DOES IRRIGATING WHILE DRILLING DECREASE BONE DAMAGE?

Justin C. Woods, MD[1]; James L. Cook, DVM, PhD[1,2]; Chantelle C. Bozynski, DVM, MS[1,2];
Jason D. Tegethoff, BA[3]; Keiichi Kuroki, DVM, PhD[4]; Brett D. Crist, MD[1,2]

ABSTRACT

Background: Heat generated during bone drilling may be associated with thermal necrosis and direct damage, leading to complications after surgery. This preclinical study evaluates the in vivo effects of saline irrigation, drilling device type, and device sharpness on heat generation and bone damage in viable cortical bone.

Methods: Bicortical drilling of each tibial diaphysis from anesthetized research dogs was performed to evaluate temperature and bone damage using five different devices with or without saline irrigation.

Results: Saline irrigation and sharp drill bits were associated with smaller temperature increases and less acute osteonecrosis. Conventional trocar tip Kirschner wires were associated with the largest temperature increase and the most acute osteonecrosis changes.

Conclusion: The use of saline irrigation during bone drilling reduces temperature change and osteonecrosis. Furthermore, we recommend that the use of dull drill bits or standard tip Kirschner wires be avoided. Lastly, drill bit design can directly contribute to bone damage during drilling.

Clinical Relevance: This study provides in vivo data from a preclinical model to validate the benefits of saline irrigation and sharp drill bits during bone drilling to regulate increases in temperature and decrease associated osteonecrosis. Risk for early implant loosening and poor surgical outcome is influenced by thermal osteonecrosis of bone such that consistent use of saline irrigation, sharp drill bits, and optimized designs may have important clinical advantages.

Level of Evidence: II

Keywords: fracture surgery; osteonecrosis; bone drilling; saline irrigation; heat generation

INTRODUCTION

Bone drilling is fundamental to the practice of orthopaedic fracture surgery. Drilling into bone generates frictional heat that may contribute to thermal osteonecrosis. Heat-induced osteonecrosis occurs when bone sustains a temperature of 47° Celsius (C) for a period longer than 60 seconds or 50°C for 30 seconds.[1,2] The threshold temperature for immediate bone death due to applied heat is 70°C.[3] Cortical bone will reach temperatures beyond 100°C in the surgical setting if no heat-counteracting measures are applied.[4] Cortical bone injury and necrosis can lead to bony resorption around the screw with the formation of fibrous tissue and subsequent loss of implant and bone interface.[5-7] The effects of bone injury that occur with specific temperature thresholds have been reported in association with oromaxillofacial implants.[8]

Fracture plating construct stability relies on screw purchase into the bone. The sufficient purchase of a screw translates into bone-plate stability by producing adequate friction between a bone and the applied plate or by providing a stable interface to resist torsional or axial load in an intramedullary nail or locking plate. Loss of the bone-screw interface in non-locking plates decreases screw pullout strength and implant stability.[9] Unstable orthopaedic implants predispose to premature implant failure, fractures, delayed union or nonunion, and increases the risk for infection.[10] Therefore, any cause for decreased screw-bone interface may contribute to significant surgical complications and minimizing the risk of bone necrosis during screw placement is important.

Regulating heat production is routinely practiced in orthopaedic surgical settings. In order to minimize heat production, it is recommended to use smaller diameter and sharp drill bits, avoid the use of blunted drill bits, drill with decreased rotational acceleration rates, use

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[1]University of Missouri Department of Orthopaedic Surgery, Columbia, Missouri, USA

[2]Thompson Laboratory for Regenerative Orthopaedics, Columbia, Missouri, USA

[3]University of Missouri School of Medicine, Columbia, Missouri, USA

[4]Veterinary Medical Diagnostic Laboratory, University of Missouri Veterinary Health Center, Columbia, Missouri, USA

Corresponding Author: Brett D. Crist, MD, cristb@health.missouri.edu, 573-882-6562

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low-frequency vibration-drilling, alter the angle of screw insertion, and irrigate during active drilling.[11-14]

