Heat Accumulation During Sequential Cortical Bone Drilling

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ABSTRACT

Significant research exists regarding heat production during single-hole bone drilling. No published data exist regarding repetitive sequential drilling. This study elucidates the phenomenon of heat accumulation for sequential drilling with both Kirschner wires (K wires) and standard two-flute twist drills. It was hypothesized that cumulative heat would result in a higher temperature with each subsequent drill pass. Nine holes in a 3 × 3 array were drilled sequentially on moistened cadaveric tibia bone kept at body temperature (about 37 °C). Four thermocouples were placed at the center of four adjacent holes and 2 mm below the surface. A battery-driven hand drill guided by a servo-controlled motion system was used. Six samples were drilled with each tool (2.0-mm K wire and 2.0- and 2.5-mm standard drills). K wire drilling increased temperature from 5 °C at the first hole to 20 °C at holes 6 through 9. A similar trend was found in standard drills with less significant increments. The maximum temperatures of both tools increased from <5 °C to nearly 13 °C. The difference between drill sizes was found to be insignificant ($P > 0.05$). In conclusion, heat accumulated during sequential drilling, with size difference being insignificant. K wire produced more heat than its twist-drill counterparts. This study has demonstrated the heat accumulation phenomenon and its significant effect on temperature. Maximizing the drilling field and reducing the number of drill passes may decrease bone injury.

Key Words: bone drilling; sequential drilling; heat accumulation; cortical bone; thermal osteonecrosis; Kirschner wire

INTRODUCTION

Bone drilling is a commonly utilized orthopaedic procedure. Single-pass drilling is used most frequently to aid in screw placement; however, multiple-pass drilling is also used in certain clinical scenarios. For instance, sequential drill passes are made when preparing a joint surface for fusion, non-union takedowns, and when fenestrating eburnated bone to accept a prosthesis, such as a tibial tray in a total knee arthroplasty. The heat generated by standard drills has been studied extensively in the past with a multitude of experiments testing different variables, including width of the drill, advancing speed, twist angle, revolutions during drilling, etc.[1-15] Studies looking at heat generated by Kirschner wires (K wires), which are often employed during sequential drilling, have been limited. A recent study by Palmisano et al compared single-pass drilling of standard drills and K wires and found significantly higher heat production with the use of K wires.[13]

One of the primary concerns with bone drilling procedures is the production of heat causing osteonecrosis—bone death resulting from the temporary or permanent loss of blood supply[14]—to ensue in surrounding bone.[4,6-16] This type of damage leads ultimately to collapse and nonhealing.[17] A specific subset of this disease caused by damage due to heat, thermal osteonecrosis, is a very complex phenomenon. It has been theorized that osteonecrosis after drilling causes osteocyte apoptosis, reduction in local blood flow, and increased local osteoclastic activity.[11,17] This phenomenon of thermal osteonecrosis results in weaker bone with less potential to heal, which is of significant consequence in the clinical scenarios that employ surgical techniques that produce significant heat, specifically single- and multi-pass drilling.[17]

Temperature and associated exposure time have also been studied significantly.[1-4,8,9,14] Numerous experimental designs have shown that a temperature of 70 °C results in immediate bone necrosis.[5,9] Lesser temperatures have also been found to cause necrosis with increased exposure times. Irreversible cell death of osteocytes occurs when bone has been exposed to temperatures of 55 °C for 30 seconds and 47 °C for 60 seconds.[14] In the literature, the threshold of 47 °C for 60 seconds[1-4,8,14] is used as a designator of bone death. Other variables that significantly influence heat production are drilling depth and cortical bone thickness.[7,8,15] It has been shown that the temperature produced by the frictional resistance during compact cortical bone drilling is directly proportional to the drilling depth.[15] While the use of normal saline irrigation during drilling has been shown to decrease maximum temperature, irrigation is not appropriate for certain clinical situations.[3,9,14] For example, irrigation while drilling to prepare a joint for fusion would potentially make visualization difficult and it would wash away the cells one is trying to access by drilling through the subchondral bone.

Heat accumulation and its effects after repetitive sequential drilling are largely unknown and have not been studied independently. Given the low thermal conductivity of bone, it is known that heat can accumulate with repetitive drilling. In this work we hypothesized that heat would accumulate, leading to an increase in the peak temperature with each subsequent drill pass of a sequential drilling sequence. The intention of this study was to examine heat production in terms of bone temperature rise during and after repetitive sequential drilling.

