Effect of sequential hole enlargement on cortical bone temperature during drilling of 6.2-mm-diameter transcortical holes in the third metacarpal bones of horse cadavers

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Objective—To compare the bone temperature and final hole dimensions associated with sequential overdrilling (SO) and single 6.2-mm drill bit (S6.2DB) methods used to create transcortical holes in the third metacarpal bones (MCIIIs) of horse cadavers.

Sample—60 MCIIIs from 30 horse cadavers.

Procedures—In phase 1, hole diameter, tap insertion torque, peak bone temperature, and postdrilling bit temperature for 6.2-mm-diameter holes drilled in the lateral or medial cortical region of 12 MCIIIs via each of three 2-bit SO methods with a single pilot hole (diameter, 3.2, 4.5, or 5.5 mm) and the S6.2DB method were compared. In phase 2, 6.2-mm-diameter transcortical holes were drilled via a 2-bit SO method (selected from phase 1), a 4-bit SO method, or a S6.2DB method at 1 of 3 locations in 48 MCIIIs; peak bone temperature during drilling, drill bit temperature immediately following drilling, and total drilling time were recorded for comparison.

Results—Hole diameter or tap insertion torque did not differ among phase 1 groups. Mean ± SD maximum bone temperature increases at the cis and trans cortices were significantly less for the 4-bit SO method (3.64 ± 2.01°C and 8.58 ± 3.82°C, respectively), compared with the S6.2DB method (12.00 ± 7.07°C and 13.19 ± 7.41°C, respectively). Mean drilling time was significantly longer (142.9 ± 37.8 seconds) for the 4-bit SO method, compared with the S6.2DB method (49.7 ± 24.3 seconds).

Conclusions and Clinical Relevance—Compared with a S6.2DB method, use of a 4-bit SO method to drill transcortical holes in cadaveric equine MCIIIs resulted in smaller bone temperature increases without affecting hole accuracy. (*Am J Vet Res* 2011;72:1687–1694)

Transfixation casting can be an effective method for treating fractures in the distal portions of horse limbs,[1–3] although limitations of the technique exist. A key limitation and the most common cause of patient morbidity is pin loosening prior to complete fracture healing.[2] In a retrospective study[2] of distal fractures in limbs of adult horses, which were treated by use of transfixation casting, the median interval to pin loosening following pin placement was 40 days. In a third of those adult horses, pin loosening was apparent within 30 days after pin placement, and in approximately two-thirds of cases, pin loosening resulted in instability, signs of pain, and the need for pin removal.[2] This suggests that events at the time of pin placement, such as thermal bone damage, can have a major role in pin loosening and that pin loosening has a considerable impact on the management of horses treated by use of transfixation casting.

Abbreviations

MCIII	Third metacarpal bone
SO	Sequential overdrilling
S6.2DB	Single 6.2-mm drill bit

Pin loosening occurs following bone resorption at the bone-pin interface created during transfixation casting.[4] Bone resorption may be caused in part by thermal and microstructural damage at the bone-pin interface at the time of initial drilling and pin placement and takes 2 to 3 weeks to become clinically apparent following initial damage.[4] Cyclic loading of pins and pin tract infections are additional factors that contribute to bone resorption and pin loosening over time.[5] Initial microfractures and thermal bone damage that occur at the time of drilling and pin insertion may exacerbate

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Received July 30, 2010.
Accepted August 25, 2010.

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Imex Veterinary Incorporated provided the 6.2-mm drill bits used in the study.
Presented in abstract form at the 34th Annual Meeting of the Veterinary Orthopedic Society, Sun Valley, Idaho, March 2007.

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the pin loosening effects of cyclic loading and pin hole infection. Therefore, minimizing thermal and microstructural damage at the bone-pin interface at the time of drilling and pin insertion is particularly important for preventing or delaying pin loosening.[4]

The critical, or threshold, temperature for thermal bone damage is that temperature above which detectable bone necrosis occurs.[6-8] The critical temperature for thermal bone damage is currently considered to be 47°C, but this has not been investigated in horses in vivo. This value for critical temperature is based on a series of classic experiments performed in vivo in rabbits in which thermal damage and bone resorption at temperatures as low as 47°C were reported,[6] with consistent osteocyte death and marked bone resorption observed following application of temperatures of 50°C for 1 minute.[7] In an in vivo drilling experiment, temperature measurements recorded by use of implanted thermocouples placed 0.5 mm from the drill hole indicated mean peak temperatures of 40°, 56°, and 89°C in rabbit, canine, and human femoral cortical bone, respectively.[8] Higher temperatures in canine and human femora were attributed to greater cortical thickness (up to 8 mm), compared with rabbit femora. Cortical thickness of MCIIIs in adult horses in reports of previous drilling studies[9,10] was up to 14 mm, which presents a considerable challenge for equine surgeons to drill transcortical holes in adult horse bones without incurring thermal bone damage.

