Comparison of insertion characteristics of tapered and cylindrical transfixation pins in third metacarpal bones of equine cadavers

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OBJECTIVE
To compare heat generation and mechanical bone damage for tapered and cylindrical transfixation pins during drilling, tapping, and pin insertion in equine third metacarpal bones.

SAMPLE
16 pairs of cadaveric equine third metacarpal bones.

PROCEDURES
For cylindrical pin insertion, a 6.2-mm hole was drilled and tapped with a cylindrical tap, and then a standard 6.3-mm pin was inserted. For tapered pin insertion, a 6.0-mm hole was drilled, reamed with a tapered reamer, and tapped with a tapered tap, and then a 6.3-mm tapered pin was inserted. Paired *t* tests and 1-way ANOVAs were used to compare heat generation (measured by use of thermocouples and thermography), macrodamage (assessed by use of stereomicroscopy), and microdamage (assessed by examination of basic fuchsin–stained histologic specimens) between cylindrical and tapered pins and between tapered pins inserted to various insertion torques.

RESULTS
Tapered pin insertion generated less heat but resulted in more bone damage than did cylindrical pin insertion when pins were inserted to the same insertion torque. Insertion of tapered pins to increasing insertion torques up to 16 N•m resulted in increased heat generation and bone damage.

CONCLUSIONS AND CLINICAL RELEVANCE
Tapered pin insertion resulted in lower heat production than did cylindrical pin insertion. However, tapered pin insertion resulted in greater bone damage, which likely was attributable to differences in the tapered and cylindrical taps. A tapered pin may be preferable to a cylindrical pin for insertion in equine cortical bone provided that improvements in tap design can reduce bone damage during insertion. (*Am J Vet Res* 2017;78:1200–1209)

Transfixation pin casting is an important method of external fixation for fractures of the distal aspect of the limbs of horses. Fixation involves placement of 1 or more transcortical pins proximal to the fracture site that are incorporated into a limb cast. The cast protects the fracture from bending forces and transfers axial forces from the pins to the ground surface, thereby reducing axial collapse at the fracture site. This combination of pins and cast enables the horse to bear full weight on the affected limb.[1] Transfixation pin casts enable repair of axially unstable fractures that may not be amenable to internal fixation (eg, comminuted fractures of the proximal or middle phalanx). Retrospective studies[2,3] on transfixation pin casting in horses have revealed fracture healing rates of 70% to 77%, which were better than the healing rates for other management techniques used previously for these types of fracture. Despite these encouraging results, substantial complications associated with transfixation pin casting hinder its success as a method of fracture fixation; the most common and important complication is loosening of the pin.

Pin loosening occurs in up to 68% of patients treated with transfixation pin casts and results in increased signs of pain and morbidity for patients and decreased overall stability of the fixation, and it may predispose a patient to catastrophic pin hole fracture.[2,4] Pin loosening results from bone resorption at the bone-pin interface, which is initiated by thermal and mechanical bone damage during pin insertion and perpetuated by increased mechanical stress on the bone-pin interface during loading.[1,5,6] The threshold for irreversible heat damage to cancellous bone in rabbits is exposure at 47°C for 1 minute, with higher temperatures requiring shorter exposure times for irreversible damage.[7,8] Mechanical bone damage also leads to bone loss because it triggers bone resorption.[9,10] Efforts to reduce pin loosening are directed at reducing the immediate thermal and mechanical damage during pin insertion[11,12] or improving pin stability over time by reducing stress on the bone-pin interface[1,4,13–16] and promoting implant osseointegration.[5,17]

The pins currently used most commonly for transfixation pin casts in adult horses are cylindrical 6.3-mm-shaft 8.0-mm-thread-diameter positive-profile threaded stainless steel pins. Hole preparation is completed with a cylindrical 6.2-mm-diameter stainless steel drill bit, which results in a hole that is 0.1 mm smaller than the core diameter of a pin to optimize the amount of radial preload and initial pin stability.[18–20] Investigators have evaluated thermal and mechanical effects of drilling standard cylindrical holes in equine third metacarpal bones for transfixation pins and found that temperatures during drilling often exceed the threshold for bone necrosis.[1,11,21]

A tapered pin and related implantation hardware (reamer and tap) have been developed as patented designs[22,23] to provide several potential benefits over use of standard cylindrical pins. The first benefit is reduced friction on surrounding bone during insertion of the tapered pin because the tapered pin should not come into contact with surrounding bone until just before it becomes tight, assuming an appropriately tapered hole has been prepared. This should result in less thermal and mechanical damage to surrounding bone during pin insertion. The second potential benefit is the ability to control the torque of pin insertion in tapered pins to optimize initial pin stability[24,25] while minimizing thermal and mechanical bone damage. A final important potential benefit for the use of tapered pins is that osseointegrative coatings (eg, hydroxyapatite) may be applied to tapered pins without the need to change drill and tap dimensions to accommodate the added thickness attributable to the coating. Studies[5,17] that involved the use of hydroxyapatite-coated cylindrical pins in equine bones revealed that coated pins necessitated an impractically high insertion torque and resulted in significantly more heat generation than did uncoated pins. A tapered pin design may allow for the successful use of hydroxyapatite-coated pins in horses without excessive friction and thermal damage during pin insertion. Uncoated tapered pins have been compared to hydroxyapatite-coated tapered pins for external fixation in humans[24] and sheep,[26,27] with superior osseointegration of coated pins to such a degree that extraction torque of the coated pins is greater than the insertion torque.