MATERIALS AND METHODS

Experiment Design

The experimental setup is shown in Figure 1. A clinically used battery-driven hand drill was attached to a servo-controlled 3-axis stage to control drilling motions. The hand drill was operated at a constant, full speed (around 800 rpm) through a drilling test. Bone samples were harvested from non-embalmed human cadaveric tibia (males, ranging 36 to 71 years of age) and stored under a -20 °C environment prior to testing. The residual soft tissue on the cortical surface was removed completely to avoid any disturbance during the initial drill bit–bone contact. The testing sample was clamped onto a fixture and moistened to 37 °C to mimic a live-body environment. The fixture was made of wood to minimize temperature loss during the test, while maintaining rigidity to hold the sample. A plastic plate was placed on the top of the fixture to affix the thermocouples by four steel tubes at proper locations. The plastic plate had an identical hole array aligned with the bone sample, allowing the tool to travel through and drill into the bone. The through-hole area of the plate was larger than the drill's cross-sectional area to prevent the drill bit from contacting the plate, affecting the testing, or loosening the thermocouple contact. As shown by a drilled example in Figure 1, the holes were arranged 3 mm apart from margin to margin; thermocouples were 2.5 mm from the hole margin and 2.0 mm below the bone surface. The hole layout was design based on clinical experiences and fixed as controlled variable in the experiment. Thermocouples were placed at the center of four adjacent holes, so the temperature rise caused by each pass was constant. The heat accumulation, therefore, could be seen from the overall temperature profile. The thermocouple depth of 2 mm was about half way through the cortical bone for two purposes: One, this depth could well secure the thermocouple tips at right positions. Second, temperature change at this depth is likely to be steady-state and repeatable, which is beneficial to the statistical analysis. To ensure minimum deviation from the designated hole locations, pilot holes 0.5 mm in depth were drilled by a 0.7-mm mini drill bit prior to the experimental tests.

In this study, three drilling tools—2.0-mm K wire, 2.0-mm standard drill bit, and 2.5-mm standard drill bit—were used for comparison and observation of heat accumulation. Each drilling tool was repeated six times on different bone samples (harvested from different cadavers). It should be noted that the hole pattern and the clear plate were identical for the 2.0-mm K wire and 2.0-mm drill bit, but those for the 2.5-mm drill bit were scaled up accordingly to ensure the same hole margin-to-margin spacing and thermocouple location with respect to the hole margin. The drilling sequence was from the top row to the bottom, from right column to the left. The drilling depth was set to 5 mm regardless of the thickness of cortical layer. Parameters for drilling movement were controlled in this experiment using a set of clinically reasonable values. The feed rate (advancing speed into the bone) was set at 1 mm/s to simulate a steady-state drilling based on hand-held testing in a prior study.[13] The time interval between passes was set at 1 s, approximated from clinical cases, regardless of the hole-to-hole distance. The total drilling time was therefore 53 s for all cases. By allowing the heat to propagate after the last hole, an additional 5 s was added into the comparison, for a total time of 58 s.

Measurement and Analysis Methods

The heat accumulation was seen as a total temperature rise adjacent to a hole during multiple passes. Ideally, one thermocouple should be used for measuring one pass. However, unlike single-hole drilling, the temperature distribution is not symmetric with respect to the hole due to the heat propagation from adjacent holes. As a result, comparing one hole to another may not always be on a maximum temperature basis. Also, the placement of nine thermocouples on the bone surface would be technically challenging due to potential interference with the drill bit. A large number of thermocouple pilot holes could also affect the bone integrity and heat transfer behavior near the bone surface. Therefore, an alternative approach in this study was using four thermocouples (denoted by TC-A, TC-B, TC-C, and TC-D) embedded within the 3×3-hole array with TC-A for holes 1, 2, 4, and 5; TC-B for holes 2, 3, 5 and 6; TC-C for holes 4, 5, 7 and

8; and TC-D for holes 5, 6, 8, and 9, as shown in Figure 2. Drilling sequence followed the ascending order from hole 1 to 9.