In cadaveric equine MCIIIs, temperatures measured during drilling are typically higher than those measured during tapping and pin placement,[11–13] and heat generated during drilling of a 6.2-mm-diameter hole in equine diaphyseal bone consistently exceeded the threshold for thermal bone damage in several recent studies.[9–13] In a study[9] examining the effect of feed rate and drill speed on bone temperature, the slowest drill speed and highest feed rate combination resulted in the lowest mean maximal temperature recorded 1 mm from the drill hole; however, all 6 feed rate and drill speed combinations exceeded the critical temperature for thermal bone damage. In another study[10] comparing the use of a step drill to a sequential drilling technique, temperatures at 1 mm from the drill hole exceeded the critical temperature for thermal bone damage in the trans cortex in 29 of 42 (69%) and 21 of 41 (51%) specimens, respectively.

To decrease the amount of heat generated during drilling of the transcortical holes required for transfixation pin placement in adult equine cortical bones, it has been recommended to use sequentially larger drill bits for creation of a 6.2-mm-diameter hole.[10,14] In support of this recommendation, drilling with a 2.2-mm drill bit prior to drilling with a 3.2-mm drill bit resulted in a substantial decrease in the mean peak cortical temperature in human cadaveric femoral bones.[15] However, it is unknown whether the recommended technique of SO in horses results in a reduction of temperature in cortical bone when clinically relevant drilling techniques are used. It is also unknown whether holes resulting from the SO process are as accurate as holes drilled with an S6.2DB. Hole enlargement in industrial manufacturing applications is routinely performed by a process of reaming rather than SO to obtain accurate holes and a consistent hole finish.[16,17] Overdrilling a pilot hole with larger drill bits is known to result in inaccuracy of the hole due to low-frequency vibrations of the drill.[18] Inaccuracies of the hole may be manifest as a hole with variation from a circular shape or a hole that is oversized. When drilling pin holes in bone, this effect may result in a poor fit of the pin at the time of initial insertion and in its rapid loosening subsequently.

Although sequential hole enlargement through overdrilling is recommended and widely used, its value and necessity remain uninvestigated. Therefore, the purpose of the study reported here was to compare the cortical bone temperature and final hole dimensions and tap insertion torque associated with SO and S6.2DB methods used to create transcortical holes in MCIIIs of horse cadavers. Our hypotheses were that sequential drilling by use of a 3.2-, 4.5-, 5.5-, and 6.2-mm drill bit sequence would result in lower cortical bone temperatures, compared with drilling with an S6.2DB, and that there would be no difference in hole diameter or tap insertion torque detected between drilling methods.

Materials and Methods

Experimental design—The study was performed in 2 phases. Phase 1 of the study was performed to determine the optimum 2-bit SO method (single pilot hole) among 3 possible pilot hole combinations; in these combinations, a final 6.2-mm-diameter hole was drilled following placement of a 3.2-, 4.5-, or 5.5-mm-diameter pilot hole. The first phase was also used to compare hole diameters and tap insertion torques associated with the three 2-bit SO (pilot hole) combinations and the S6.2DB method. Phase 1 involved unicortical drilling of 12 cadaveric MCIIIs obtained from 6 horses (24 holes/group). The optimum 2-bit SO method selected was subsequently compared with a 4-bit SO method (use of 3.2-, 4.5-, 5.5-, and then 6.2-mm drill bits) and a S6.2DB method in phase 2. The second phase of the study compared cortical bone temperature with drill bit temperature directly among the selected 2-bit SO method from phase 1, the 4-bit SO method, and the S6.2DB method. Phase 2 involved transcortical drilling of 48 cadaveric MCIIIs obtained from an additional 24 horses (48 holes/group).

Bone collection and preparation for drilling—Pairs of MCIIIs were collected from adult horses that were euthanized by IV administration of a barbiturate overdose for reasons unrelated to this study. The bones were stripped of soft tissue, wrapped in saline (0.9% NaCl) solution–soaked towels, placed in plastic bags, and frozen at –20°C until the time of the study. At that time, bones were thawed to room temperature (approx 23°C) overnight. For phase 1 of the study, drilling was performed at room temperature. For phase 2 of the study, bones were warmed to 38°C in a saline solution bath. Each bone was held in place for drilling by use of a custom drilling stand in which each end of the bone was secured.

