entering the workpiece during grinding process.

To successfully implement IHTM, a proper grinding thermal model is needed. Most of the thermal models of traditional grinding process are based on the theory of Jaeger [15], which modeled the temperature of a semi-infinite subject under a heat source moving at a constant speed. Malkin and Guo [16] presented a comprehensive overview of the analytical methods to calculate grinding temperature. Brinksmeier et al. [17] also provided an overview of modeling and simulation of grinding process. However, the thermal model for grinding using a spherical shape tool has not been investigated, as it involves 3-D thermal analysis. In this study, we have expanded Malkin's triangular heat flux model [16] to the 3-D case. Finite element thermal model (FETM), which has been successfully implemented in the modeling of traditional grinding processes [18], is employed as the base for IHTM.

In this paper, the goal is to develop a methodology to determine the heat generation and temperature distribution in bone grinding using a spherical diamond tool. The concept of 3-D FETM-based grinding model is first introduced, and followed by the bone grinding experiments. Then, details of the IHTM incorporating with the grinding model and experimentation to solve the heat generation are presented. Results and discussion are given based on the IHTM and FETM.

2. Model for the Spherical Grinding Tool

The concept of 3-D grinding FETM for bone temperature calculation is presented in this section. Figure 1 shows the overall configuration of the shank, spherical grinding tool, and bone. A tilt angle, α , is defined as the angle between the tangent of surface and the axis of the grinding tool. The tilt angle was set at 30° in this study to approximate the real procedure. Based on our discussion with neurosurgeons and observation, the manner in which neurosurgeons operate the bur can be likened to a paint-brush motion.

The spherical tool is decomposed into elemental grinding wheels (EGWs) along the rotating axis. An example of four EGWs is shown in Fig. 1 with the radius marked as r_1 to r_4 for EGW #1 to #4, respectively. The size of each EGW is determined by its radius r_i and width b_w along the rotating axis (Fig. 1). The number of EGWs in contact with the bone surface is determined by α and the depth of cut, a_c . Each EGW is assumed to perform grinding with its own tangential speed (v_s) and tangential force (F_t).

The heat flux of each EGW is

$$q = \varepsilon \frac{F_t v_s}{b_w l} \quad (1)$$

where l is the contact length between EGW and bone surface in the YZ-plane (Fig. 2(b)) and ε is the partition ratio defined as the percentage of power consumption that is transferred to the bone as thermal energy.

To apply this concept to the bone FETM, Figs. 2(a) and (b) show the schematic configuration of spherical tool and EGW on the bone in the XZ and YZ planes, respectively. The proposed FETM does not consider the material removal, thus heat is directly applied on a flat surface without taking account the actual spherical shape between the tool and bone interface. From the view on the XZ plane (Fig. 2(a)), the elements are lined up with the EGWs. The size of element in the X-direction, marked as $b_E (= b_w / \cos \alpha)$, is the projection of the width of EGW in the feeding (X) direction. In the transient heat transfer calculation, the time step is determined by b_E and the tool feed rate. In each time step, the EGW is shifted by b_E in the X-direction, as illustrated by the dashed EGW in Figs. 1 and 2(a). In this manner, the depth of cut of each EGW, marked as a_1 to a_4 in Fig. 2(a), is defined as the difference in cutting depth between the adjacent EGWs in a time step. Mathematically, the depth of cut can be generalized as:

$$a_i = r_i - r_{i-1} - b_E \sin \alpha \quad (2)$$

where i is the designated number for each EGW. The first wheel is always the one at the front toward the feeding direction. If a_i is negative, it represents that the EGW is inactive in grinding and no heat is generated.

Assuming that the tangential force of an EGW is proportional to a_i with a constant factor k and the rotational speed of the tool is ω , Eq. (1) can be modified to:

$$q_i = \varepsilon \frac{(ka_i)(\omega r_i)}{b_e l} \quad (3)$$

where q_i is the heat flux for the element corresponding to EGW # i , e.g., q_1 to q_4 in Fig. 2(a). As for the traverse direction, the YZ plane view in Fig. 2(b), a triangular heat flux shape is assumed based on the EGW rotational direction to define the leading ($-Y$) and trailing ($+Y$) edges, which can be analogized to Guo and Malkin's 2-D grinding thermal model [19]. In FETM, depending on the number of elements in the Y-direction, this triangular shape is discretized into a step function. The arc contact length l of each EGW and the bone surface is simplified by a straight line, l_{bi} , as illustrated in Fig. 2(b).

