Comparison of insertion characteristics of two types of hydroxyapatite-coated and uncoated positive profile transfixation pins in the third metacarpal bone of horses

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**Objective**—To determine the effect of 2 hydroxyapatite pin coatings on heat generated at the bone-pin interface and torque required for insertion of transfixation pins into cadaveric equine third metacarpal bone.

**Sample Population**—Third metacarpal bone pairs from 27 cadavers of adult horses.

**Procedures**—Peak temperature of the bone at the cis-cortex and the hardware and pin at the trans-cortex was measured during insertion of a plasma-sprayed hydroxyapatite (PSPA)–coated, biomimetic hydroxyapatite (BMHA)–coated, or uncoated large animal transfixation pin. End-insertional torque was measured for each pin. The bone-pin interface was examined grossly and histologically for damage to the bone and coating.

**Results**—The BMHA-coated transfixation pins had similar insertion characteristics to uncoated pins. The PSHA-coated pins had greater mean peak bone temperature at the cis-cortex and greater peak temperature at the trans-cortex (70.9 ± 6.4°C) than the uncoated pins (38.7 ± 8.4°C). The PSHA-coated pins required more insertional torque (10,380 ± 5,387.8 Nmm) than the BMHA-coated pins (5,123.3 ± 2,296.9 Nmm). Four of the PSHA-coated pins became immovable after full insertion, and 1 gross fracture occurred during insertion of this type of pin.

**Conclusions and Clinical Relevance**—The PSHA coating was not feasible for use without modification of presently available pin hardware. The BMHA-coated pins performed similarly to uncoated pins. Further testing is required in an in vivo model to determine the extent of osteointegration associated with the BMHA-coated pins in equine bone. (Am J Vet Res 2007;68:1160–1166)

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Transfixation casting is a form of external skeletal fixation used in horses primarily to treat comminuted phalangeal fractures that are unsuitable for repair with internal fixation. The technique requires placement of transfixation pins transversely through the third metacarpal or third metatarsal bone and their incorporation into a limb cast that encompasses the foot. The cast acts as the sidebars of a traditional external skeletal fixator, and weight-bearing loads are transferred from the bone through the pins and cast to the ground. This provides protection from axial collapse of comminuted fractures and allows weight bearing on the fractured limb during healing. Although advancements in technology and surgical techniques have improved the success of transfixion casting, pin-related complications remain its primary limiting factor. These complications include premature pin loosening, catastrophic fracture through pin holes, pin tract infections, and bone sequestration at the pin hole. Pin-related complications still occur despite research efforts to optimize pin size and configuration, and they ultimately result in limitation of the overall effectiveness, reliability, and safety of transfixation casting in horses.

The weak link of both the transfixation cast in horses and traditional external skeletal fixation used in other species, including humans, is the BPI. Bone resorption and pin loosening result from mechanical and thermal damage during pin insertion, as well as cyclic mechanical loading during limb use. The large body mass, and the thickness and density of the bones of horses, creates a challenge in the successful placement and maintenance of transfixation pins. Bone temperatures in the range of 47°C to 55°C cause irreversible bone damage in rabbits, although this has not been studied specifically in horses. Temperatures of 55°C have been exceeded in recent studies in equine cadaver...
third metacarpal bones that assessed drilling methods and pin technologies. Cyclic loading of pins results in poor osteogenesis, bone resorption, and subsequent fibrous tissue deposition at the BPI. Pin tract infections are also believed to contribute to the breakdown of BPI stability; although some investigators suggest these local infections are simply coincidental with pin loosening. Regardless, pin loosening and infection both contribute to patient morbidity through pain; loss of construct and fracture stability; increased risk of catastrophic failure through an enlarged pinhole; and the need for additional surgery to replace pins, debride infected pin tracts, or reconfigure fracture fixation.

Hydroxyapatite is the principle inorganic microcrystalline component of bone matrix, providing a rigid structural scaffold within which the organic components of bone tissue are organized. Hydroxyapatite has been used in humans as a pin coating to prevent pin loosening through the promotion of osteointegration. There are several methods of applying hydroxyapatite to metallic implants, each resulting in different coating properties. Experimentally, uncoated, tapered, threaded external fixation pins loosened as early as 2 weeks following insertion in canine tibias because of micromotion, resulting in bone resorption with subsequent fibrous tissue deposition at the BPI. When hydroxyapatite was applied to pins, histologic evidence of osteointegration and higher pin extraction torque measurements were found, compared with uncoated pins. These findings led to the clinical use and evaluation of hydroxyapatite pin coatings. In human trials, reduced pin tract infection rates, increased extraction torque, and longer periods of pin stability, compared with uncoated pins, have been confirmed in clinical studies as benefits of hydroxyapatite pin coatings.

