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Assessment of heat generation and its effect during cortical bone drilling using infrared camera and histology

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Orthopedic bone drilling involves human as a part of action thus the role of drilling must be concise with its prime objective only. Excess heat generation and physical damage during drilling will lead to extended problems i.e. osteonecrosis and permanent death to the bone cells. To avoid that particular lose to the bone the heat generation should be as low as possible. In this study, an experiment is performed on bovine bone with varying rotational speed (600, 800, 1000, 1200 RPM) while keeping all other drilling parameters constant. Heat generation during bone drilling is measured using thermal imaging camera. After experiments, the histology examinations are performed to observe by morphological changes in drilled bones. From results, heat generation is observed to be increased with the rotational speed and results are shown with the help of thermo-graphic images. Histopathology of drilled bone specimens is also carried out for better understanding of changes in morphology of bone with change in temperature raise during bone drilling. Results conclude that heat generation in bone drilling is strongly concord with drill rotational speed ($P \leq 0.014$). Histopathology of drilled bones shows that level of osteonecrosis is increased in terms of number of empty lacunas with temperature raise.

Keywords: Bone, Bone drilling, Heat generation, Osteonecrosis, Thermal imaging, Histopathology

1 Introduction

Bone drilling is often performed during surgical treatment of fractured bones. The holes produced in cortical bones are required for placing hardware implants such as, plates, and other devices with screws or pegs. These constructs immobilize the fractured bones maintaining an anatomic position facilitating the healing process. Drilling during orthopedic surgery is a purely mechanical process, in which a metal drill bit is used to create a cylindrical cavity in the bone[1-2]. Bone removal begins when the drill tip touches the bone and initiating shear deformation of bone material. Bone material removal follows in the form of fragments exiting out through the drill flute guide ways and result in the form of cylindrical cavity[3-4]. During the shear deformation and frictional contact of metal to bone, the temperature at the drill-bone interface may increase rapidly above 150ºF causing cell death[1-4]. The localized heat generated from drilling disperses poorly due to bone's low thermal conductivity[4-6]. The concentrated heat generated leads to permanent damage of local bone cells[7-11]. Studies have reported, empty lacunas in the osteocytes of bone cells[1,12-14] as evidence of thermal damage. The clinical consequence of osteocyte death is bone resorption around screws and pegs. This causes further problems such as loss of fracture repair fixation, construct strength, or even an infection[1,15]. Limiting heat generation is paramount to preventing fracture repair complications. Studies have attempted to maintain the bone temperature low, and under the osteocyte damage threshold using different parametric combinations[16-21], tool specifications[18-19,21-29] and different drilling conditions[29-35]. It has been observed from previous studies that rotational speed is a major factor which contributes to heat generation at higher speeds more so than compared to other drilling parameters[4,9-11,21]. Thompson[36] conducted an in vivo experimentation and observed an increase in heat generation with increasing the rotational speed within the range of 125 to 2000 RPM. Nam et al.[37] also observed an increase in heat generation with an increase in rotational speed and increasing drilling force as well. These experiments were conducted on bovine bone at loading conditions of 500 gm and 1000 gm with rotational speeds of 600 RPM and 1200 RPM. Sharawy et al.[38] also found that there is a significant increase in temperature while drilling a pig jaw bone at rotational speeds of 1225 to 2500 RPM. Pandey and Panda[1], concluded in their comprehensive

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review of bone drilling that there is an increase in heat generation in direct proportion to rotational speeds up to 10,000 RPM. Pandey and Panda[11] also conducted experiments for varying rotational speed and feed rate using different parametric combinations. From their results and observations, they concluded that low rotational speeds and low feed rates had better results in terms of heat generation with drilling of cortical bovine bones. Despite all of this previous drilling research, it remains unclear which of the slower rotational rates remain below osteocyte damaging temperatures. The purpose of the present study is to examine osteocyte damage from four low to intermediate drill rotational speeds (600, 800, 1000, 1200 RPM) while keeping all other drilling parameters constant. A thermal imagining camera is used to record the heat generated during drilling. The second purpose of this study is to correlate drill rate, and thermal imaging with histopathology to identify the slower rotational rates which remain below osteocyte damaging temperatures.