Drilling procedures—Drilling procedures were designed to simulate surgical conditions as closely as possible. Drilling was performed by use of an orthopedic drill[a] with a maximum rotary speed of 340 revolutions/min and maximum torque of 15 N•m. The same operator (TBL) performed drillings in each phase of the study. Saline solution irrigation at a rate of 150 mL/min was directed onto the drill bit adjacent to the bone during drilling. Drilling was performed in a horizontal direction so that irrigation fluid would not contact the trans cortex of the bone. The drill was removed from the hole at approximately 5-second intervals to allow irrigation of the drill bit tip and to remove bone debris from the drill flutes. Standard, commercially available orthopedic drill bits[b] of 3.2-, 4.5-, and 5.5-mm sizes were used for pilot holes. Final holes were all drilled by use of a commercially available 6.2-mm drill bit.[c] All drill bits were replaced after 12 uses.

Cortical bone temperature measurements—In phase 1, thermocouples were placed 1 and 2 mm from the edge of 6.2-mm-diameter unicortical drill hole positions. In phase 2, thermocouples were placed 0.5, 1, and 1.5 mm from drill hole positions at the cis and the trans cortices by use of a customized drilling jig to maintain accuracy (**Figure 1**). Cortical bone temperature was measured by use of implantable thermocouples[d] connected to a 14-channel analog-digital input-output board[e] with associated calibration[f] and data transfer[g] software. Data were transferred directly to a software program spreadsheet[h] during the drilling process. Temperatures were recorded during drilling at a rate of 1 Hz and for approximately 2 minutes following completion of drilling. Thermocouple holes were drilled with a 2.4-mm drill bit to a depth of 5 mm. Thermally conductive paste[i] was used to coat thermocouples prior to implantation. Room temperature was monitored during each procedure by use of an additional thermocouple positioned adjacent to the drilling station. Bone temperature was monitored at a site in the dorsal aspect of the cortex (ie, distant from the drill holes) during each procedure. A contact thermocouple[j] was used to measure peak drill bit temperature of the 6.2-mm drill bit immediately following drilling.

Phase 1—A complete block design was used to assess 4 drilling groups in the first phase of the study. Unicortical 6.2-mm-diameter holes were drilled alone or by use of 2-bit SO methods (each with a 3.2-, 4.5-, or 5.5-mm-diameter pilot hole) at 4 diaphyseal locations. Both the medial and lateral aspects of 12 MCIIIs were used. Bones were measured from the carpometacarpal joint to the distal end of the lateral condyle, and the mid-diaphysis was marked at the midpoint of the bone length. A template centered on the mid-diaphysis was used to mark 4 evenly spaced drilling locations and the corresponding thermocouple locations. Final diameter measurements were made for the holes in the lateral cortical region. To perform measurements at 3 separate hole depths, the lateral aspect of each bone was sectioned twice in a longitudinal (sagittal) plane. The diameter of the hole at each of the 3 depths was measured by use of digital calipers.[k] Measurements were made at 4 evenly spaced positions around the hole. Hole accuracy was further assessed via measurement of the tap insertion torque of the holes in the medial cortical region. Measurements were made following full engagement of a large-animal 6.3-mm transfixation pin tap[l] in the hole by use of a digital torque wrench[m] with a chuck adaptor[n] and a previously reported measurement technique.[11]

Phase 2—A complete block design was used to assign 1 of 3 drilling methods to 3 diaphyseal drilling locations in each bone used in the second phase of the study. Drilling locations on the diaphysis were at the midpoint bone length mark and at 30 mm proximal and 30 mm distal to this mark. The block design was repeated 4 times, with drilling group allocations being the same for each bone pair. Twenty-four pairs of MCIIIs were used. All holes were drilled in a lateral to medial direction through the bones. A 6.2-mm-diame-