An example of data analysis is shown in Figure 3 using raw temperature data for the 2.0-mm drill bit. The profile that first responds to the heat is TC-A, and then B, C, and D as the drill proceeds. In the figure, the vertical lines represent the time and the corresponding drilling pass (hole number). The time interval between the lines was 6 s, including 5 s drilling time plus 1 s travel time between passes. The intersected temperatures, as marked by dots, were extracted for establishing a thermocouple vs. hole chart, as shown in Figure 4. All the data were processed in an identical manner.

RESULTS

Temperature

Temperature results as a function of holes 1 to 9 are shown in Figure 4 for all three tools, where the error bars represent standard errors based on the six combined tests. Temperature of K-wire drilling increased more rapidly with the number of holes drilled compared to both the 2.0-mm and 2.5-mm drill bits. The initial condition of the experiments was set around 37 ± 1 °C, thus a temperature rise over 10 °C could expose the bone tissue to risk. On average, for K-wire drilling, the temperature rise reached 18 °C at hole 5 of TC-A. The maximum temperatures (TC-B, C, and D) remained at about 20 °C as the drilling proceeded through hole 9. In comparison, the temperature rise of the 2.0-mm drill bit increases to only about 13 °C and that of the 2.5-mm drill bit increases to a slightly higher level, which is still much lower than the values of the K wire.

Although the 2.5-mm drill seems to generate a greater temperature change, the difference from the 2.0-mm drill bit is statistically insignificant ($p > 0.05$). However, the differences between the K wire and drill bits are clear. Statistically significant differences ($p < 0.05$) can be found between the K wire and the 2.0-mm drill bit at every hole except hole 3, and a difference can be found along the last three holes between the K wire and 2.5-mm drill bit.

Based on our observations in Figure 4, heat in the first row did not affect the drilling in the third row and vice versa. The statistical analysis showed a p-value > 0.05 between TC-A, hole 5 and TC-D, hole 9 for all cases. Therefore, temperature profiles of TC-A and TC-B are nearly identical to those of TC-C and TC-D. Temperatures of TC-C and TC-D do not respond to the drilling-induced heat until the second row (starting at hole 4.) Temperatures of TC-A and TC-B stop rising when the drilling proceeds to the third row (starting at hole 7), though they still remain.

Using the average temperature at four thermocouples, the temperature field within the 5-mm by 5-mm region (cornered by four thermocouples) was interpolated to observe both the temporal and spatial distribution at the ends of drilling holes 3, 6, and 9, as shown by the contour lines in Figure 5. The hole in the middle is hole 5, where the data should be void after the hole is drilled.

For all drilling tools, it can be seen that the heat is propagated to TC-C and TC-D after drilling hole 3. The overall temperature fields are at or below 12 °C. After drilling hole 6, significant higher temperature field results from use of K wire, which ranges from 12 °C to 25 °C, whereas the temperature fields of the drill bits are still within 15 °C. Although the larger drill bit creates a slightly higher temperature, the difference between these two sizes (2.0 mm and 2.5 mm) is, again, not obvious.

After drilling the last hole, the temperatures at the lower end of the region were still above 12 °C for K wire and above 5 °C for drill bits. This phenomenon could result in a larger thermal dose in the system, consequently injuring bone tissues due to prolonged exposure at high temperatures. Consider that after drilling the nine holes (58 s after initiation), the average temperatures across the four thermocouples were 18.6 °C, 9.9 °C, and 11.1 °C, for 2.0-mm K wire, 2.0-mm drill, and 2.5-mm drill, respectively.

Histology

It can be concluded that K wire produces much more heat than the standard drill bits, and consequently leads to a larger area of bone damage. After drilling was completed, three selected bone samples (one from each case) were decalcified and sectioned to be studied microscopically. Figure 6 shows representative slides of both a K wire and standard drills at hole 5. The photomicrograph highlights the bony destruction encountered. The K wire (Fig. 6A) demonstrates noticeably increased bony destruction and change in bony architecture when compared to the standard drill of the same size (Fig. 6B), correlating with increased temperatures measured during drilling as well as different drill designs. The result of excessive heat produced by K-wires is consistent with the literature[13,18,19]. K-wires exerted higher forces and heat than standard drills due to lack of cutting flutes to remove bone debris. It should also be noted that the differently sized standard drills show grossly similar bony destruction (Figs. 6B and 6C). It should also be noted that all samples have a paucity of osteocytes with empty lacunae surrounding the drill margin.