2 Materials and Methods

2.1 Cortical bovine bone collection and processing

To perform the experiments cortical bovine bone was acquired from the slaughter house. Bovine bones were used to perform the experiments due to its thermo-mechanical similarity with human bones[2-4,8-9,11,14]. While collecting the bones from slaughter, some precautions measures have been considered. All bovines must be healthy and free from any serious health issues. Age of the bovine must be within the range of 11-14 years, so that the results and observations must not differ due to bone properties. Acquired bones were kept in the saline solutions directly after slaughtering and kept them up to the experiments. The experimental procedures were done on the same day of slaughtering at room temperature (70°F).

2.2 Drilling procedure

The experiments were performed on a vertical computer numeric control (CNC) drilling/milling machine on which an automatic system adjusted the rotational speed with a numeric control program. Bone specimens were fixed to the drilling platform bed with screws as shown in Fig. 1(a-b). One of four rotational speeds (600, 800, 1000, 1200 RPM) were applied to individual and separate bone specimens while keeping all other parameters fixed (shown in Table 1). The temperature produced was recorded by the thermal imaging camera. Drilling was ceased once 120°F was reached, and drilling penetrated both cortices. Each experiment was performed five times at room temperature (70°F) with a new drill bit each time. No drill bits were reused. No bone specimen was drilled more than once. No irrigation was included during the drilling process. A drill bit using for drilling procedure is sown in Fig. 1b.

2.3 Histopathology

First the drilled hole region with a 5-7mm surrounding region of bone was cut away from the remaining bone specimen. Next, the block sample was decalcified for later micro-sectioning and staining. These small specimens were treated in fresh 10% nitric acid and acid change after every 2 days until the decalcification was complete. When the bones tissues oftened the specimens were immersed in10 vol % formaldehyde diluted in distilled water. Final preparation included washing out the nitric acid and formaldehyde under running water, and embedding in wax. The bone specimen fixed in wax was sectioned (4-6µm) by the means of a microtome cutting apparatus and stained with hematoxyline–eosine (H&E)[39-41]. The histopathology of these specimens was studied with an optical microscope (NIKON Make).

3 Results

The drilling tests resulted in very consistent temperatures for each of the 5 trials with small stand

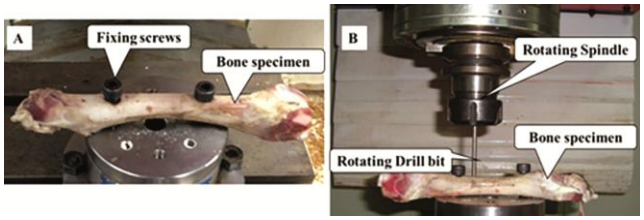

Fig. 1 — (a) Bone specimen fixed on machine table and (b) bone specimen drilling.

Table 1 — Parametric values used for experimentation.

Drilling parameters	Parameters value
Feed Rate	10 mm/min
Drill diameter	4.5 mm
Type of drill bit	Standard Surgical Twist Drill
Rotational Speed	600,800,1000,1200 RPM
Infrared camera	
Camera Manufacturer	Fluke Thermography
Camera Type	Ti32-12050463 (9Hz)
Emissivity	0.95

deviations. The experimental temperature observations are shown in Table 2. Figure 2(a-d) shows the graphical representation of temperature recorded during experimental trials and their variations around the average values. Figure 3(a-d) shows the thermal images received from the infrared camera for four different rotational speeds.

3.1 Data analysis

Each of the experimental observations was statistically tested (statistical software MINITAB) for Pearson correlation coefficient, and P-Value between the rotational speed and average maximum temperature recorded for each rotational speed tested.