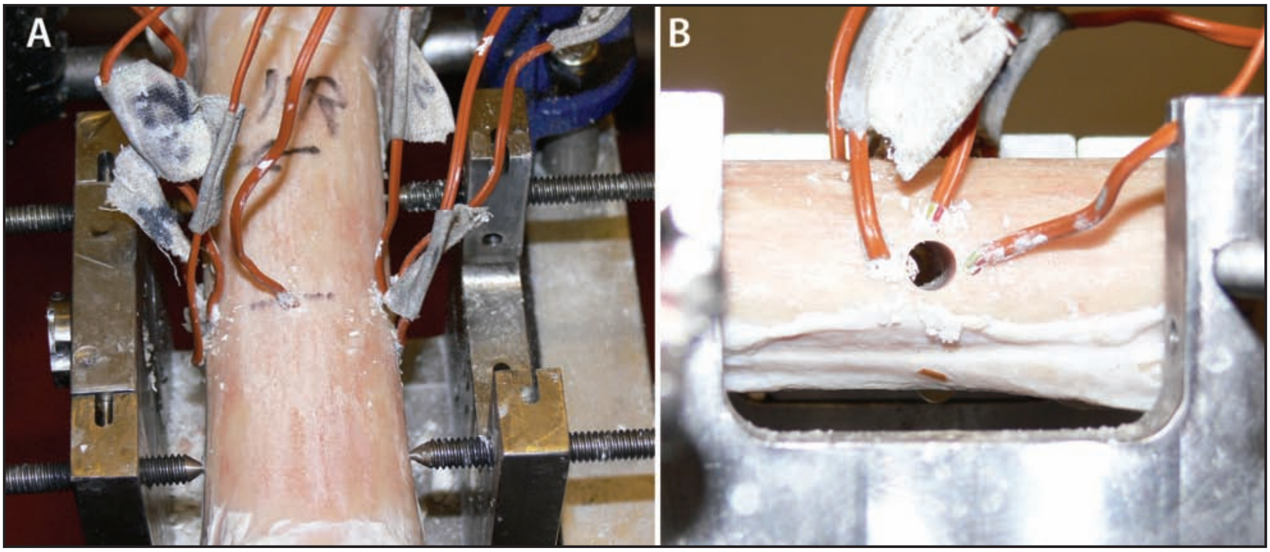

Figure 1—Photographs of an MCIII obtained from a horse and positioned within a custom bone drilling jig that allowed accurate placement of thermocouples at 0.5, 1, and 1.5 mm from the margin of a 6.2-mm-diameter hole prior to drilling. A—Top view of the drilling setup. Holes were drilled from left to right (lateral to medial aspect of the cortex). B—Side view of the trans (medial) cortex to illustrate the positioning of thermocouples relative to the final drilled hole.

ter hole was drilled alone, following a 5.5-mm-diameter pilot hole (pilot hole combination selected from phase 1) or following SO of 3.2-, 4.5-, and 5.5-mm-diameter pilot holes. Cortical temperatures were recorded during the drilling of all pilot holes as well as during drilling of the final 6.2-mm-diameter hole. A surface thermocouple was used to measure the temperature of the drill bit each time it was removed from a hole during drilling and after completion of drilling. The peak temperature of these measurements was recorded for each hole. The custom drilling jig was fitted with inserts to align the 3.2-, 4.5-, and 5.5-mm drill bits to complete accurate drilling of the pilot holes. This ensured that variables influencing pilot hole drilling did not influence the axial accuracy of the final 6.2-mm-diameter hole and thus the proximity of the hole margin to the thermocouples, particularly at the trans cortex. The final 6.2-mm-diameter hole was drilled freehand in all instances.

Statistical analysis—Maximum bone temperature increase and maximum drill bit temperature were recorded for each drilling location. In phase 1, hole diameter and tap insertion torque were also analyzed. In phase 2, drilling time for each hole (time from initial temperature rise at the cis cortex to cessation of temperature rise at the trans cortex as viewed on temperature vs time graphs generated from the temperature output data) was analyzed and maximum bone temperature increase was separated into cis and trans cortex data for each hole. The interval during which bone temperature exceeded 47°C was also recorded for each drill hole. For each drilling group, a mean value for each variable of interest was calculated from data obtained from each bone in the group and used for analysis. An ANOVA was used to compare the drilling methods. Data were transformed where necessary to achieve a normal distribution and to meet model assumptions. Bone and hole position were considered blocking factors and included in the model as fixed effects. The other fixed effects included in the model for hole diameter were drilling method, measurement depth, and measurement position. Measurement position around the hole was recorded as a number (1 through 4) and kept consistent among all specimens to account for the anisotropic structure of cortical bone. Fixed effects included in the model for maximum bone temperature increase and maximum drill bit temperature in the first phase of the study were bone, hole position, cortical region (medial or lateral), and drilling method. For the tap insertion torque, cortex was not included in the model as these measurements were obtained only for the medial aspect. Cortex was not included in the model for maximum bone temperature increase and maximum drill bit temperature in the second phase of the study because maximum temperature increase for each cortical region was analyzed separately, and maximum drill bit temperature was measured over the entire drilling procedure through both cortical regions. Pairwise comparisons were performed by use of a Tukey test. A χ^2 test was used to compare the proportion of drill holes in which the temperature exceeded 47°C for each drilling method. Values of $P < 0.05$ were considered significant.