Osteointegration is the process of bone ingrowth into the hydroxyapatite coating. Hydroxyapatite provides a scaffold to which osteoblasts can attach and form matrix. This is known as osteoconduct. For osteointegration to occur, several reactions take place at the surface of the hydroxyapatite coating. Initially, superficial hydroxyapatite crystals dissolve when exposed to fluid at the BPI. This is followed by precipitation of bone apatite on the surface of the coating. Next, there is ion exchange with absorption and incorporation of protein into the coating. This precedes cell attachment, proliferation, and differentiation. Finally, there is extracellular matrix formation and mineralization at the BPI. The dissolution property of hydroxyapatite is inversely proportional to the crystalline structure of the coating (ie, the higher the percentage of crystallinity, the less soluble the coating). More rapid osteointegration occurs when the dissolution rate of the hydroxyapatite coating is higher.

We are unaware of any studies evaluating the use of hydroxyapatite-coated pins in equine third metacarpal bone. The purpose of the study reported here was to assess the insertion characteristics of hydroxyapatite-coated transfixation pins into cadaveric equine third metacarpal bone. Specifically, the objective was to measure the effect of 2 types of hydroxyapatite coatings on the heat generated within bone and the torque required during insertion of large animal transfixation pins into cadaveric equine third metacarpal bone. We hypothesized that hydroxyapatite-coated transfixation pins would generate more heat and would require greater torque for insertion than uncoated pins.

Materials and Methods

Insertional characteristics of PSHA-coated transfixation pins, BMHA-coated transfixation pins, and uncoated transfixation pins were compared by use of a balanced incomplete block design. The 3 possible pairings for pin comparisons (ie, PSHA vs uncoated, BMHA vs uncoated, and PSHA vs BMHA) were evaluated with 27 pairs of equine third metacarpal bones. Pin pairs were randomly assigned to bone pairs until there were 9 pairs of bones for each type of pin comparison. Within a paired comparison, a left or right bone was randomly assigned to each pin type. A set of hardware (drill bits and taps) was assigned to each individual subgroup so that within each pair, the same number of holes were drilled and tapped with the respective hardware, such that all drill bits and taps were used 9 times.

Paired right and left third metacarpal bones were collected within 12 hours after death from 27 horses (11 Quarter Horses, 8 Thoroughbreds, 3 Appaloosas, 2 Arabians, 1 Paint, 1 Standardbred, and 1 Lipizzaner), ranging from 2 to 24 years of age (median = 8 years), euthanatized for reasons other than lameness. After group allocation, the age distribution among groups was similar. Bones were dissected free of soft tissues, wrapped in towels soaked in saline (0.9% NaCl) solution, and frozen at –20°C for storage. Bones were thawed for 24 hours at room temperature (20°C), and temperature was then raised to 37°C in an incubator for 8 hours immediately prior to testing. Bones were left in the towels during the thawing and warming process and not allowed to dry out.

Fifty-four stainless-steel, centrally threaded, positive profile large animal transfixation pins with a 6.3-mm core diameter, 8.0-mm thread diameter, and 64-mm thread length were used for this study. Eighteen pins were left uncoated, while 1 of 2 hydroxyapatite coatings was applied to the entire threaded portion of the remaining 36 pins. A PSHA coating (30- to 60-µm thickness) and a solution-based BMHA coating (3- to 8-µm thickness) were each applied to 18 transfixation pins.

Pin insertion—Identical pin insertion methods were used for the placement of all pins. The location of pin placement was the mid-diaphysis, determined by fluid at the BPI. This is followed by precipitation of bone apatite on the surface of the coating. Next, there is ion exchange with absorption and incorporation of protein into the coating. This precedes cell attachment, proliferation, and differentiation. Finally, there is extracellular matrix formation and mineralization at the BPI. The dissolution property of hydroxyapatite is inversely proportional to the crystalline structure of the coating (ie, the higher the percentage of crystallinity, the less soluble the coating). More rapid osteointegration occurs when the dissolution rate of the hydroxyapatite coating is higher.