The correlation coefficient calculated was 0.986, which indicates that the temperature produced during bone drilling is highly correlated with the rotational speed of the tool. The P value is 0.014, which shows the change in rotational speed significantly affect the temperature rise with in this selected range of rotational speed. Figure 4 illustrates the relationship between rotational speed and temperatures recorded during the drilling in relation to the threshold temperature of116-122 °F for osteocyte damage.

3.2 Histopathology Results

A total of four bone samples, drilled at 4 different rotational speeds were studied by histology. No empty lacunas were noted from the 600 RPM bone sample. The other 3 higher speeds of 800, 1000, and 1200 all demonstrated empty lacunas within 0.5 mm of the drill edge. Figure 5(a-d) demonstrate empty and filled lacunas, indicating that there is thermal damage to the bone above 800 RPM and no damage in the lowest 600 RPM case. One specimen shown in Fig. 5a, was drilled with the lowest Rotational speed (600

Table 2 — Temperature (ºF) recorded using infrared camera during drilling.

Experimental Trail	RPM 600	RPM 800	RPM 1000	RPM 1200
Trail 1	102.6	126.3	136.4	152.4
Trail 2	102.8	126.7	136.1	151.5
Trail 3	102.0	125.8	135.8	152.6
Trail 4	102.1	126.4	136.6	152.8
Trail 5	103.0	126.6	136.5	152.0
Average ± SD(ºF)	102.5 ± 0.4(ºF)	126.4 ± 0.4(ºF)	136.3 ± 0.3(ºF)	152.3± 0.4(ºF)

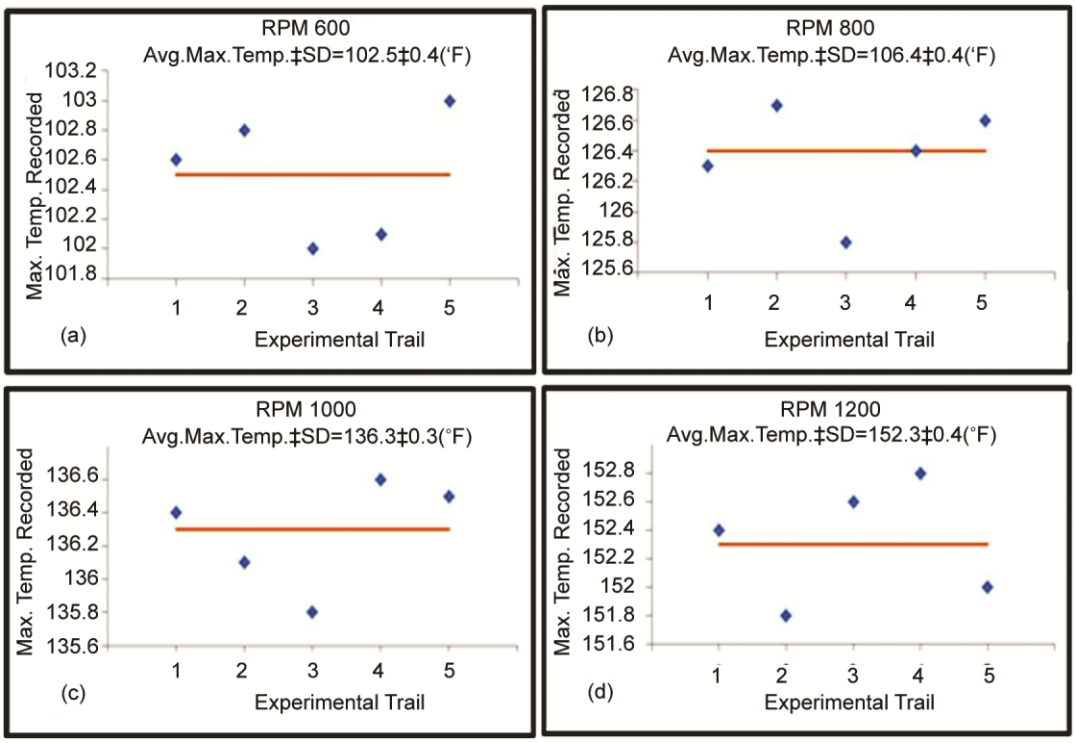

Fig. 2 — Variation in temperature about the average value (a) at 600 RPM, (b) at 800 RPM, (c) at 1000RPM and (d) at 1200 RPM.