Use of a tapered pin in horses requires the creation of a tapered hole because of the high density and thickness of equine cortical bone, compared with those bone characteristics in other species. Tapered self-tapping pins can be inserted into cylindrical holes in humans and sheep, whereas this would result in excessive bone damage in horses.[4] To accommodate a tapered pin design in horses, a tapered hole must be created and tapped prior to pin insertion. Creation of a tapered hole is accomplished with a tapered reamer, which is followed by tapping with a tapered tap; creation of the tapered hole reduces the volume of bone removed by the tapered tap. Reaming is widely used in orthopedics for other situations including total hip arthroplasty[28] and intramedullary canalization prior to rod placement. To the authors' knowledge, pin hole reaming has not been compared to standard transcortical drilling.

The objective of the study reported here was to compare insertion characteristics between a standard cylindrical pin and a new tapered pin design. The goal of the present study was to optimize transfixation pin insertion in large animal patients. We hypothesized that preream drilling and subsequent reaming would result in less heat generation than standard drilling, the tapered tap would result in less heat generation than the cylindrical tap, insertion of the tapered pin to the same maximal insertion torque as the cylindrical pin would result in less heat generation and bone damage than insertion of the cylindrical pin, and there would be an optimal insertion torque for the tapered pin that would result in greater pin stability than the cylindrical pin with comparable heat production and mechanical bone damage during insertion.

Materials and Methods

Sample

Sixteen pairs of equine third metacarpal bones were harvested within 24 hours after the horses were euthanized; horses were owned by the university and euthanized for reasons unrelated to the study reported here. Horses with diseases of the third metacarpal bones were excluded. Horses (9 geldings and 7 mares) ranged from 3 to 29 years of age. Breeds included Quarter Horse (n = 5), Thoroughbred (2), Standardbred (2), Pasofino (1), Morgan (1), Trakehner (1), and Appaloosa (1); there were 3 mixed-breed horses. Body weight ranged from 323 to 590 kg. Approval by an animal care and use committee was not required for this study because it involved cadaveric bone material and no use of live animals.

Bones were stripped of soft tissues, wrapped in gauze soaked in saline (0.9% NaCl) solution, sealed in a plastic bag, and frozen at –20°C. Bones were removed from the freezer and thawed at room temperature (21°C) for 24 hours prior to use. Bone pairs were randomly allocated to each experiment by use of a random numbers table. Within each experiment, locations of the tapered and cylindrical holes (proximal or distal aspect of the mid-diaphysis) were randomly assigned for the right bone of each pair by means of a coin toss, and the left bone of the pair was assigned the opposite pin placement. Bones were moistened with saline solution or saline solution–soaked gauze for the duration of all experiments.

Bone preparation

Dimensional measurements were obtained for each bone. A metal rod[a] was positioned in a hole drilled across the condyles at the distal end of the third metacarpal bone to establish the lateral-to-medial orientation for each bone for each experiment **(Figure 1)**. The center of the bone on its long axis (proximal to distal) and short axis (lateral to medial) was marked with a pencil, and a 2.0-mm-diameter hole was drilled from dorsal to palmar into the dorsal cortex (dorsal thermocouple hole). This thermocouple was used to measure baseline bone temperature during subsequent procedures. The drill bit was left in place. Pencil marks were also placed on the dorsal cortex at 1 cm proximal and 1 cm distal to the center hole. Bone width was measured at these 3 locations (center hole, 1 cm proximal to the center hole, and 1 cm distal to the center hole); all measurements were recorded.

Radiography

Radiographs were obtained of each bone with the condylar rod in place. Bones were placed on a stand by use of the condylar rod so that the lateral side was the topmost surface on a table-top radiography machine.[b] A 25-mm-diameter metal ball was placed level with the sagittal center of the bone to allow calibration of measurements. Images were obtained and analyzed by use of radiographic imaging software[c] to measure width of the dorsal cortex, width of the palmar cortex, and diameter of the medullary canal at the center of the bone and at 1 cm proximal and 1 cm distal to the center hole.

Experimental procedures

Bone temperatures for each drilling, reaming, tapping, and pin-placement procedure were measured by use of thermocouples[d] implanted into the bone at predetermined locations. To ensure consistency in thermocouple placement and drilling locations was maintained, each bone was clamped at both ends and leveled by use of a spirit level[e] placed on the dorsal cortex. The condylar rod was inserted into holes in the clamps to ensure that each bone had the same orientation. The location of the center of the medulla in a dorsal-to-palmar direction was calculated by use of measurements obtained from radiographs by adding the dorsal cortical width to half of the medullary width at each hole location. This location was identified on the lateral side of each bone by use of a right-angled ruler[f] and marked with a pencil at 1 cm proximal and 1 cm distal to the long axis center of the bone. These marks served as the centers of the drilling locations. A 3.2-mm drill bit[g] and electric drill[h] were then oriented on a sliding horizontal drill guide so that the drill bit was level and was centered on a drilling location **(Figure 2)**. Each pilot hole was drilled slowly with frequent removal of the drill bit for flute cleaning; in addition, sterile saline solution was applied to the cis cortex at a rate of 150 mL/min during drilling of a pilot hole to minimize heat generation. Thermocouple holes were created by use of a wooden template centered at each pilot hole. A drill bit was placed through a pilot hole to position the template in a consistent position for all bones. A 2.0-mm drill bit[i] was used to create thermocouple holes located 2 mm dorsal and 1 mm palmar to the anticipated edges of subsequent drilled or reamed holes at both the cis and trans cortices **(Figure 3)**. Overall, each bone had 2 pilot holes drilled from lateral to medial (1 cm proximal and 1 cm distal to the long axis center), and each pilot hole had 4 associated thermocouple holes (2 at the cis cortex and 2 at the trans cortex). Sterile saline solution was applied to the cis cortex at a rate of 150 mL/min during subsequent drilling, reaming, tapping, and pin-insertion procedures to minimize heat generation.