Related studies insist that irrigation while drilling is the superior method for temperature regulation.[2,3] Irrigation reduces drill site temperature by heat conduction—i.e., irrigation acts as a coolant to provide lubrication to decrease friction and facilitate the removal of bony debris that may obstruct drill flutes and decrease heat dissipation. When drill sites were irrigated externally with normal saline at a rate of 500 mL per minute, the local temperature never increased beyond threshold temperatures of 50 °C.[5]

Previous reports examining the effects of drilling on bone have focused primarily on cadaveric and tissue explant models, which do not account for the influences of live cells and blood supply on resultant damage.[2,3,9,12] Therefore, the purpose of the present study was to evaluate the effects of saline irrigation on regulating temperature increase and acute bone damage using different drill bits and Kirschner wire devices commonly used in fracture surgery in a live translational model. The study was designed to test the hypothesis that temperature change and initial cortical bone damage will each be significantly ($P < 0.05$) different based on the type of drill bit or wire used for bone drilling and that saline irrigation will effectively mitigate temperature change and damage.

METHODS

With approval from our institutional animal care and use committee, skeletally mature purpose-bred research dogs ($n = 5$) were premedicated, anesthetized, and prepared for aseptic surgery of both hindlimbs as part of an unrelated terminal procedure. Rectal temperature was measured during the procedure. For each canine, both tibias ($n = 10$) were treated as matched pairs to allow for drill bit type and irrigation assignments as described. A medial approach to expose the tibial diaphysis was performed, and hemorrhage was controlled with electrosurgery. Five diaphyseal drill sites were marked on the medial tibial diaphysis each 2 cm apart (Fig. 1A). Each drill site was assigned to one of the five drilling devices to be tested, and right and left tibias were alternated to receive or not receive saline irrigation during drilling, creating 10 treatment groups for comparison ($n = 5$ per treatment group) with the following:

- New (sharp) 2.5 mm drill bit (DePuy Synthes, West Chester, PA, USA)
  - o With saline irrigation (SDB+)
  - o Without saline irrigation (SDB-)
- Dulled 2.5 mm drill bit (DePuy Synthes) – dulled by performing 10 bicortical drill tunnels in femoral cortical bone
  - o With saline irrigation (DDB+)
  - o Without saline irrigation (DDB-)
- New 2.5 mm drill bit (Osteocentric Technologies, Inc, Austin, TX, USA)
  - o With saline irrigation (ODB+)
  - o Without saline irrigation (ODB-)
- New drill-tip 1.6 mm Kirschner wire (DePuy Synthes)
  - o With saline irrigation (DKW+)
  - o Without saline irrigation (DKW-)
- New spade-tip 1.6 mm Kirschner wire (DePuy Synthes)
  - o With saline irrigation (SKW+)
  - o Without saline irrigation (SKW-)

Drill devices were rotated among drill site locations for each dog so that each device was assigned to each location and order of drilling in equal numbers. Immediately prior to drilling, the temperature (°C) of the tip of the drilling device was measured at the cis[15] (near) cortex using a calibrated infrared thermometer gun (Fisherbrand, Thermo Fisher Scientific, Waltham, MA, USA) (Fig. 1B). High-speed (910 rpm) single-pass bicortical drilling of each site was performed using standard surgical power equipment (Arthrex 600 System, Arthrex, Inc., Naples, FL, USA) and the assigned drilling device with or without saline irrigation. A single board-certified veterinary orthopaedic surgeon with more than 20 years of experience performing open reduction internal fixation procedures performed the bone drilling for this experiment. Drilling was performed using a standard surgical technique with consistent pressure based on tactile response according to the manufacturer's instructions. Based on flute design, Osteocentric drill bits (ODB) bits were advanced with relatively less pressure during drilling. Per the manufacturer, OsteoGuard drill bits (Osteocentric Technologies, Inc.) are designed with a unique cutting tip, longer flutes with uniform volume, and no side cutting to remove less bone more efficiently with less damage.

Drill sleeves were used during the drilling process.