In this study, all k , ω , and ε are assumed constant under the same cutting condition, and thus the ratio of heat flux distribution can be determined by a_i , r_i , b_e , and l_{bi} of each EGW, such that

$$q_i = (\varepsilon k \omega) \left(\frac{a_i r_i}{b_e l_{bi}} \right) = q_m R_h \quad (4)$$

where R_h is the normalized heat flux ratio (0 to 1) and q_m is defined as the heat flux magnitude, which is a constant for all EGWs. The heat flux distribution of the spherical grinding can be mapped to FETM mesh of the bone surface with a given q_m . The q_m is solved using the experimental temperature data and the analysis method introduced in the following section.

3. Experimental Setup

An experimental study with the settings close to the real bone grinding in neurosurgery was performed. The overall setup of the grinding experiment is shown in Fig. 3(a). Three linear stages (Siskiyou Model 200cri) with 1 μ m resolution were built to control the three-axis movement of the grinding tool. Four type K thermocouples (Omega Engineering, Part #5TC-TT-K-36-72) with 0.13 mm in diameter were placed on the bone surface to record the bone temperature at 2 Hz, as shown in Fig. 3(b). The spindle drove the diamond tool (Stryker 4.0 mm Diamond Round Bur #5820-12-40) with 76 FEPA (200/230 ANSI mesh) average diamond abrasive size (Fig. 3(c)) at rotational speed of 60,000 rpm, which is the speed used in skull base neurosurgery for bone grinding. Correspondingly, the maximum peripheral grinding speed is 12.6 m/s on the spherical tool.

The cortical portion the bovine femur bone was selected in the experiment since it is, in general, thermally homogenous [22]. In addition, the cranial bone is mostly cortical around the operation region. The fresh bone sample was kept hydrated and frozen before the grinding test. The bone sample was machined to a tile-shape (Fig. 3(b)) with 20 mm in length, 20 mm in width, and 6 mm in depth using the CNC surface grinder (Chevalier Model Smart-B818), thus the surface was completely flat. To ensure the sample was level on the fixture and parallel to the feeding path, a dial indicator, secured on the spindle, was used to scan across the surface. This setup enabled consistent depth of cut (i.e., constant heat generation) across the bone surface during the grinding test. A straight ground groove of 20 mm was created in one pass on the bone surface, as the top view shown in Fig. 3(d). Grinding process parameters are listed in Table 1. Depth of cut and feed rate were selected to best represent those in the clinical endonasal approach. The depth of cut was ascertained by slowly moving the tool toward the bone surface (with a small step of 10 μ m) until it barely touched, and then another 400 μ m to the start point. Both forward and backward directions were performed separately on two different bone samples to observe the

difference during the paint-brush motion. Four thermocouples, denoted as TC1, TC2, TC3, and TC4, were positioned 5 to 6 mm apart from each other and about 2 mm from the edge of the groove, as shown in Fig. 3(d). Since the measured temperatures are used to calculate heat magnitude, a proper distance from the thermocouple to the edge of the groove, marked as d in Fig. 3(d), is critical for IHTM. If d is too small, the thermocouple position error is significant due to high temperature gradient. This can result in error in heat calculation. If d is too large, the temperature reading is not sensitive enough to calculate the heat source. In this study, d about 2 mm was observed to have the best sensitivity and robustness. The actual position was determined by high-resolution photo image of the bone workpiece.