Drilling versus reaming (experiment 1)

Each initial 3.2-mm-diameter pilot hole served as a hole for the subsequent standard drilling of a 6.0-mm-diameter or 6.2-mm-diameter hole. A 6.2-mm

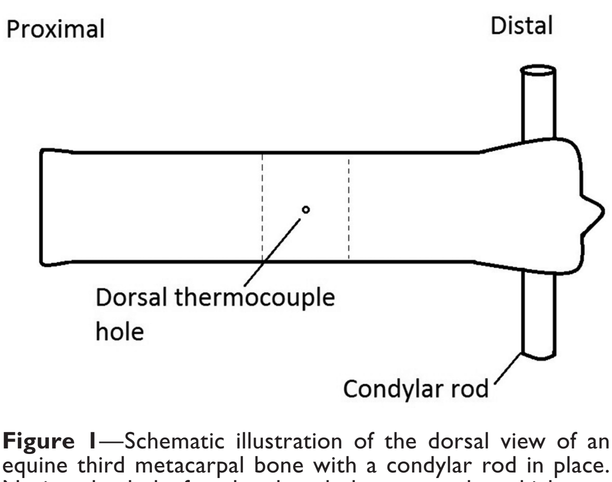

Figure 1—Schematic illustration of the dorsal view of an equine third metacarpal bone with a condylar rod in place. Notice the hole for the dorsal thermocouple, which was drilled at the longitudinal center of the bone. Dashed lines represent the transverse plane for each experimental hole drilled 1 cm proximal and 1 cm distal to the longitudinal center of the bone.

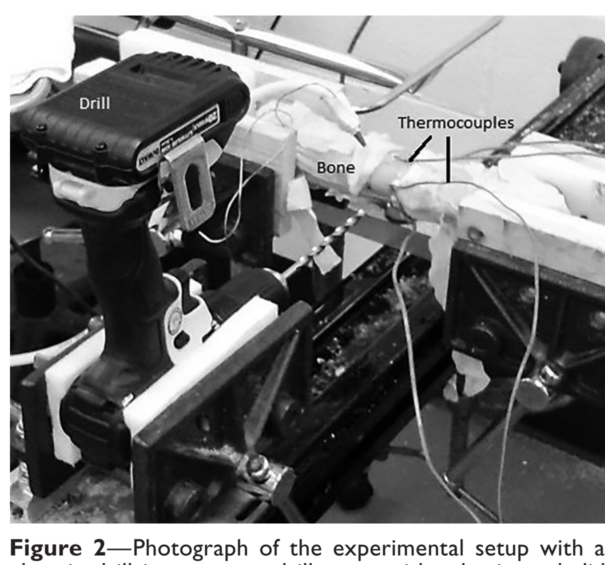

Figure 2—Photograph of the experimental setup with an electric drill in a custom drill press with a horizontal slide and an equine third metacarpal bone held in position by use of a vise system and wooden blocks. Thermocouples are positioned dorsal and palmar to the anticipated drilling location to measure bone temperature during drilling.

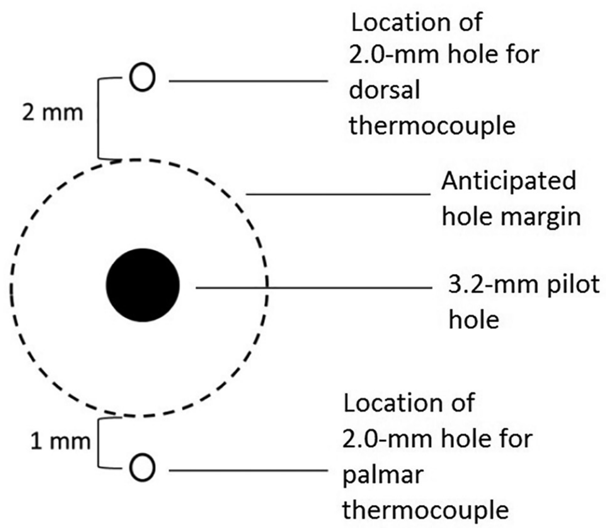

Figure 3—Schematic illustration of the cross section of an equine third metacarpal bone that indicates the position of the pilot hole, thermocouple holes, and anticipated hole margin (dashed line).

drill bit[j] was used to create the hole for the cylindrical pin group. A 6.0-mm drill bit[k] was used to create the pre-ream hole for the tapered pin group; that hole then was reamed with a tapered reamer[l] of 5.7° until the hole in the trans cortex was 6.2 mm in diameter. Interval between preream drilling and reaming was not standardized, but changing of the preream drill bit and tapered reamer was made as quickly as possible, similar to a clinical surgical setting. No attempt was made to provide additional cooling of the preream drill hole prior to reaming. The same investigator (MKA) performed all drilling procedures, with a similar rate of feed and drilling speed (approx 900 rpm; maximum, 1,450 rpm) and as much consistency as possible to approximate a clinical situation. Once drilling had commenced, there were no pauses in the drilling process, and flutes were not cleaned.

Tapered pin versus cylindrical pin (experiment 2)

All holes were prepared in each specimen such that sufficient time elapsed and surrounding bone had cooled after drilling procedures before the start of tapping and pin insertion. Tapping was performed manually with a torque wrench[m] to allow measurement of the maximum torque of each complete forward turn during tapping. Tapping for both the cylindrical tap[n] and tapered tap[o] occurred with 2 complete forward turns and then one-half turn backward to clear the flutes. Only the maximum torque of the forward turns was recorded. Both cylindrical and tapered holes were tapped until 3 threads of the tap were visible beyond the trans cortex.

The cylindrical pin[p] used in the study was a stainless steel positive-profile pin with a core diameter of 6.3 mm and thread diameter of 8.0 mm. The tapered pin[22,23] used in the study was a stainless steel positive-profile pin with a leading core diameter of 6.3 mm and leading thread diameter of 7.5 mm, which enlarged at a taper of 5.7° to reach a maximum core diameter of 7.0 mm and maximum thread diameter of 8.2 mm at a thread length of 85 mm. Pin placement was performed manually by use of the torque wrench, which was similar to the procedure used for tapping. Both pin types were inserted with consecutive complete turns. Maximum insertion torque for each turn was recorded. For each pair, the cylindrical pin was inserted before the tapered pin so that the maximal insertion torque of the tapered pin could be matched to the torque of the final turn of the cylindrical pin. Thus, each pair of pins (1 cylindrical and 1 tapered) had an equivalent insertion torque.