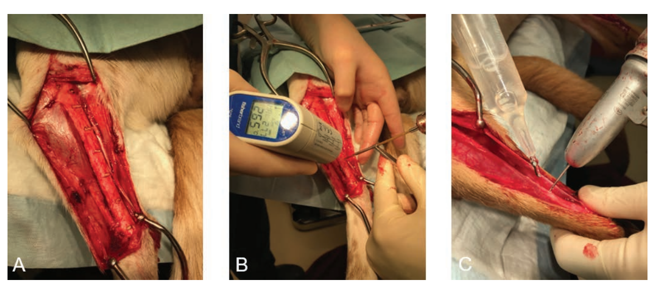

Figure 1. (A) Tibial diaphysis shown with drill sites spaced 2 cm apart. (B) Traceable® Infrared Thermometer Gun measuring drill bit temperature immediately upon cessation of drilling. C. 60-cc bulb syringe applying irrigation at drill bit tip during active drilling of cortical bone.

Saline irrigation was performed using room-temperature sterile isotonic saline via 60 ml bulb syringe delivered in standard clinical fashion (Fig. 1C). Immediately after drilling, the temperature (°C) of the tip of the drilling device was measured at the cis cortex using a calibrated infrared thermometer gun.[16]

Immediately after the completion of drilling, dogs were humanely euthanized while still under anesthesia. Histological examination of bone necrosis tends to occur in a pattern. Eriksson and Albrektsson described thermal osteonecrosis as occurring over several weeks.[1] Pathologists note the earliest signs of bone ischemia are seen by day two in the marrow spaces with loss of nuclear staining of marrow cells, osteocyte depletion, and the appearance of large round, ovoid spaces filled with fat. By day 15, osteocytic lacunae are empty and trabecular surfaces are devoid of cells while capillaries, fibroblasts, and foamy histiocytes may be appreciated at the border of the necrotic zone.[7]

The tibias were immediately disarticulated and dissected free from all soft tissues. Each drill site with 1 cm of surrounding bone circumferentially was collected and processed. The cis (near) and trans (opposite) cortices were separated and analyzed individually. Half of the samples were processed for scanning electron microscopy (SEM),[17] and the other half were processed for histology.

Samples destined for SEM were fixed in 2% paraformaldehyde, 2% glutaraldehyde in 100 mM sodium cacodylate buffer pH = 7.35. All specimen preparation was performed at our university's electron microscopy core facility. Fixed tissues were rinsed with 100 mM sodium cacodylate buffer, pH 7.35 containing 130 mM sucrose. Secondary fixation was performed using 1% osmium tetroxide (Ted Pella, Inc., Redding, CA, USA) in cacodylate buffer using a Pelco Biowave (Ted Pella, Inc.) operated at 100 Watts for 1 min. Specimens were then incubated at 4 °C for 1 hour, initially rinsed with cacodylate buffer, and further rinsed with distilled water. Using the Pelco Biowave, a graded dehydration series (per exchange, 100 Watts for 40s) was performed using ethanol. Samples were dried using the Tousimis Autosamdri 815 (Tousimis, Rockville, MD, USA), and samples were sputter-coated with 20 nm of platinum using the EMS 150T-ES Sputter Coater. Images of the drill site and surrounding bone were acquired with a FEI Quanta 600F scanning electron microscope (FEI, ThermoFisher Scientific, Hillsboro, OR, USA) using a high-vacuum secondary electron (Everhart-Thornley) detector at 25X to 25,000X magnification, a voltage of 5 or 20kV and spot of 3 or 8.

Samples destined for histology were fixed in 10% neutral buffered formalin fixative. Once properly fixed, the bone specimens were demineralized with 10% ethylenediaminetetraacetic acid (EDTA) in PBS, sectioned in two at the drill site when sufficiently softened, and processed for H&E staining.

An in-house scoring system was created to evaluate severity/extent of four histologic changes at the drill site (total out of 12 points) for both H&E staining and SEM:

1. loss of osteocytes from lacunae/bone necrosis (out of 3 points),
2. bone coagulation (thermal injury) (out of 3 points),
3. soft tissue coagulation (out of 3 points), and
4. debris in/neighboring the drill site (out of 3 points)

The highest score represents the most severe pathology. Histologic scoring of the drill sites was performed by two board-certified veterinary pathologists blinded to treatments. Both pathologists scored all sites and their mean scores were used for statistical analyses based on strong inter-observer agreement ($r^2 = 0.91$).