4. Analysis Method

4.1 FETM

The bone thermal model was established using the finite element analysis software ABAQUS v6.8 (Dassault Systèmes Simulia Corp., Providence, RI). The mesh for the 20 mm $\times$ 20 mm $\times$ 6 mm bone is shown in Fig. 4. The element type was DC3D8 (8-node linear heat transfer brick element). Linear elements with proper mesh sizes can save more computational time than using quadratic 20-node elements. The slot in the middle is where the grinding tool and heat source passes over with the width of 2.4 mm, which is determined by the 0.4 mm depth of cut and the 4 mm tool diameter. Fine meshes were applied near the grinding path due to the large temperature gradient and for precise identification of thermocouple locations; while more coarse meshes were arranged near the edge and bottom for the benefit of less computational time. Along the slot, the surface was meshed by 2×52 elements. Each element size is 0.38 mm in the feeding direction, which corresponds to 12 EGWs on the spherical grinding tool. In the traverse direction (Y-direction), the contact length (l_{bi}) of each EGW is assumed the slot width (2.4 mm). Since this FETM is used for IHTM, which involves many iterations to converge to the solution, it is beneficial to have simple meshes but without significantly affecting the output results. Numerical test for this model will be performed in a later section.

With 12 EGWs, $\alpha = 30^\circ$, and $a_c = 0.4$ mm, only EGWs #1 to #4 contact the bone surface, as shown in Fig. 5(a). EGWs #5 and #6 do not cut because mathematically no material is left from EGW #4 due to the effect of tilt angle. The radius for EGWs #1 to #4 are 0.799, 1.323, 1.625, and 1.818 mm, respectively; thus, the calculated depths of cut are 0.013, 0.331, 0.109, and 0.001 mm using Eq. (2). The depth of first cut, 0.013 mm, is determined by the distance between the bone surface and the center of EGW #1, i.e., 0.786 mm. In the traverse direction, since the contact length of each EGW is the same (two elements in this study), there are in total eight elemental surfaces in contact, highlighted in Fig. 4, as a moving heat source. Based on the triangular distribution, the heat flux for the two elements traverse to the forward/backward direction should be 1:0.33. Therefore, using Eq. (4), the ratio (R_h) of the heat fluxes on the eight element surfaces can be expressed as in Fig. 5(b), where the maximum is set to be 1.

The bone density is 2050 kg/m³ by measuring volume and weight. The specific heat is 516 J/kg-K, which was determined using heat balance test by mixing a frozen bone sample (-20°C) and water under room temperature. Initial bone temperature distribution was assumed uniform and equal to room temperature of 23°C . The convection heat transfer on the surfaces is neglected due to small temperature difference. The thermal conductivity of bone varies widely in literature [20] and is difficult to ascertain, so the IHTM solves two unknowns: the heat flux magnitude, q_m , and the bone thermal conductivity, k .

4.2 IHTM

A multi-variable inverse problem is established for q_m and k by using the inputs of temperature readings at thermocouples TC1, TC2, TC3, and TC4. The q_m and k are both assumed time-independent throughout the grinding process. The IHTM applies the optimization process to minimize the objective function, which is determined by the difference between the experimentally measured and FETM-calculated temperatures at the thermocouple locations. In this study, the objective function is defined as:

$$F(q_m, k) = \sum_{i=1}^I \sum_{j=1}^J (T_{ij}^{\text{exp}} - T_{ij}^{\text{FETM}})^2 \quad (5)$$

where I is the number of time steps, J is the number of thermocouples, T_{ij}^{exp} is the experimentally measured temperature, and T_{ij}^{FETM} is the FETM-calculated temperature at time step i and thermocouple j . The searching approach adopts either active set method or sequential quadratic programming (SQP), which are both available in the MATLAB (MathWorks Inc., Natick, MA) optimization toolbox. Initial values are firstly generated within the upper and lower limits, which are set $[0, 10^6]$ W/m² and $[0, 10]$ W/m-K for q_m and k , respectively. Then, the FETM result is fed back to the algorithm together with the input temperatures to calculate the objective function. Based on that, the optimization algorithm decides the next iteration until the solutions cannot further minimize the objective function by at least δ . The δ is called exit criterion for this IHTM, which was set 0.01 in this study.