DISCUSSION

Thermal osteonecrosis of bone is a result of the combined effects of elevated temperature and exposure time. This study experimentally investigated and compared repetitive sequential drilling in a defined sequence. By controlling for all variables except heat production, the maximum temperatures and heat accumulation could be studied. Each drill bit was examined with a tooling microscope at the end of each sequence. The absence of appreciable wear is evidence that no increased friction from a dulling cutting edge affected the temperature readings.

There are many clinical scenarios in which either K wires or differing sizes of twist drills are utilized for repetitive sequential drilling. This study found that K wire produced significantly higher peak temperatures and accumulated significantly more heat than same size (2.0 mm) or even larger (2.5 mm) twist drills. K wires produced a higher temperature rise at each drill hole and a maximum temperature rise over 20 °C by the ninth hole. Given the threshold of 47 °C for thermal damage, the absolute temperatures measured for the second through ninth holes were sufficient to cause necrosis. As for the first hole, the initial drill pass did not introduce enough heat into the system for the first thermocouple to register temperatures consistent with osteonecrosis. However, it is important to note that the temperature was extracted 2.5 mm from the hole margin. Previous work shows that a single K-wire pass can create a temperature rise of 48.7 °C at 0.5 mm and 18.3 °C at 1.5 mm from the hole margin, which can lead to osteonecrosis around the hole margin.[13] This study, however, focused more on the heat accumulation, particularly between the holes, rather than the maximum temperature adjacent to the hole. Thermocouples located in the middle of surrounding holes provide the information of heat propagation and accumulation. Therefore, although the peak temperature rise at hole 9 is greater than that at hole 1 (Fig. 4), it does not necessarily mean a higher temperature adjacent to the hole margin. Instead, it indicates that more heat has accumulated in the drilling area as the drill bit proceeds.

Based on the data collected from all tools, it was found that the temperature rose rapidly with each subsequent pass until the seventh hole. This shows that the second row of holes received heat input from passes 1-6 as the heat dispersed throughout the bone, whereas the last row of holes (7-9) was not affected by the heat dispersed into the bone during passes 1-3, but only that from passes 4-6. Conversely, the maximum temperatures for holes 1-3 were not increased by the heat created in holes 7-9. Also, because of the similar temperature profiles and magnitudes across TC-A to TC-D, the heat-sink effect of a drill bit or K wire may not be significant. That is, although the tool temperature increases there is minimal heat transfer due to the low conductivity of bone. The major thermal damage factor should still be a result of cumulative heat inside the bone from multiple passes. Similar temperature profiles across thermocouples also suggest a nearly constant heat flow over time, which indicates low tool wear and low additional heat flow from the heated drilling tool.

The data collected have large variations, likely due to bone sample inconsistency (among different cadavers), drilling path deviation at the initial contact, and thermocouples disturbed by bone debris and environmental water. Also because of that, the effects of thermal anisotropy of cortical bone were not considered in the experiment since the resultant temperature deviation would be relatively small. For example, Lundskog used an infrared thermography and found a nearly circular isotherm at a drilling spot.[20] Davidson and James measured the thermal conductivity in radial, tangential, and axial direction and found a small range from 0.53 to 0.58 W/mK.[21]

After studying the data it is clear that there is a compelling argument to avoid K wires when a clinical scenario requires multiple drill passes. The temperatures recorded for twist drills were significantly lower than those for K wires and caused less bony destruction as evidenced by photomicrographs of drilled bone (Fig. 6). Although previous work has shown that both 2.0-mm and 2.5-mm twist drills produce temperatures consistent with osteonecrosis at up to 1.5 mm from the hole margin, the data collected in this study for twist drills show a much lower magnitude between the holes (or 2.5 mm from the hole margin) compared to that of the K wire. The average field temperature (across the four thermocouples) after drilling 9 holes was up to 50% lower with the drill bits as compared to the K wires.

Two twist drills of different sizes, 2.0 mm and 2.5 mm, were tested using an identical experimental setup. Similar trends were found with these two sizes. The larger drill (2.5 mm) produced slightly more heat throughout drilling; however, this was found to be statistically insignificant in this study. The overall trend correlates with previous studies of the effects of drills of varying sizes.[1,4,7-10,13,15]

When looking at the accumulation of heat in the system throughout the drilling sequence the trends mimic the results of the highest temperatures. After drilling the nine holes, the average temperatures across the four thermocouples were 18.6 °C for the 2.0-mm K wire and 9.9 °C and 11.7 °C for the 2.0-mm and 2.5-mm drills, respectively. This shows that K wire produces significantly more heat throughout the drilling sequence than do twist drills, again demonstrating that twist drills are a better tool for sequential drilling procedures in regards to heat production.