Tapered pin at various insertion torques (experiment 3)

Tapered pin holes were created and tapped as previously described, and tapered pins then were inserted to torques of 4, 7, 10, 13, and 16 N•m. These insertion torques were chosen on the basis that the median insertion torque of the cylindrical pin was approximately 10 N•m. Thus, tapered pins were assessed at lower and higher insertion torques than those typically used for standard cylindrical pins.

Temperature measurement

Maximum thermocouple temperature (cis or trans) at each location was used for data analysis. Change in bone temperature at each site was calculated as the maximum temperature at each location minus the baseline temperature of the bone at the dorsal cortex.

A contact temperature probe[q] was used to measure temperature of the hardware (ie, drill bit, reamer, tap, or pin). Baseline temperature of the hardware was measured by probe contact immediately prior to the start of the drilling, reaming, tapping, or pin-placement procedure. The probe also was applied to the hardware immediately after breakthrough of the trans cortex of a bone. Maximum temperature of the hardware was recorded. Change in temperature of the hardware was calculated as the maximum temperature of the hardware minus the baseline temperature of the hardware. Bone temperature and hardware temperatures were recorded by use of compatible software.[r,s]

Infrared imaging[t] also was used to record temperature change for each procedure. Emissivity was set at 0.9, which approximates but does not overestimate emissivity of bone.[29] Before each procedure was performed, a baseline infrared image of the trans cortex was obtained at a distance of 0.5 m. Immediately after breakthrough of the trans cortex was achieved, a second infrared image was obtained at the same location. The maximum temperature for each image was recorded. Change in temperature recorded by use of infrared images was calculated as the maximum temperature recorded at breakthrough of the trans cortex minus the baseline temperature.

Assessment of bone damage

Each pin was carefully removed from the bone after temperature measurements were completed. Thermocouple values were monitored during pin removal to ensure that there was not a substantial (ie, > 2°C) increase in bone temperature during pin removal. A bone saw[u] was used to section each bone transversely at locations 1 cm proximal to and 1 cm distal to each pin hole as well as through the center of each pin hole. Specimens were briefly rinsed in water to remove marrow fat. Distance of each thermocouple to the respective hole edge (outer thread diameter) was measured on transected specimens by the use of digital calipers.[v] Each specimen then was placed in a bag and labeled.

The proximal side of each hole was used for stereomicroscopic assessment of macrodamage. These sections were stained with 0.01% basic fuchsin to provide contrast and then evaluated by use of a stereomicroscope. Investigators (MKA and WRJ) separately recorded the number of visible chips per cortex, number of cracks per cortex, total number of threads per cortex, and total number of threads with visible damage (chips or cracks) per cortex. A mean score then was calculated for each variable and used for statistical analysis. On the basis of these data, the percentage of damaged threads for each cortex was determined.

The distal side of each hole was used for microdamage assessment. Specimens were placed in 70% ethyl alcohol for 2 weeks.[30] Specimens then were stained with 1% basic fuchsin by use of a series of ethanol solutions of increasing concentration (range, 70% to 100%) at 103 kPa with continuous shaking over a 3-week period, similar to a method described elsewhere.[30]

After samples were dehydrated, they were embedded in methylmethacrylate. Sections (thickness, 80 µm) were cut with a diamond saw and fixed to acrylic slides, which were then ground and polished. Slides were examined separately by 2 investigators by use of a microscope with illumination via both plain and fluorescent light. Specific outcomes for microdamage assessments included number of threads with diffuse surface microdamage (defined as areas of stain uptake along the thread edge), number of threads with diffuse deep microdamage (defined as areas of stain uptake away from the edge of the threads and not continuous with the thread edge), number of threads with morphological microdamage (defined as any threads that had an incomplete or poorly formed thread profile or fractured thread tips), number of small microcracks per cortex (defined as cracks that emanated from the thread edge but were shorter than the depth of the thread), and number of large microcracks per cortex (defined as cracks that emanated from the thread edge and were longer than the depth of the thread). From these data, the percentage of threads with diffuse surface and deep damage and the percentage of threads with morphological microdamage were determined.

Data analysis

Maximum change in bone temperature at each thermocouple location (cis and trans), hardware temperature, and hole margin temperature (measured by use of infrared images) was compared for each experiment by use of 2-tailed paired *t* tests. Paired *t* tests were performed on the distance from the thermocouple hole to the final hole edge to ensure that there were no differences in thermocouple distance between groups.

Temperature data for various insertion torques of tapered pins were compared by use of a 1-way ANOVA.[w] Variables examined were mean change in temperature for the cis thermocouple, trans thermocouple, hardware probe, and infrared images. Data were tested for normality and then logarithmically transformed prior to analysis to improve normality of the distribution. Factors included in the general linear model were bone, limb (left or right), and torque group (4, 7, 10, 13, or 16 N•m).

Primary outcomes for macrodamage assessments (determined by use of stereomicroscopy) were the mean percentage of damaged threads, mean number of chips per cortex, and mean number of cracks per cortex. Primary outcomes for microdamage assessments (made by use of epiflourescent microscopy of basic fuchsin–stained histologic specimens) were the mean percentage of morphological thread damage, mean number for both small and large microcracks, and mean percentage for both diffuse surface or deep microdamage. Paired *t* tests were used for comparison of all data for cylindrical and tapered pins when both were inserted to the same insertion torque (experiment 2). A 1-way ANOVA was used for comparison between tapered pins inserted to various insertion torques (experiment 3).