Results

Phase 1—Mean hole diameter and the mean tap insertion torque for each of the drilling methods tested in the first phase of the study were calculated (**Table 1**). There were no significant differences in hole diameter with regard to drilling method (three 2-bit SO methods and the S6.2DB method; $P = 0.72$), measurement depth ($P = 0.67$), or measurement position ($P = 0.12$). Neither bone ($P = 0.44$) nor drill hole position in the bone ($P = 0.61$) affected the hole diameter. There were also no significant interactions between factors. Mean tap insertion torque was not significantly ($P = 0.65$) different among drilling methods; there was also no significant effect of bone ($P = 0.34$) or hole position ($P = 0.94$) on mean tap insertion torque.

Maximum bone temperature increase and the maximum drill bit temperature during drilling associated with the 2-bit SO methods were compared (**Table 2**). For maximum bone temperature increase, there were no significant ($P = 0.13$) differences among drilling methods; however, pilot hole drilling with a 5.5-mm drill bit prior to drilling the final 6.2-mm-diameter hole resulted in lower mean maximum bone temperature increase. Bone ($P < 0.02$) and cortical region (P

Table 1—Mean ± SD hole diameter, tap insertion torque, maximum bone temperature increase, and maximum drill bit temperature associated with each of three 2-bit SO methods and an S6.2DB method used to drill unicortical 6.2-mm-diameter holes in MCIIIs obtained from horses following euthanasia.

Drilling method	Hole diameter (mm)	Tap insertion torque (N•m)	Maximum bone temperature increase* (°C)	Maximum drill bit temperature† (°C)
S6.2DB	6.16 ± 0.41^{a}	5.854 ± 0.924^{a}	6.39 ± 2.22^{a}	30.40 ± 3.63^{a}
2-bit SO				
3.2–6.2 mm	6.23 ± 0.18^{a}	5.821 ± 1.068^{a}	6.22 ± 1.85^{a}	$28.92 \pm 4.83^{a,b}$
4.5–6.2 mm	6.20 ± 0.05^{a}	5.373 ± 1.254^{a}	5.98 ± 2.75^{a}	$29.21 \pm 7.01^{a,b}$
5.5–6.2 mm	6.22 ± 0.12^{a}	5.530 ± 1.194^{a}	5.22 ± 1.59^{a}	26.75 ± 4.52^{b}

Data were obtained by use of a complete block design from 12 MCIIIs from 6 horses (24 holes/group). For the 2-bit SO methods, the final 6.2-mm-diameter hole was drilled following drilling of a 3.2-, 4.5-, or 5.5-mm-diameter pilot hole.

*Cortical bone temperature changes were measured by use of thermocouples that were placed at a depth of 5 mm at 1 and 2 mm from the edge of 6.2-mm-diameter unicortical drill hole positions. †A contact thermocouple was used to measure peak drill bit temperature of the 6.2-mm drill bit immediately following drilling.

[a,b]Within a column, drilling group values with different superscript letters are significantly ($P < 0.05$) different.

Table 2—Mean ± SD maximum temperature increase (cis and trans cortices), maximum drill bit temperature, and duration of drilling associated with a 2-bit SO method, a 4-bit SO method, and an S6.2DB method used to drill transcortical 6.2-mm-diameter holes in MCIIIs obtained from horses following euthanasia.

	Maximum temperature increase* (°C)			
Drilling method	**Cis cortex**	**Trans cortex**	**Maximum drill bit temperature† (°C)**	**Drilling time (s)**
S6.2DB	12.00 ± 7.07[a]	13.19 ± 7.41[a]	45.23 ± 12.94[a]	49.7 ± 24.3[a]
SO				
2-bit	9.47 ± 7.22[a]	10.71 ± 5.99[a,b]	48.96 ± 15.53[a]	93.5 ± 32.3[b]
4-bit	3.64 ± 2.01[b]	8.58 ± 3.82[b]	46.75 ± 8.04[a]	142.9 ± 37.8[c]

Data were obtained by use of a complete block design from 48 MCIIIs from 24 horses (48 holes/group). For the SO methods, the final 6.2-mm-diameter hole was drilled following drilling of a 5.5-mm-diameter pilot hole (2-bit method) or 3.2-, 4.5-, and 5.5-mm-diameter pilot holes (4-bit method). Drilling time was calculated as time from initial temperature rise at the cis cortex to cessation of temperature rise at the trans cortex as viewed on temperature-versus-time graphs of the drilling procedures.