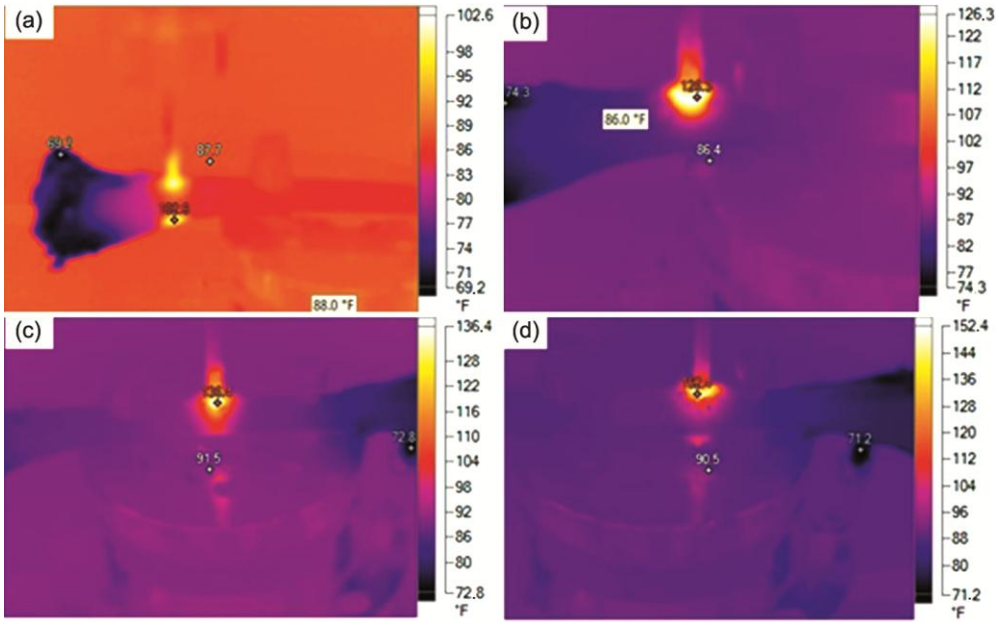

Fig. 3 — Maximum temperature recorded using infrared camera while drilling the bone (a) at 600 RPM, (b) at 800 RPM, (c) at 1000 RPM and (d) at 1200 RPM.

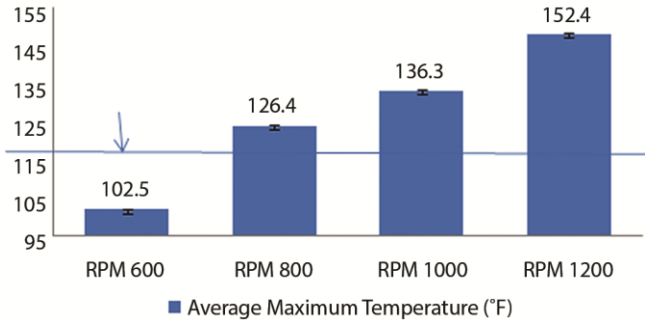

Fig. 4 — Average maximum temperature corresponding to different rotational speeds.

RPM) and the temperature was observed as 102ºF which is lower than the threshold of116.6ºF – 122ºF. In Fig. 5b, the image shows the histopathology of the bone specimen drilled with the rotational speed of 800 RPM. In this image, lacunas near the drill site were found to be empty. The maximum temperature recorded was 126ºF in this case and the effect of crossing the threshold is evident near the drill site where two lacuna regions are marked as empty in Fig. 5b.