For all tests, significance was set at values of $P < 0.05$.

Results

Sample

Bone width (medial to lateral) ranged from 34.6 to 41.1 mm at the proximal hole location and from 35.2 to 42.2 mm at the distal hole location. Medullary height (dorsal to ventral) ranged from 10.3 to 15.5 mm at the proximal hole location and from 10.2 to 15.5 mm at the distal hole location. There were no significant differences between thermocouple distances for any comparisons in which thermocouples were used.

Drilling versus reaming (experiment 1)

Mean ± SD change in bone temperature at the cis cortex was 3.50 ± 2.34°C for standard drilling, 1.95 ± 0.52°C for preream drilling, and 3.42 ± 2.71°C

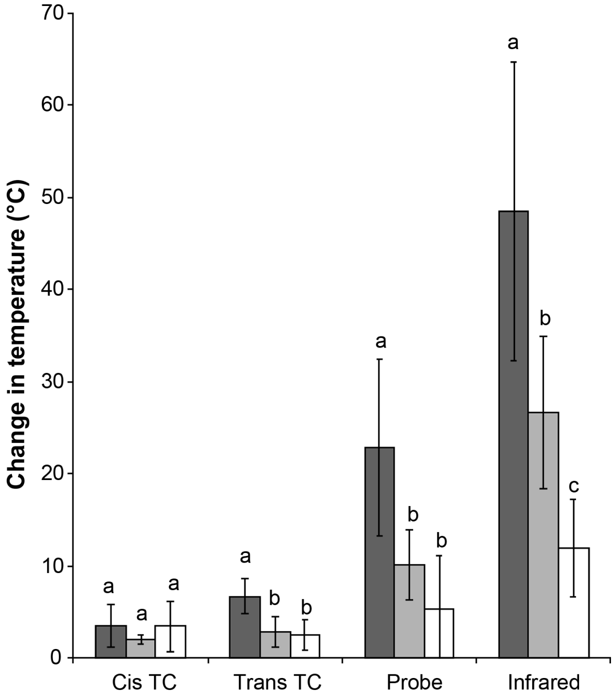

Figure 4—Mean ± SD peak change in bone temperature during standard drilling of a 6.2-mm hole (dark gray bars; n = 10), preream drilling of a 6.0-mm hole (light gray bars; 10), and reaming (white bars; 10) recorded by use of a thermocouple at both the cis and trans cortices (Cis TC and Trans TC, respectively) and infrared images of the trans cortex, and hardware (ie, drill bit, reamer, tap, or pin) temperature recorded by use of a contact temperature probe placed on the hardware immediately after breakthrough of the trans cortex. [a–c]Within a temperature measurement method, values with different letters differ significantly ($P < 0.05$).

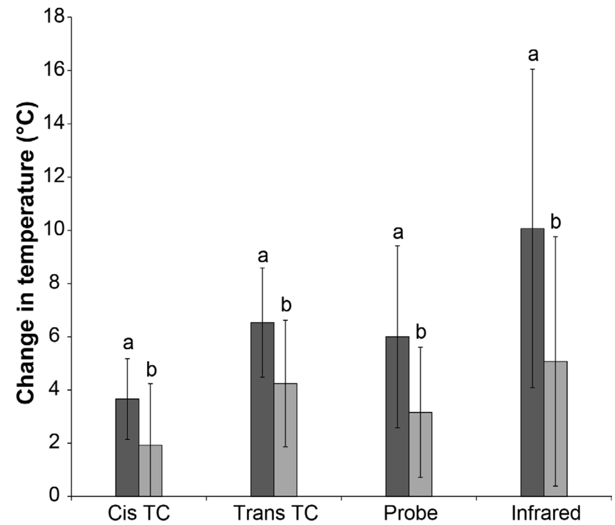

Figure 5—Mean ± SD peak change in bone temperature during tapping of equine third metacarpal bones with a cylindrical tap (dark gray bars; n = 10) and tapered tap (light gray bars; 10) recorded by use of thermocouples at both the cis and trans cortices and infrared images of the trans cortex, and hardware temperature recorded by use of a contact temperature probe placed on the hardware immediately after breakthrough of the trans cortex. [a,b]Within a temperature measurement method, values with different letters differ significantly ($P < 0.05$).

for reaming; these values did not differ significantly **(Figure 4)**. Mean change in bone temperature at the trans cortex was 6.70 ± 1.86°C for standard drilling, 2.84 ± 1.67°C for preream drilling, and 2.48 ± 1.63°C for reaming. These values differed significantly between standard drilling and preream drilling ($P < 0.001$) and between standard drilling and reaming ($P < 0.001$) but not between preream drilling and reaming ($P = 0.59$).

Thermocouple distance from reamed holes ranged from 0.65 to 1.89 mm at the cis cortex and from 1.10 to 2.01 mm at the trans cortex. Thermocouple distance from drilled holes ranged from 0.95 to 1.70 mm at the cis cortex and from 0.75 to 1.82 mm at the trans cortex.

Mean ± SD change in hardware temperature was 22.86 ± 9.54°C for standard drilling, 10.07 ± 3.81°C for preream drilling, and 5.28 ± 5.82°C for reaming (Figure 4). There was a significant difference in values between standard drilling and preream drilling ($P = 0.005$) and between standard drilling and reaming ($P < 0.001$) but not between preream drilling and reaming ($P = 0.09$).

Mean ± SD change in bone temperature at the hole margin was 48.46 ± 16.23°C for standard drilling, 26.61 ± 8.26°C for preream drilling, and 11.92 ± 5.32°C for reaming. These values all differed significantly (all $P \leq 0.002$).