*Cortical bone temperature changes were measured by use of thermocouples that were placed to a depth of 5 mm at 0.5, 1, and 1.5 mm from drill hole positions at the cis and the trans cortices.

See Table 1 for remainder of key.

< 0.03) had a significant effect on maximum bone temperature increase. Maximum drill bit temperature was significantly ($P = 0.02$) lower following drilling of a 5.5-mm-diameter pilot hole prior to drilling the final 6.2-mm-diameter hole, compared with drilling the 6.2-mm-diameter hole without a pilot hole. Bone ($P < 0.01$) and cortical region ($P < 0.01$) had a significant effect on maximum drill bit temperature. Based on the results of the first phase of the study, pilot hole drilling with a 5.5-mm drill bit was chosen as the 2-bit SO method for the second phase of the study.

Phase 2—Maximum bone temperature increase at the cis and trans cortex, maximum drill bit temperature, and drilling time to complete each 6.2-mm-diameter hole were compared (**Table 2**). Mean maximum bone temperature increase at the cis cortex was significantly ($P < 0.01$) lower in the 4-bit SO method group, compared with the 2-bit SO or S6.2DB method group. Mean maximum bone temperature increase at the trans cortex was significantly ($P = 0.03$) lower in the 4-bit SO method group, compared with the S6.2DB method group. Mean maximum drill bit temperature was not significantly ($P = 0.64$) different among drilling groups. The range of peak bone temperatures during drilling was 39.7° to 65.1°C for the 4-bit SO method group, 39.3° to 71.5°C for the 2-bit SO method group, and 37.9° to 68.9°C for the S6.2DB method group. The range of peak drill bit temperatures during drilling was 32.4° to 58.1°C for the 4-bit SO method group, 33.1° to 89.5°C for the 2-bit SO method group, and 36.2° to 80.4°C for the S6.2DB method group.

Drilling time was significantly ($P < 0.01$) longer for the 4-bit SO method group, compared with the 2-bit SO and S6.2DB method groups. Drilling time was significantly ($P < 0.01$) longer for the 2-bit SO method group, compared with the S6.2DB method group. The proportion of drill holes in which temperature exceeded 47°C was significantly ($P < 0.01$) lower for the 4-bit SO method group (3/24 [12.5%]), compared with the 2-bit SO (12/24 [50%]) and S6.2DB (18/24 [75%]) method groups. The mean ± SD interval during which drill hole temperature was > 47°C at the cis cortex was 6.1 ± 10.6 seconds, 3.0 ± 5.5 seconds, and 0.3 ± 1.2 seconds for the S6.2DB, 2-bit SO, and 4-bit SO method groups, respectively. For the trans cortex, the mean ± SD interval during which drill hole temperature was > 47°C was 4.6 ± 6.8 seconds, 3.2 ± 8.0 seconds, and 1.3 ± 3.8 seconds for the S6.2DB, 2-bit SO, and 4-bit SO method groups, respectively.

Discussion

The purpose of the study reported here was to determine whether the recommended practice of sequential hole enlargement by overdrilling for creation of 6.2-mm-diameter holes for transfixation pin placement in bones of horses is beneficial in minimizing the bone temperature increase that occurs during drilling and whether there are any detrimental effects on hole accuracy when the overdrilling method is used. The results indicated that the temperatures generated within cadaveric equine MCIIIs surrounding 6.2-mm-diameter drill holes created by use of a 4-bit SO method were lower than those created by use of an S6.2DB or 2-bit SO method involving a 5.5-mm-diameter pilot hole. The longer drilling time required to perform the SO methods may contribute to the lower temperatures recorded by allowing heat generation and dissipation to occur over a longer period. Drilling single pilot holes, such as 3.2-, 4.5-, or 5.5-mm-diameter holes used in phase 1 of the study, prior to drilling the final 6.2-mm-diameter hole did not appear to have a clinically relevant effect on hole accuracy.