4.3 Numerical Validation of IHTM

Numerical testing was performed to ensure the robustness of IHTM, such as the existence and uniqueness of the solutions, and the sensitivity of solutions to the measurement errors. In this study, the numerical validation was conducted by the following procedures. First, a set of temperature data were created by given q_m (1×10^5 W/m²) and k (0.5 W/m-K) via FETM and used as inputs, denoted as T^{exa} . Then, the measured temperature T^{exp} was artificially created by adding random errors [21], such that

$$T^{\text{exp}} = T^{\text{exa}} + \mu\sigma \quad (6)$$

where $\mu\sigma$ is the random error, representing the noise or disturbance in real data. The μ is randomly generated for each data point of T^{exa} and the μ follows a normal distribution with zero mean and standard deviation of 1°C. The σ is the multiplier for μ to control the magnitude of measurement errors. The testing data were then imported into IHTM to evaluate how close the outcome solutions would be converged to the given q_m and k . The validation results with $\sigma = 0$ and 0.5 are shown in Table 2. The discrepancy of the variables was found within 4%, which indicates that the IHTM is reliable and not sensitive to measurement errors.

4.4 Numerical Validation of FETM Mesh

Another numerical validation was to ensure the convergence of FETM result since it may vary for different mesh configuration. The current mesh shown in Fig. 4, based on 12 EGWs, gives a reasonable computation time, but the accuracy of the solutions, compared to finer meshes, is uncertain. Thus, the FETM results using both 12 EGWs and 96 EGWs (finer mesh) are compared, where 96-EGW case represents an ideal condition with a smooth heat flux distribution. Figure 6 shows the heat flux assignment for the two cases. The 12-EGW case has the larger heat flux region (1.5 mm) than that of 96-EGW case (1.0 mm) because of

the EGW size. However, the total thermal power (heat flux times area) is the same for both cases. Figure 7 shows the temperature results at four designated thermocouple locations: 2 mm away from the ground slot and 6 mm apart from each other in the feed direction. Temperatures at TC1 and TC2 are fairly consistent, while at TC3 and TC4 have only about 10% different at the peak temperature. Overall, the 12-EGW case is accurate and suitable for IHTM since the computational time is more than 10 times faster.

5. Results and Discussion

Using FETM and IHTM presented in Sec. 4, the results of q_m and k for both forward and backward grinding experiments were solved and shown in Table 3. Similar k was obtained from both cases and fell within a reasonable range reported in literatures, as reviewed in [22]. The result of k indicates the repeatability and accuracy of the IHTM. For q_m , it was twice larger in forward motion because of different heat flux distributions. The total thermal power is similar: 0.38 and 0.34 W for forward and backward grinding direction, respectively. Figure 8 shows the heat flux distribution on the surface mesh for both cases. The highest heat generation is on the second EGW (#2) for the forward case and on the third EGW (#7) for the backward case. A potential for such difference could be the slightly higher average EGW peripheral grinding speed in backward direction in comparison with that of the forward direction.

Figure 9 shows the temperature fitting results from IHTM and the actual measurements at four thermocouple locations over time. Temporal profile of the temperature is significantly affected by the heat flux distribution of the heat source (Fig. 8), thus good agreement of temperature at all four thermocouples indicates the proper FETM thermal model for spherical grinding tool. For both grinding motions, TC1 and TC2 exhibit higher temperature than that of TC3 and TC4. This phenomenon verified the assumption of the triangular distributed heat flux in the traverse direction (Fig. 2(b)), which generates more heat on the TC1/TC2 side (-Y) than that on the other side (+Y). In Fig. 9(a), the slight temperature rise in the beginning of grinding over the calculated profile was due to the bone debris that covered on the sample surface during grinding. The higher temperature readings in backward motion of Fig. 9(b), compared to forward motion, were simply because the actual thermocouple locations were closer to the heat source.

Having known the q_m , the temperature distribution over time can be visualized by FETM. Figure 10 shows the temporal and spatial temperature distribution for the forward motion case. The dashed box is the heat source along the ground groove. The initial temperature was set 37°C in this calculation to mimic the temperature effect in human body. Assuming 50°C as the threshold for bone and tissue thermal damage, a large damage region can be observed. Similar phenomenon also occurs for backward motion. To clearly see the temperature gradient around the heat source, Fig. 11 shows both top and cross-section view of temperature results when the heat source is at midway across the bone surface. For a transient moving heat source problem, the temperature distribution near the moving heat source should be the same over time, which is determined by the ratio of bone thermal diffusivity and the moving heat source speed [23], thus results at this certain moment are used to lead into the following discussion. The highest temperature over 200°C was observed at the tool-bone contact interface (not shown in the scale), and the edge of ground slot was around 100°C. The 50°C threshold boundary propagates to about 3 mm from the ground slot in the traverse direction and 3 mm underneath the slot for both forward and backward cases. Due to the low thermal diffusivity of the bone, the temperature descends rapidly and does not affect the area significantly beyond 3 mm from the slot edge and surface. It is noted the above high bone temperature is the result under dry grinding – the worst scenario in surgery. A sample with flood irrigation was also tested for comparison