Tapered pin versus cylindrical pin (experiment 2)

Mean change in bone temperature at the cis and trans cortex and as measured by use of the infrared image for the cylindrical and tapered tap were graphed **(Figure 5)**. For all comparisons, the cylindrical tap resulted in a change in bone temperature that was almost twice the change in bone temperature for the tapered tap. Mean ± SD change in bone temperature at the cis cortex for the cylindrical tap (3.66 ± 1.52°C) was significantly greater than that for the tapered tap (1.92 ± 2.31°C). Mean change in bone temperature at the trans cortex for the cylindrical tap (6.54 ± 2.05°C) also was significantly ($P = 0.02$) greater than that for the tapered tap (4.25 ± 2.38°C). Mean change in hardware temperature for the cylindrical tap was 6.00 ± 3.42°C, which differed significantly ($P = 0.04$) from the mean temperature change for the tapered tap (3.16 ± 2.44°C). Mean change in bone temperature at the hole margin was 10.06 ± 5.98°C for the cylindrical tap, which differed significantly ($P = 0.04$) from the mean temperature change for the tapered tap (5.08 ± 4.69°C).

Mean temperature change was significantly (all $P < 0.02$) greater (more than 2-fold) for cylindrical pin insertion than for tapered pin insertion for all methods of temperature measurement (cis and trans thermocouples, hardware probe, and infrared imaging; **Fig-**

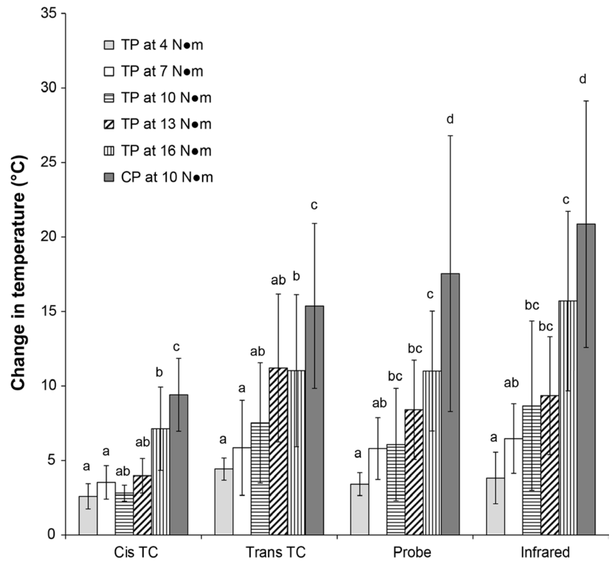

Figure 6—Mean ± SD peak change in bone temperature during insertion of a cylindrical pin (CP) to 10 N•m and tapered pin (TP) to various insertion torques as recorded by use of thermocouples at both the cis and trans cortices and infrared images of the trans cortex, and hardware temperature recorded by use of a contact temperature probe placed on the hardware immediately after breakthrough of the trans cortex. For each pin-torque combination, n = 6. [a–d]Within a temperature measurement variable, values with different letters differ significantly ($P < 0.05$).

ure 6). At an insertion torque of 10 N•m, mean ± SD change in bone temperature at the cis cortex for the cylindrical pin (9.40 ± 2.44°C) differed significantly ($P < 0.001$) from that for the tapered pin (2.80 ± 0.54°C). Mean change in bone temperature at the trans cortex for the cylindrical pin (14.01 ± 4.14°C) also differed significantly ($P = 0.01$) from that for the tapered pin (5.08 ± 1.00°C). Mean change in hardware temperature for the cylindrical pin (14.02 ± 9.33°C) differed significantly ($P = 0.01$) from the mean temperature change for the tapered pin (3.39 ± 3.11°C). Mean change in bone temperature at the hole margin for the cylindrical pin (22.43 ± 5.90°C) differed significantly ($P = 0.02$) from that for the tapered pin (4.95 ± 3.58°C).

Thermocouple distance for tapered pins ranged from 0.26 to 3.10 mm at the cis cortex and from 0.97 to 3.99 mm at the trans cortex. Thermocouple distance for cylindrical pins ranged from 0.63 to 3.30 mm at the cis cortex and from 1.30 to 4.15 mm at the trans cortex.

Stereomicroscopic assessment of macrodamage revealed that the mean ± SD percentage of damaged threads for the tapered pins (56.4 ± 28.4%) differed significantly ($P < 0.001$) from the percentage for the cylindrical pins (5.3 ± 7.4%). Mean number of chips per cortex for the tapered pins (6.2 ± 4.1 chips/cortex) differed significantly ($P < 0.001$) from the value for the cylindrical pins (0.3 ± 0.5 chips/cortex). Mean number of cracks per cortex for the cylindrical pins (0 ± 0.1 cracks/cortex) also differed significantly ($P < 0.001$) from the value for the tapered pins (0.6 ± 0.7 cracks/cortex).

Microscopic assessment of microdamage revealed that there was significantly ($P = 0.01$) more morphological thread damage for the tapered pins (mean ± SD percentage of morphological thread damage, 22.8 ± 14.0%) than for the cylindrical pins (mean, 1.8 ± 5.1%). The mean number of small and large microcracks did not differ significantly between cylindrical and tapered pins. Similarly, the mean number of specimens with diffuse surface or deep microdamage did not differ significantly between cylindrical and tapered pins.

Tapered pin at various insertion torques (experiment 3)

Mean change in temperature at the cis and trans cortices and as measured by use of the hardware probe and infrared images for the cylindrical pin and for tapered pins inserted to various insertion torques were graphed (Figure 6). There were no significant differences in thermocouple distance recorded for the various experimental groups.

For each temperature measurement, there was a pattern whereby increasing insertion torque resulted in a greater change in temperature. For all temperature measurements (cis cortex, trans cortex, hardware probe, and infrared image), the highest torque (16 N•m) resulted in a significantly greater mean change in temperature than did torque at 4 or 7 N•m. However, the change in temperature for the cylindrical pin was significantly greater than the change in temperature for any of the tapered pins. There were no significant differences in microdamage or macrodamage among the tapered pins.