Statistical Analysis

Each continuous outcome measure (Δheat, structural damage, zone of necrosis) was compared among groups for cis or trans cortices using one-way ANOVA with multiple pairwise comparisons with corrections. Within-group comparisons were made for cis versus trans cortices and irrigation versus no irrigation using paired t-tests. Differences were considered statistically significant at $P < 0.05$. Correlations between change in temperature and bone damage or necrosis were assessed using Pearson Product Moment Correlations with $r > 0.7$ considered strong.

RESULTS

Rectal temperature was consistent among dogs at a mean of 37.8 °C (range, 36.1-38.3). Immediately prior to drilling, the temperature of the tip of the drilling device was consistent among dogs at a mean of 25.4 °C (range, 22-28.6).

Heat Generation

Saline irrigation while drilling resulted in smaller temperature increases than drilling without saline irrigation for all groups except for 1.6 mm spade-tip Kirschner wires (SKW- = 4.7 °C ± 2.9; SKW+ = 2.9 °C ± 1.3) (Fig. 2). The effects of saline irrigation on change in temperature did not reach statistical significance for any drilling device tested ($P > 0.1$). Sharp 2.5 mm drill bits with saline were associated with the smallest increase in temperature after drilling (SDB+ = 0.2 °C ± 0.7). Overall, SKW- reached the highest temperature change of 7.6 °C and SDB+ achieved the lowest temperature change of -0.1 °C. One-way ANOVA with pairwise comparisons

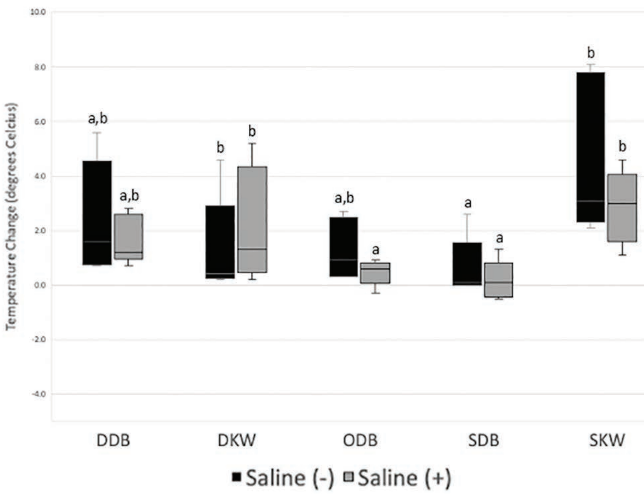

Figure 2. Mean ± standard deviation of change in temperature of drill sites before and after drilling using 10 drilling techniques. These box-and whiskers plot for median, interquartile range, minimum, and maximum values for temperature change for each drilling device tested. Note: different letters above plot indicate statistically significant differences (P < 0.05) among groups with "a" representing the smallest change in temperature.

produced the following statistically significant differences: SDB-, SDB+, and ODB+ had significantly smaller temperature increases compared to DKW- and DKW+ ($P < 0.03$). SDB-, SDB+, and ODB+ also had significantly smaller temperature increases than SKW- and SKW+ ($P < 0.042$). Surprisingly, dull drill bits did not show any statistically significant differences to other groups for change in temperature.

Bone Damage

H&E

One-way ANOVA comparison among groups showed significant findings. SKW- and SKW+ had significantly higher total histopathologic scores than all other groups ($P < 0.05$) (Table 1). ODB+ had a significantly lower histopathologic score than both DDB-, DDB+, DKW-, and SDB- ($P < 0.05$) (Table 1). There were no other statistically significant findings.