using the grinding condition listed in Table 1. Though significantly reduced, the 50°C threshold is still found to propagate to about 0.5 mm underneath the heat source, due to the fact that high wheel rotational speed may limit the saline contact at the bone-tool interface. Thus, potential thermal injury to adjacent optic nerves and carotid artery is possible when the cranial bone is ground thinner and thinner.

Furthermore, Fig. 11 also shows asymmetric temperature distribution on the two sides of grinding spot, which is a visualization of the phenomenon in Fig. 9. The higher temperature is always found on the right side (i.e., TC1/TC2) of the spindle rotation direction, in both forward and backward feed motions. The threshold boundary is about 30–40% larger on the right side.

6. Conclusions

A methodology to quantify the temperature distribution during the bone grinding was developed. This methodology included a 3-D FETM thermal model for spherical grinding tool and an IHTM for heat determination. The 3-D FETM model decomposed the spherical grinding tool into EGWs and each has the individual grinding to create 3-D heat flux distribution. The IHTM utilized optimization algorithm to match up the FETM model with the experiments to find the unknown heat generation rate. The comparison with experimental measurements had validated the accuracy of the proposed approach.

This study provided a basic understanding of grinding-induced bone temperature rise and demonstrated that, under the worst scenario (dry grinding), the region about 3 mm from the tool-bone interface could have high potential for thermal injury. In clinical operation, the continuous irrigation is applied, which would have a wide range of temperature effect. Using the developed methodology in this study, more research can be done on the irrigation type, size of diamond abrasive, and tool rotational speed. In addition, anisotropic bone micro-structure (osteonal orientation) could result in different grinding forces and heat [24], which can also be investigated with this thermal model.

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Fig. 1.
3-D configuration of the spherical grinding tool consisting of elemental grinding wheels

Fig. 2.
Configurations of EGWs on the bone in (a) XZ plane view and (b) YZ plane view

Fig. 3. Experimental setup: (a) overall experiment layout, (b) close-up view of the grinding setup, (c) the spherical grinding tool, and (d) top view of the bone specimen, ground groove and thermocouple locations.

Fig. 4.
FETM model of bone grinding with moving heat source

Fig. 5.
 (a) Configuration of EGWs for the experimental case and (b) the corresponding heat flux ratio on the contact element surfaces in FETM

Fig. 6.
Heat flux distribution in grinding region with (a) 12 and (b) 96 EGWs

Fig. 7.
Comparison of FETM temperatures at four thermocouples using 12 and 96 EGWs

Fig. 8.
Heat flux distribution $q(\times 10^5 \text{ W/m}^2)$ for (a) forward and (b) backward grinding results

Fig. 9. Measured and FETM calculated temperature at thermocouple positions: (a) forward feed and (b) backward feed

Fig. 10.
Bone temperature temporal and spatial distribution for forward motion at 20, 40 and 55s

Fig. 11. Bone temperature spatial distribution at 30s: (a) forward motion and (b) backward motion

Table 1

Experiment parameters for bone grinding

Tests	Feed rate (mm/min)	Cutting Depth (mm)	Motion	Rotational Speed (rpm)
1	20	0.4	Forward	60,000
2	20	0.4	Backward	60,000

Table 2

IHTM validation analysis results

σ	$q_m (\times 10^5 \text{ W/m}^2)$	$k (\text{W/m-K})$
0	0.989	0.506
0.5	1.029	0.52

Table 3IHTM Results of q_m and k

Tests	Heat flux magnitude q_m ($\times 10^5 \text{W/m}^2$)	Thermal conductivity k (W/m-K)	Thermal Power P (W)
Forward	4.31	0.55	0.38
Backward	2.73	0.59	0.34