Previous studies evaluating drilling temperature in equine cortical bone have used either implantable thermocouples[9,10] or contact thermocouples applied to the drilling hardware[12,13] to assess cortical bone temperature. We decided to use both methods of temperature measurement, as in a previous study,[11] in an effort to offset the disadvantages of each system. A principle disadvantage of contact thermocouples is the variability in temperatures measured at the drill bit tip.[19] In the present study, every effort was made to contact the outer edge of the drill bit tip during measurement (corresponding to the location closest to the hole margin). Another disadvantage of contact thermocouples is the assumption that the drill bit temperature corresponds to the temperature within the bone at the hole margin.[20] Studies[20,21] of drilling in bone and metal have revealed that the process of cutting at the drill tip and the formation of bone chips results in higher temperatures in the drill bit and the bone chips than in the bone that remains in situ. This is due to the additional heat generated in the drill bit and the bone chips as they contact each other after separation of the bone chips and their advancement along the drill flute. However, accumulation of bone chips in the drill flute and their contact with the side of the hole as well as friction between the drill bit and the hole results in additional heat generation in the bone. In an effort to mimic the clinical situation, we performed freehand drilling and removed drill bits at approximately 5-second intervals to clean and rinse flutes with saline solution during all drilling procedures. This process of cleaning and rinsing drill bits may have contributed to variability of the maximum drill bit temperature measurements in the present study.

The primary disadvantage of an implantable thermocouple system is that thermocouples are placed at a set distance from the drill hole margin and the temperature at the actual hole margin must be extrapolated. In previous studies[9–11] in horses, thermocouples were positioned at least 1 mm from the predicted hole margin. In an effort to minimize this distance, a custom drilling jig that allowed accurate placement of implantable thermocouples within 0.5 mm of the final hole margin in cis and trans cortices was constructed for use in the present study. It was estimated in a previous study[22] that temperatures at locations 0.5 mm from the drill hole may be as much as 13°C lower than those at the hole margin itself. A linear regression model of bone temperature during drilling equine cortical bone predicted that the temperature declined by 8.8°C between 1 and 2 mm from the hole margin under various controlled drilling conditions.[9] Taking these estimates into consideration, the lowest mean maximum temperature increase (at the cis cortex with the 4-bit SO method) reported here was still likely to exceed the threshold for thermal damage to bone (47°C) at the hole margin. However, this threshold is based upon results of studies[6,7] that used up to 1 minute of exposure time; for thermal damage over an exposure time of several seconds, as in the present study, temperatures may need to be as high as 90°C for bone necrosis to occur.[8] None of the temperatures recorded in the present study reached that value, although the upper range of peak bone temperatures did approach 70°C within all drilling method groups and the maximum individual drill bit temperatures were near 90°C. It is clear that drilling dense equine cortical bone can result in bone temperatures that may cause thermal bone damage and that any means that effectively reduce these temperature increases during drilling should be applied by equine surgeons.

In the present study, the bone temperature increases for the 4-bit SO method were similar to those detected in a previous study by Bubeck et al[10] comparing a step drill with a sequential 3-bit SO method, in which mean maximum temperature increases during sequential drilling were in the range of 4° to 8°C. However, several differences in methods between the 2 studies make direct comparisons difficult. In the previous study, temperature measurements were made 1 mm from the hole margin, compared with measurements made 0.5-mm from the hole margin in the present study. Bubeck et al[10] used a drill press with 3 separate drilling force levels and only a single cleaning of the drill bit during drilling, whereas freehand drilling and regular drill bit removal and cleaning (approx every 5 seconds) were used in the present study to simulate a clinical situation as closely as possible. In the previous study,[10] a drill speed of 760 revolutions/min was used, whereas the maximum rotary speed of the drill used in the present study was 340 revolutions/min; however, this drill speed depends upon the drilling torque and so is typically lower than the maximum value during the drilling procedure. Drill speed and feed rate (related to drilling force) have been shown to have an effect on bone temperature during drilling in horses' bones.[9] The drilling time reported by Bubeck et al[10] for the step drill was similar to that reported here for an S6.2DB, and the time reported for a sequential 3-bit SO method was only slightly lower than the time for the 4-bit SO method used in the present study.

Previous studies[8,10] of femora in humans and other animals have revealed that the recorded temperatures in the trans cortex are higher than those in the cis cortex, as was the case in the present study. Reasons for this may include the thickness of the cortex, the lack of cooling fluid reaching the trans cortex during drilling, or the accumulation of heat in the drill bit over the entire drilling procedure.[8,10] Another reason for the observed difference between cis and trans cortex bone temperature may be the location of the thermocouples relative to the drilling direction within each cortex. Temperature variation with drilling depth was shown to occur in a study[20] that used modeling of bone drilling, and temperatures were generally greater at deeper depths into the cortex. The difference between the cis and trans cortex temperatures was consistent among drilling groups in the present study and should be considered by equine surgeons when drilling transcortical holes. Although more time-consuming, regular removal and cleaning of drill bits, flushing of drill holes, and allowing complete cooling of drilling hardware would minimize this effect.