Saline irrigation while drilling was associated with lower histopathology scores compared to drilling without irrigation across all drilling techniques (Table 1). Further, subcategory analyses showed that SKW+ and SKW- had significantly higher osteocyte loss/bone necrosis and bone coagulation (thermal injury) scores at drill sites than all other groups with or without saline ($P < 0.05$). This finding is characterized by large numbers of empty bone lacunae and prominent basophilia of the disrupted bone matrix at/extending out from the drill site, respectively (Fig. 3 A and B). In contrast, the drill sites created with ODB were less disrupted with only small numbers of empty bone lacunae and

Table 1. Mean ± Standard Deviation of Total Histopathologic Scores

Saline Irrigation	SDB	DDB	ODB	DKW	SKW
Yes	5.6 + 0.8	5.8 + 1	4.6 + 1.5	5.3 + 1.9	8.5 + 1.4
No	6.0 + 2.2	6.3 + 2.6	5.2 + 1.1	6.2 + 1.2	9.1 + 1.5

Note: In-house scoring system attributes up to 3 points (1=mild, 2=moderate, 3=marked) for four different attributes: osteocyte loss/bone necrosis, bone coagulation, soft tissue coagulation, and debris at neighboring drill site. The maximum score possible is 12. A higher score equals more damage.

Key: SDB=sharp drill bit, DDB=dulled drill bit, ODB=Osteocentric drill bit, DKW=drill-tip Kirschner wire, SKW=spade-tip Kirschner wire.

small quantities of basophilia of the bone matrix immediately neighboring the drill site (Fig. 3 C and D). Other treatment groups (for example, SDB+ in Fig. 3 E and F) occasionally showed moderate disruption of bone at the drill site associated with moderate quantities of empty bone lacunae and basophilia of the bone matrix (but not as extensive as the spade tip 1.6 mm Kirschner wire group).

SEM

Similar to the histology findings, SEM showed that drill sites created by SKW had more surface and drill site microfractures and structural disarray of organic scaffolding. ODB created the least damage when compared to the other drilling devices (Fig. 4).

DISCUSSION

This novel preclinical study examined the in vivo effects that saline irrigation, drilling device type, and device sharpness have on heat generation and bone damage in viable cortical bone. Five different drill bits and wires commonly used for orthopaedic surgery were compared using temperature measurements, histologic assessments, and scanning electron microscopy (SEM). The results of this study confirm that saline irrigation provides a counterregulatory effect on heat generation produced by drilling into the bone. As a result, concomitant saline irrigation was associated with less disruption of cortical bone secondary to osteonecrosis as represented by histopathology scores and SEM imaging assessments.

There were also notable differences between drilling instruments. Compared to their dulled counterparts, sharper drill bits were associated with smaller temperature increases with or without saline irrigation. Importantly, standard trocar tip 1.6 mm Kirschner wires (SKW) were associated with the highest temperature increase and most severe histopathologic changes in