Discussion

The greatest temperature changes recorded in the study reported here were during pin insertion, which was followed by during standard drilling. Temperature changes for cylindrical pins were high enough to infer, on the basis of data from previous ex vivo and clinical studies,[2,11,21] that heat-induced bone necrosis likely would have occurred at the hole edge in live patients. Thermocouples recorded changes of 9°C at the cis cortex and 14°C at the trans cortex during cylindrical pin insertion, compared with only 2.8°C at the cis cortex and 5.1°C at the trans cortex during tapered pin insertion. Examination of infrared images revealed that even greater temperature changes could be expected at the interface between hardware and bone (22.4°C at the trans cortex). Even the tapered pin with the tightest insertion (ie, highest insertion torque) that we could reasonably achieve (16 N•m) generated less heat than did insertion of the cylindrical pin. On the basis of the temperature changes in bone detected during pin insertion, use of a tapered pin in clinical patients would minimize the risk of thermal bone necrosis, compared with the risk of thermal necrosis with insertion of a standard cylindrical pin.

The cylindrical tap also resulted in more heat production during insertion than its tapered counterpart for all methods of temperature measurement. This could be explained by differences in bone contact between the tapered configuration and cylindrical configuration. For the cylindrical tap, the full depth of the threads are created at the leading edge of the tap, and the remaining threads of the tap continue to contact the bone as the tap is advanced. The design of the tapered tap results in removal of a small amount of bone at each thread location, and each thread in the bone gets gradually deeper the farther the tap is advanced. We believe that a more gradual removal of bone during thread formation as well as reduced metal-on-bone contact during tap insertion resulted in less friction and heat production during the tapping process for the tapered pins. Therefore, the tapered configuration had advantages over the cylindrical pin with regard to heat generation during both tapping and pin insertion.

In the present study, preream drilling and reaming generated lower temperatures of hardware and bone than did standard drilling. Performing sequential drilling[11] or use of a step drill[12] generates less heat in equine cortical bone than does use of a single large drill bit. Removing a smaller amount of bone in several steps reduces the work at each step, which results in less heat production. It is possible that preream drilling and reaming resulted in less heat production in the present study because the work of drilling was divided into 2 separate steps. It also was possible that the difference in initial drill bit size and differences in drill bit design (length of drill flutes and helix angle) resulted in less heat generation during the drilling process for tapered holes.

The present study had several limitations that may result in different temperature changes in clinical settings. In clinical settings, it would not be expected that a bone would completely cool between hole preparation, tapping, and pin insertion because less time would elapse between steps; thus, heat generation at each step would be additive, which would further emphasize the need to reduce heat generation at every step as much as possible. Analysis of bone temperature measurements for the present study suggested that it requires ≥ 10 seconds for equine cortical bone to cool 1°C (unpublished data of MKA). It could be argued that subcutaneous tissues and skin may insulate unexposed bone and prevent access of lubrication fluids, which results in less heat dissipation in a live patient, as compared with the outcome for an ex vivo situation. In contrast, there may be more cooling mechanisms, including blood flow and greater moisture content, in live bone than in thawed experimental bones. Differences in heat convection between ex vivo and in vivo situations are expected to be small[31,32] and should not have affected comparisons between experimental groups of the study reported here. In the present study, we elected to compare temperature change, rather than maximum temperature, because temperature change is more easily applied and interpreted relative to in vivo bone temperature.

Two established methods of measuring bone temperature were used: implantable thermocouples and thermography. Thermocouples are a widely used method of temperature measurement for drilling studies.[17,21,33] However, a major limitation is that thermocouples must be positioned a specified distance away from the hole edge to avoid being damaged during drilling procedures, which results in substantial underestimation of the temperature at the hole edge.[21] Mathematical modeling has revealed that heat dissipates through bone in a nonlinear manner; there is a steep temperature gradient that exists at the hole margin, and the gradient becomes shallower with increasing distance from the hole.[21,31,32] There is also inaccuracy in thermocouple placement that results from use of a small-diameter drill bit on a rounded surface consisting of hard cortical bone as well as variability inherent in the drilling process, which results in the anticipated hole margin not aligning perfectly with the final hole margin. Although this variability was expected to be the same between experimental groups, it still reduced the accuracy of the results and made it difficult to anticipate the temperature at the hole margin where bone necrosis was expected. Thermography and the hardware probe were used to obtain measurements of the temperatures at the hole edge and of the hardware, respectively. Thermography offers the advantage of a maximum temperature measurement at the hole edge; it is noninvasive and relatively easy to use, but it can be limited because of accuracy (error, ± 1°C).[34] Furthermore, it can be difficult to interpret the specific objects that are emitting heat in thermography images. Thermographic imaging was performed with the hardware in place; therefore, although we intended to measure bone temperature, we actually recorded the maximum temperature at the interface of the 2 objects (bone and hardware). Because of their intimate contact, we expected the temperature of both the bone and hardware to be similar at this interface. Temperatures measured at the interface by use of thermography were consistently higher than both the hardware temperature measured by use of the probe and the bone temperature measured by use of implanted thermocouples; thus, we believe this likely reflected the steep temperature gradient away from the hole edge, rather than gross inaccuracies in measurement. A disadvantage for use of the contact probe was that it measured hardware temperature, not bone temperature, and not all of the heat in the hardware would be transferred to the bone. Heat also was transferred to bone chips that were formed during drilling and tapping, or it was dissipated into the environment or the irrigation fluid. The advantage of use of multiple techniques in the present study was that it provided additional support for the temperature comparisons and provided some insight into the steep temperature gradient that exists within 1 to 2 mm of the edge of a hole.[21]

We elected to place thermocouples dorsal and palmar to the hole margin, rather than proximal and distal, to ensure that there was a section of untouched diaphyseal bone between the 2 experimental groups in each bone. Drilling for thermocouple placement could generate heat, and we did not want to introduce the possibility that heat associated with drilling 1 thermocouple hole could affect the adjacent experimental site. We also wanted to ensure that there was adequate bone proximal and distal to each experimental site so that transection of the bones at the end of the experiment would not cause damage to the experimental sites. We did not want to separate the 2 holes by > 2 cm because of the risk of entering metaphyseal bone or thinner cortical bone, which would have influenced temperature and microdamage assessments.