Given that in certain clinical situations using irrigation to decrease thermal exposure is not applicable other potential options have been previously studied. First, the use of a step drill or a drill with different proximal and distal diameters has been studied and found to not show a significant decrease of temperature in surrounding bone with single hole drilling.[22] Second, experimental drill designs including internally cooled drills utilizing channels through the center of the drill where cooled irrigant is passed have been studied. These have aimed to decrease overall heat production and the development of the drill as a heat sink. Augustin et al found that the use of an internally cooled drill was successful at decreasing temperature rise of surrounding bone during drilling.[22] This a potential option to be studied, however, given that the cooled irrigant exits at the tip of the drill this may inhibit the extravasation of the marrow components your are attempting to access similarly to conventional irrigation.

Limitations of this study include its ex-vivo study design, which allowed for more experimental control for quantitative comparison; however the results may not be the most accurate depiction of in-vivo conditions. Also, the results of this study were compared on a relative basis with a set of given conditions because manual drilling is difficult to specify. Another limitation is the use of multiple cadaveric specimens of various ages, which may have contributed to temperature variation between samples, instead of minimizing it. Lastly, the histology tests reflect only the high-temperature damage around the hole margin, not the heat accumulation-induced damage between holes.

CONCLUSIONS

For all drill bits tested temperatures close the hole margins were high enough to cause osteonecrosis. The maximum temperature and accumulated heat increased with each drill pass, supporting our hypothesis. The ninth hole was found to experience a temperature rise approximately four times higher than that of the first for each drill bit tested. K wires were found to create more heat with each subsequent hole when compared to twist drills. The accumulation of heat was also significantly higher with the use of K wires in comparison to twist drills, leading to the conclusion that K wires should be avoided for repetitive drill passes. For twist drills, size had a relatively insignificant effect on heat generated at each hole as well as the heat that accumulated in the system throughout the drilling experiment. Given the heat accumulation and heat dispersion effects of adjacent holes during drilling it is concluded that attempting to maximize the drilling field as much as possible and reducing the total number of drill passes to the clinically necessary minimum may reduce the risk of thermal injury to bone.

FUTURE DIRECTIONS

To the authors knowledge this is the only study of its kind to look at sequential drill passes and heat accumulation, and we feel that this is an important topic that warrants further investigation. The current study suggests that increasing the space between drill holes may decrease the accumulation and thus the thermal effects of sequential drilling; however, this needs to be studied further. This work also questions the idea of thermal dose, which is a measurement of exposure time to heat being introduced to a system. In the future, a finite element analysis model may be employed to study thermal dose and to optimally adjust the space between drill passes as well as time between each pass. This would allow the sequence of drill passes to be manipulated to find the most appropriate sequence to reduce thermal effects.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Erin Bigelow for her help with bone sample procurement and processing. This experiment was funded by an internal grant awarded by the University of Michigan, Department of Orthopaedic Surgery Research Advisory Committee. The authors have no potential conflicts of interest to disclose.

FIGURE CAPTIONS

Figure 1. The experimental setup.

Figure 2. Hole positions and thermocouple arrangement.

Figure 3. An example of temperature data from four thermocouples for the 2.0-mm drill bit.

Figure 4. Temperature vs. hole position during sequential drilling with (a) 2.0-mm K wire, (b) 2.0-mm twist drill, and (c) 2.5-mm twist drill. Error bars represent standard errors based on the six tests of each case.

Figure 5. Interpolated temperature field by four thermocouples at the end of drilling holes 3, 6, and 9 with (a) 2.0-mm K wire, (b) 2.0-mm drill bit, and (c) 2.5-mm drill bit. The area for the 2.5-mm drill bit is larger for the same thermocouple to hole-margin distance.

Figure 6. Representative photomicrographs of decalcified bone samples with (a) 2.0-mm K wire, (b) 2.0-mm standard drill bit, and (c) 2.5-mm standard drill bit.

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