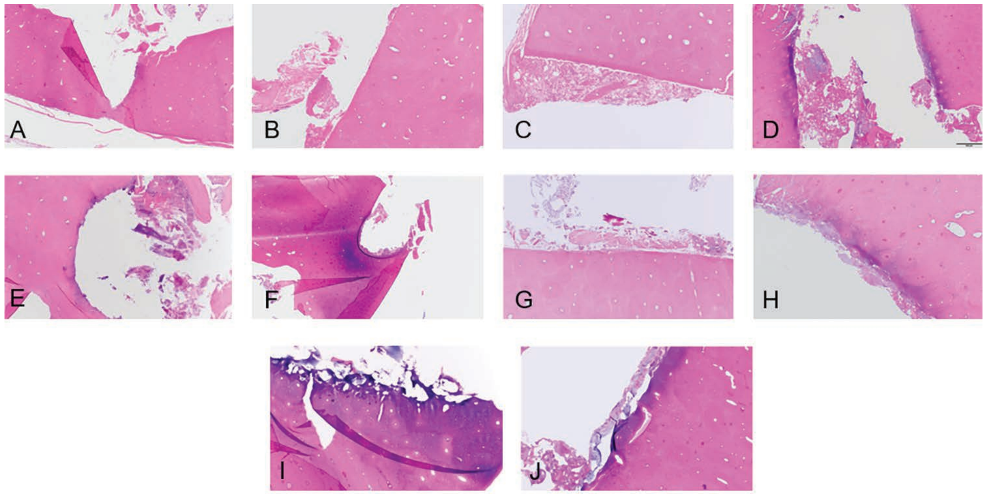

Figure 3. Representative H&E images of drill sites in tibial cortices with increasing severity of bone coagulation (thermal damage) and osteocyte loss/bone necrosis for selected drill types. Bone necrosis is characterized by empty osteocytic lacunae (osteocyte loss) within areas of bone coagulation (basophilia) neighboring or surrounding the drill site. Bone and cellular debris is commonly seen within drill sites. Left column (A, C, E, G, I) represent drill bits and K-wires without saline irrigation. Right column (B, D, F, H, J) represent drill bits and K-wires with saline irrigation. In-house pathology scores (out of 3) for the following images are based on bone coagulation, and osteocyte loss/osteonecrosis:

A. ODB- scores (1,1)
B. ODB+ scores (1,1)
C. DDB- scores (1,1)
D. DDB+ scores (2,3)
E. DKW- scores (2,1)
F. DKW+ scores (1,2)
G. SDB- scores (1,1)
H. SDB+ scores (2,2)
I. SKW- scores (3,3)
J. SKW+ scores (2,2)

B, C, E, G, H, I, J (10x magnification; scale bar = 200 µm). A, D, F (4x magnification; scale bar = 500 µm).

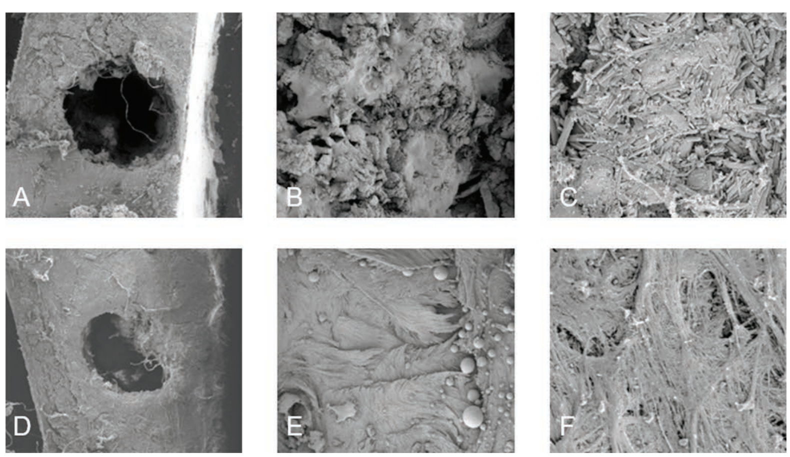

Figure 4. (A-E). Representative scanning electron microscopy (SEM) images visualizing varying degree of bony damage, debris, and necrosis of drill sites produced by osteocentric drill bits with saline (ODB+) and without saline (ODB-). Left column (A-C) represents drill sites subjected to drilling without saline. All images of the left column taken from the cis (near) cortex of the tibial specimen. Right column (D-F) shown to represent drill sites subjected to drilling with saline. All images of the left column taken from the trans (far) cortex of the tibial specimen. Magnification across rows is held constant. Top row (A,D) is shown at 25x magnification (scale bar = 2 mm); middle row (B,E) is shown at 280x magnification (scale bar = 200 µm); bottom row is shown at 4,000x magnification (scale bar = 10 µm). Comparative observation of either column shows that drill sites created by Osteocentric drill bits (ODB) in the presence of saline had less structural disarray of organic scaffolding than DePuy Synthes drill sites (SDB) created without saline.

the presence of saline irrigation and without. In contrast, the Osteocentric drill bits (ODB) performed the best in terms of limiting bony damage, drill site debris, and osteonecrosis as seen on H&E and SEM. Interestingly, though ODB outperformed all other drill bits from H&E and SEM standpoints, sharp DePuy Synthes drill bits (SDB) performed the best in terms of limiting temperature increases. The clinical significance of this trend may suggest that variables inherent to each drill bit other than their ability to regulate temperature increase in the presence of saline irrigation could influence drilling-related bone damage such that multiple factors, including saline irrigation, sharpness, and design, should be considered for optimizing bone drilling for subsequent implant placement.