Results of microdamage and macrodamage assessments were surprising. There were few differences between tapered pins for various insertion torques, which suggested that the observed damage was associated with tapping, rather than with pin insertion. Furthermore, the cylindrical pin had significantly less damage than did the tapered pins in terms of morphological microdamage (defined as abnormal morphology of the threads observed during histologic examination) and the number of visible chips per cortex detected by use of the stereomicroscope. Differences in the amount of mechanical bone damage between tapered and cylindrical pins were likely attributable to differences in the cylindrical and tapered taps. The 4-fluted tapered tap that was used in the present study did not advance as smoothly as did the cylindrical tap. It was more flexible than the cylindrical tap, and it tended to have movements that were less smooth while being advanced during rotation, compared with movements for the cylindrical tap. Modifications may include fewer flutes, which will result in a stiffer tap that advances more smoothly during rotation.

We chose to remove the pin prior to assessment of mechanical damage, and we do not think that this decision negatively affected the results. Had the mechanical damage for the cylindrical pins been greater than for the tapered pins, there may have been concerns that increased friction associated with extracting the cylindrical pin added to the observed mechanical damage; however, this was not the case. Alternatively, we could have tried to cut the pin along its longitudinal axis with a diamond saw when transecting the hole and to carefully lift the pin out of the threads, rather than unscrewing it. Two problems identified with that approach included the technical challenge of accurately cutting a solid metal pin in situ and possible negative consequences with regard to bone damage assessments associated with metal vibration during cutting of the pin. It was believed that carefully and slowly removing the pin was the best option. Every effort was made to carefully and slowly remove the pin so that damage assessments were not substantially influenced by pin removal.

Use of radiographs to guide hole placement to ensure that holes were in the center of the medulla and were not tangential to the dorsal or palmar cortex was essential for the study reported here. The lateral surface of the third metacarpal bone is not symmetric, and it can be difficult for a surgeon to identify the center of the medulla without radiographic guidance. It was important that holes were not tangential to the dorsal or palmar cortex because this would have been expected to greatly influence temperature and microdamage data by adding more bone substrate for all steps of pin placement. In live patients, it is important to not enter either cortex because this may weaken the cortex and predispose to the development of a fracture across the pin hole.[4,35] A clinical modification of the method for the present study that involved use of radiographic guidance to guide hole placement may help reduce the incidence of pin hole fractures as a result of more accurate pin placement in equine third metacarpal bones.

In the present study, there were lower drilling, reaming, tapping, and insertion temperatures for the tapered pins than for a standard cylindrical pin. The greatest temperature changes were recorded during cylindrical pin insertion. Despite the fact there was greater thermal production during cylindrical pin insertion procedures, mechanical bone damage was greater for the tapered pins. We believed that differences in bone damage observed in the study had more to do with differences in the rigidity between the cylindrical and tapered tap than with inherent differences in the tapered and cylindrical pin designs. Additional studies with a modified tapered tap and comparison of biomechanical differences between the 2 pin types should be performed before establishing recommendations for use in clinical patients.

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Footnotes

a. Round rod, plain 3/16-in X 36-in, Crown Bolt, Aliso Viejo, Calif.
b. Advantx digital radiology, GE Healthcare, Milwaukee, Wis.
c. Asteris Keystone PACS, Asteris Inc, Stephentown, NY.
d. Implantable thermocouple type K, Omega Engineering Inc, Stamford, Conn.
e. Johnson 9-in magnetic aluminum torpedo level, Johnson, Mequon, Wis.
f. BGood adjustable 300-mm engineer combination try square set right angle guide, Sears, Hoffman Estates, Ill.
g. 3.2-mm premium industrial grade high-speed steel black oxide drill bit, Home Depot, Atlanta, Ga.

h. 14.4 V 0.5-in (13-mm) cordless compact drill and driver kit, Dewalt, Baltimore, Md.
i. 5/64-in drill bit, Dewalt, Baltimore, Md.
j. 6.2 X 175-mm StickTite drill bit, PN 32062, IMEX Veterinary Inc, Longview, Tex.
k. 6.0 X 175-mm drill bit, PN 78565900, MSC Industrial Supply, Melville, NY.
l. Tapered reamer prototype, IMEX Veterinary Inc, Longview, Tex.
m. Electrotork electronic torque wrench, Snap-On Inc, Kenosha, Wis.
n. Cylindrical tap, part No. 2114T, IMEX Veterinary Inc, Longview, Tex.
o. Tapered tap prototype, IMEX Veterinary Inc, Longview, Tex.
p. Cylindrical Duraface full-pin for large animals, PN 22140, IMEX Veterinary Inc, Longview, Tex.
q. Temperature surface probe type K, Omega Engineering Inc, Stamford, Conn.
r. Logging software for TC-08 data acquisition module, Omegasoft, Stamford, Conn.
s. Logging software for PT-104A data acquisition module, Omegasoft, Stamford, Conn.
t. Flir E5 infrared camera with MSX, Flir Systems, Boston, Mass.
u. Bone band saw, Mar-med Inc, Cleveland, Ohio.
v. Neiko 01409A electronic digital caliper, Ridgerock Tools Inc, Gardena, Calif.
w. SAS, version 9.2, SAS Institute Inc, Cary, NC.

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