From Fig. 5c, it is demonstrates that increasing bone temperature from a faster drill speed further affects the morphology of bone in terms of more empty lacunas in the drilled bone vicinity. The temperature rose with a rotational speed of 1000 RPM on average to136.3ºF, which is 13.3% above the threshold temperature which damages osteocytes. At higher drill speeds and higher bone temperatures, more lacunas are empty on a wider distribution some of which are over 1.0 mm away from the drill site are void of osteocyte nucleus material. In Fig. 5d, histopath image of this specimen shows the most dramatic effect of rotational speed on the morphology of bone. The rotational speed of 1200 RPM generated temperatures averaging 152.4ºF. The bone histology in this drilling scenario shows empty lacuna widely distributed over the histology slice and the full image shown. The temperature raised was high enough to empty the lacunas near the drill's edge as well as millimeters away from the drill site.

3.3 Discussion

Mechanical procedures producing bone temperatures above 122° F have been repeatedly shown to cause osteocyte damage[1,9,10,13,14]. Most of the previous studies have been conducted at RPMs which generate sufficient heat to kill osteocytes. In this study, infrared camera and histology successfully demonstrate that a drill rate of 600 RPM does not generate elevated temperatures resulting in safe osteocyte. Equally important was the observation that drilling at 600 RPM with a fresh drill bit successfully drilled through both cortices without cellular death. Higher drill speeds resulted in a wider distribution of empty lacuna in histology. The clinical significance of this can be extrapolated from the current views of heat

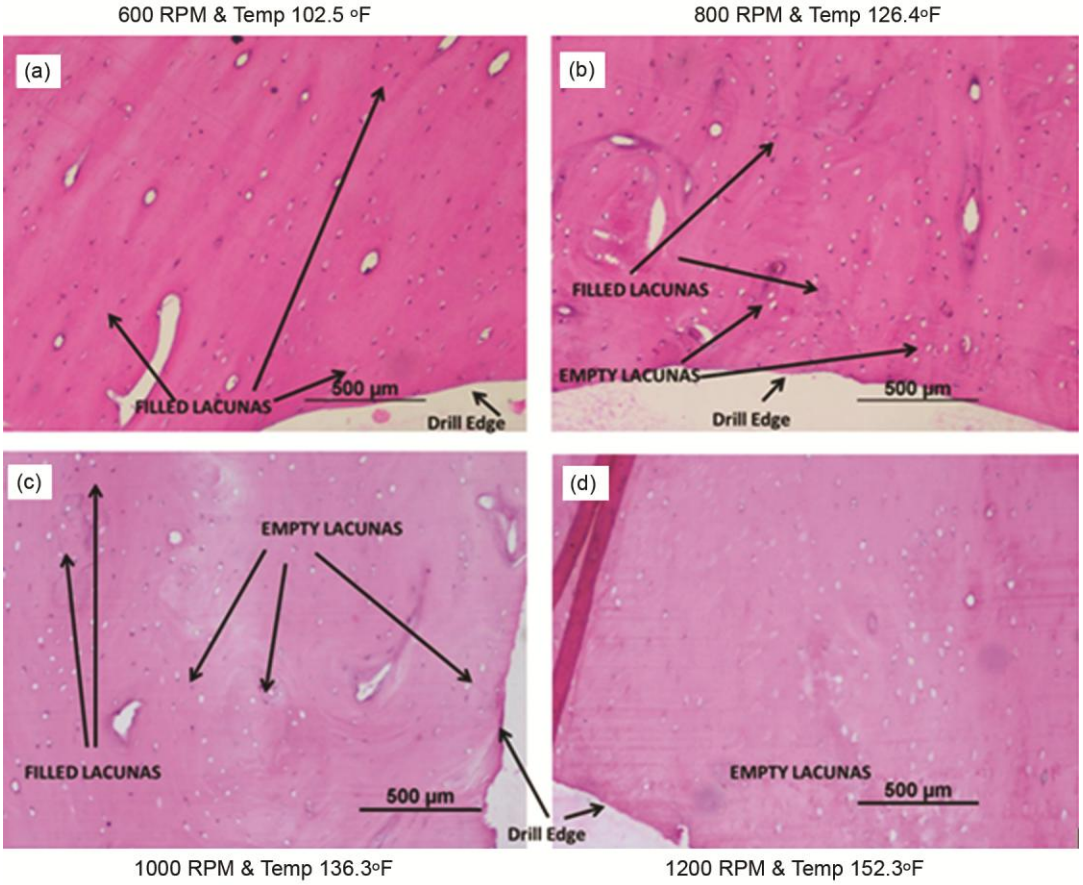

Fig. 5 — Histopathology of bone specimens for (a) at 600 RPM, (b) at 800 RPM, (c) at 1000 RPM and (d) at 1200 RPM