A complete block design was used to minimize the effect of individual bones on drilling temperatures among experimental groups in the present study. Systematic assignment of each drilling group to a single drilling position within each bone allowed the effect of bone density and cortical thickness to be minimized in the assessment of bone temperatures during drilling. Previous studies in horses have used either this design[9,10] or a paired study design[11–13] to overcome the strong effect that cortical thickness and bone density have on drilling temperatures. Our data analysis detected a significant effect of bone and cortex in the statistical model for cortical bone temperature.

In phase 1 of the present study, an assessment of drilling accuracy was performed through direct measurement of final hole diameter at 4 separate, evenly distributed locations around the hole and at 2 depths within each hole. These measurements were made in an effort to detect differences in hole diameter that may arise from drilling a pilot hole prior to drilling the final 6.2-mm-diameter hole. We also performed measurement of tapping torque as a clinically relevant variable that is expected to be directly related to hole roundness.[23,24] Although a lobing effect can occur during drilling and is exacerbated when a drill bit for an overdrilling method is used,[18] any effect on final hole accuracy as it relates to the tapping torque and ultimately, by extension, to the initial stability of a large animal transfixation pin appears to be negligible from the results of our study. One limitation in the approach taken to determine drill hole accuracy was the use of hole diameter for measurement, rather than a more precise method such as profilometry, where measurements of hole radius allow better detection of lobing.[18] Despite this limitation, our hole measurements agreed well with findings of a previous study[10] involving bones of horses and additionally agreed with the conclusions reached from the tap insertion torque measurements.

Heat dissipation through the bone is a time-dependent process. Drilling time was significantly longer when the 4-bit SO method was used in the present study. A more direct comparison of the temperatures generated by use of the drilling methods evaluated in this study would require that all drilling procedures be performed over the same interval. It is possible that if this were the case, the overdrilling methods may not result in significantly reduced bone temperature increases, compared with the S6.2DM method. The fact that surgeons have to take time to change drill bits when the SO methods are used may be as beneficial in reducing the bone temperature and reducing the cutting energy required for the final 6.2-mm-diameter hole by creating a pilot hole. Bone temperature measurements increased during the SO procedures, even for the initial 3.2-mm-diameter pilot hole, as detected by thermocouples positioned > 2 mm from the drill bit.

The use of sequential hole enlargement through the process of overdrilling with successively larger drill bit sizes to create a 6.2-mm-diameter hole in the MCIIIs of cadaveric horses was beneficial in reducing the maximum temperature increase measured 0.5 mm from the hole margin. The overdrilling process did not result in clinically relevant inaccuracy of the hole dimensions and should be used to minimize the risk of thermal bone damage during the placement of large animal transfixation pins in horses. In addition, taking ample time to perform the hole drilling procedure as well as use of established surgical principles such as regular drill removal and cleaning and flushing of drill bits and drill holes will reduce the possibility of thermal bone damage and early pin loosening during transfixation casting in horses.

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a. Large battery reamer/drill, Synthes Inc, Paoli, Pa.
b. Orthopedic drill bits, Securos Veterinary Orthopedics, Fiskdale, Mass.
c. 6.2-mm drill bit, Imex Veterinary Inc, Longview, Tex.
d. Precision fine wire K-type thermocouple, Omega Engineering Inc, Stamford, Conn.
e. I/O A-D conversion board, Omega Engineering Inc, Stamford, Conn.
f. InstaCal 5.31, Measurement Computing, Middleboro, Mass.
g. DAS Wizard 2.03, Measurement Computing, Middleboro, Mass.
h. Microsoft Excel, version 10.0.6501, Microsoft Corp, Redmond, Wash.
i. Omegatherm 201, Omega Engineering Inc, Stamford, Conn.
j. Temperature surface probe Type K, Omega Engineering Inc, Stamford, Conn.
k. Electronic caliper, 6 inch, LS Starrett Co, Athol, Mass.
l. Part No. 2114T, Imex Veterinary Inc, Longview, Tex.
m. Electrotork Electronic Torque Wrench, Snap-On Inc, Kenosha, Wis.
n. Adapt-A-Drive, Milwaukee Electric Inc, Brookfield, Wis.

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