Much of the recent literature involves oromaxillofacial surgery.[18-20] Other current studies involve either cadaveric human, bovine, rabbit, or porcine models.[1-4] One study by Lundskog et al.[21] from 1972 did use living human bone to evaluate thermal properties. Of the animal models, canine and porcine bone has been shown to be the most representative of human cortical bone.[22] Our study is unique in that we used live canine models with drilling taking place at baseline physiologic temperatures during general anesthesia to show the effects on perfused bone and surrounding tissue. In essence, we were able to evaluate the effects of drilling on live tissue using valid and applicable basic science outcome measures.

Drilling into bone in one form or another is ubiquitous in orthopaedic surgery. The friction generated with drilling produces heat that may reach temperatures above physiologic levels. The poor thermal conductivity of bone inhibits heat dissipation. Therefore, if no countermeasures are applied while drilling, local drill site temperatures reach threshold measurements associated with deleterious bony effects including necrosis.[2-5,23,24]

Why does this matter? Circumferential osteonecrosis at a drill site can lead to poor outcomes.[7] If osteonecrosis occurs, less viable bone remains to produce a compressive force to support bone purchase with screws.[8] Implants with unsatisfactory purchase are associated with early loosening and poor surgical outcomes such as higher rates of infection, implant instability, and reoperation.[25,26]

Bone changes occur at set temperatures with instant osteonecrosis occurring at temperatures at or above 70°C or above 47°C for 1 min. Temperatures can exceed 100°C if counterregulatory measures to heat production are not employed.[1-4] Therefore, careful application of these compensatory measures should be practiced by orthopaedic surgeons to manage heat production. Heat-reducing measures include, but are not limited to, decreasing the drill bit diameter, slowing rotational drilling speeds, avoiding the use of blunt drill tips, and irrigating during drilling to facilitate heat-dissipation.[9-12]

Limitations of the study must be considered when interpreting and applying these data. Temperature measurement was performed using a non-contact infrared instrument to determine drill device tip temperature. While this method is accurate and was standardized for the experiment, it does not provide a measure of bone temperature. As such, comparisons among drilling devices must be limited to the relative change in temperature as presented. However, the associated bone damage relative to temperature change does provide direct clinically applicable data, especially based on the use of live bone in a surgically-based animal model. Saline irrigation was performed at a constant rate by hand, which is representative of the standard practice in the operating room. As such, the exact rate of irrigation was not measured. One study suggests that irrigation at 500 mL/min successfully limited drill site temperatures to below 50°C.[4] Our goal was to recreate what occurs in surgery to determine if irrigating makes a practical difference.

Future studies may seek to clarify what factors are responsible for how individual drill bits or wires influence osteonecrosis in the setting of controlled temperature over the long term. For example, a future study may include another animal model in the context of induced osteotomies followed by the use of a standard plating technique with drilling occurring with or without saline irrigation to compare rates of implant loosening and failure, infection, and reoperation. Admittedly, the question may arise whether this is clinically relevant and if it affects patient outcomes. Although this may be challenging to verify, the authors feel strongly enough that they have incorporated this into their clinical practice and wanted to evaluate this in a controlled basic science model.

The use of saline irrigation during bone drilling reduces temperature change and bone necrosis. Furthermore, we do not recommend using dull drill bits or standard tip Kirschner wires if trying to minimize heat generation and osteonecrosis. Lastly, drill bit design can directly contribute to bone damage during drilling. Taken together, these results provide in vivo data from a preclinical model to validate the benefits of saline irrigation and sharp drill bits during bone drilling to regulate increases in temperature and decrease associated osteonecrosis. Risk for early implant loosening and poor surgical outcome is influenced by thermal osteonecrosis of bone such that consistent use of saline irrigation, sharp drill bits, and optimized drill device designs may have important clinical advantages.

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