generation. First, it has been proposed that the osteocyte death results in a series of events. These events include osteocyte death, bone resorption, and then either fixation failure or even an infection from avascular material in a surgical site. Strengths of this study include: bovine bones were selected for the experiments and they are thermo-mechanically similar with human bones[2-4,8-9,11,14]. Also, the drilling speeds were monitored by temperature sensative cameras and by histologic analysis.This provided 2 independent metrics for analyzing the impact of different drill speeds and temperatures produced. Furthermore, the 4.5mm drill bit used is in common orthopaedic use today.In other words,the experimental conditions used are very similar to current clinical practice. Limitations of this study include that histology was not repeated for each trial. The reason behind this is that the camera was sufficient in tracking the impact of variable drill speeds, and repeating the histology for every case was unnecessary. Another limitation is that only one drill bit was tested, there are many other sizes commonly used which may not follow the same heat generation patterns as the 4.5 mm drill we tested. Osteonecrosis in bone has been observed when the temperature exceeds 47ºC (116.6ºF) for one min and has also been observed with 50ºC (120 ºF) for 30 seconds[1,12]. None of the drilling tests performed in this experimentation required 30-60 seconds. Feed rate used 10mm/min is also not advisable for many conditions but suggested by the different surgeons and researchers in most of the cases.The main theme of drilling research is that bone necrosis can be induced during bone drilling in some orthopedic surgeries which may cause a compromised healing process, low anchorage of fixed implants and failed restoration of a fractured bone[1,9]. If thermal necrosis is common with the drilling process and it can theoretically be eliminated with the use of a balanced set of drilling parameters[4,8-9,12-13]. Feed rate is one variable easily altered in the laboratory or the surgical suite. In this experimental study, the chosen feed rate of 10 mm/min can increase the drilling time and heat generated. Alternatively, the shear force developed per revolution may be reduced with the lower feed rate[14-17].

In this study rotational speed was varied within the targeted range of 600-1200 RPM. This study found no osteocyte damage at 600 RPM. This is a clinical benefit however, it should be remembered that a low rotational speed generates more torque which can cause other damage around the drill site such as cracks. Likewise, higher rotational speeds are directly correlated with high heat generation and screw or peg fixation issues[37-39]. Since the end point in heat generation from drilling is osteocyte death, this study focused on the histology of bone with temperature changes resulting directly from rotational speed changes.

Currently, it unknown that how much osteocyte death will cause the screw or peg failure? In other words, osteocyte death have to be a circumferential distance of 2 millimeters or more in order for enough bone to resorb and result in screw or peg loosening. This was not an objective of this study and could be studied in the future research.

4 Conclusions

A drill speed of 600 RPM generates average bone temperatures of 102.5°F, and no osteocyte damage on histology. Drill speeds of 800-1200 RPM produce bone temperatures from 126.4-152.3°F, and osteocyte damage as evidenced by empty lacunas on histology. Further study is warranted to quantify the extent of osteocyte damage with various drill speeds. The zone or volume of osteocyte damage should be studied in such a way so as to identify the minimal amount leading to fixation loss and or an infection. This information will bring us closer to knowing the best drilling parameters causing the least amount of bone damage. Two clinical applications of our results include; designing drills that cannot exceed 600 RPM, and including intra-operative temperature monitoring of bone drilling. If a bone hole is drilled with elevated temperatures resulting, the surgeon may then use this information to re-drill in another location to ensure definitive screw or peg fixation.

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