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Figure 1—Photograph of PSHA-coated large animal transfixation pin. The pin coating extends approximately 10 mm past the threaded portion of the pin.
by measuring 50% of the length of the bone. This was measured from the most distal articular surface of the lateral condyle to the proximal articular surface of the third metacarpal bone at the medial edge of the fourth carpal bone. All pins were placed in a lateral to medial direction. The drilling position was located at the lateral-most aspect of the bone. Bones were positioned in a custom drilling jig to ensure that the drilling was performed perpendicular to the long axis of the bone and in a frontal plane (Figure 2). One pin was placed per bone. A low-speed, high-torque pin driver was used for all drilling, tapping, and pin placement. Saline solution kept at room temperature was delivered at a constant flow rate of 150 mL/min by a regulated fluid pump delivery system to irrigate the drill bit, tap, and pins at the cis-cortex during all placement procedures. An implantable thermocouple was placed 5.1 mm proximal to the center of the planned pinhole in the cis-cortex to measure peak bone temperature during drilling. A 4.0-mm pilot hole was made prior to drilling the final pinhole with a 6.2-mm drill bit. Immediately following penetration of the 6.2-mm drill bit through the trans-cortex, a surface temperature probe was used to measure the temperature of the drill tip, which was recorded. Pinholes were flushed with saline solution to remove any bone debris. An 8.0-mm tap was used to create the pin threads. Immediately following completion of tapping through the trans-cortex, the temperature of the first thread of the tap was measured and recorded. The tap was removed, the pinhole was flushed again, and a transfixation pin (PSHA, BMHA, or uncoated) was inserted into the bone. Immediately upon the first thread exiting the trans-cortex, its temperature was measured and recorded. The temperatures of the drill, tap, and pin were assumed to be comparable to the temperature of the immediately adjacent bone. A surface thermocouple was used on the trans-cortex to obtain consistent temperature recordings. Following pin placement, a measure of the peak torque achieved during rotation of the pin a further half turn was made by use of a digital torque wrench with chuck adaptor. Both ends of the pins were then cut 2 cm from the bone surface with a bolt cutter as is performed clinically when casting material is applied over the pins.

**Structural evaluation**—Digital photographs were obtained of the bone at both cortices to record any gross damage caused by drilling, tapping, and pin placement. A 5-cm length of the mid-diaphyseal region of the bone, including the inserted pin, was isolated. This was placed in a parallel motion saddle and aligned to achieve a cut through the long axis of the pin and transversely through the 2 bone cortices with a 0.2-mm diamond grit cutting band. Photographs of the cut surface of both medial and lateral cortices were obtained before and after lifting the pins from the bone. The proximal half of each specimen was processed for microscopic evaluation. Bone samples were stored in 70% isopropyl alcohol and air-dried before staining the cut surface of the bone with basic fuchsin prior to examination. The BPI of both cortices and the corresponding pin surface were examined with a stereomicroscope (23 to 500×), and photographs were obtained to record microstructural damage of the bone and pins. The number of microfractures seen at the BPI was counted and recorded. All pins were grossly examined for defects or cracks in the coating. One pin sample of each coating type was air-dried, mounted on a stub, and sputter coated with gold-palladium prior to examination of the coating via scanning electron microscopy.

**Statistical analysis**—Sample size calculations were performed on the basis of insertion torque variability data in other species to achieve a power of 0.8. Parametric distribution of data was assessed with the Shapiro-Wilk test for normality. Measurements of normally distributed data (temperature and torque) were compared by use of paired t tests. The number of microfractures per bone sample at the BPI was compared by use of a Wilcoxon signed rank test. A value of P < 0.05 was considered significant. Statistical tests were performed with computer software.

**Results**

The drilling and tapping temperatures were not significantly different for any paired comparison (Table 1). During pin insertion, the bone temperature at the cis-cortex was significantly higher for the PSHA-coated pins, compared with the uncoated pins. Mean ± SE temperature of the first thread of the PSHA-coated pins (70.9 ± 6.4°C) at the trans-cortex was almost double that of the uncoated pins (38.7 ± 8.4°C; P < 0.001).

For the BMHA-coated versus uncoated pin comparison, the bone temperature at the cis-cortex during pin insertion (P = 0.83) and the temperature of the first thread of the pins at the trans-cortex (P = 0.19) were not significantly different between groups.

When comparing the PSHA- and BMHA-coated pins, the bone temperature at the cis-cortex was not significantly different between groups (P = 0.093). However, the temperature of the first thread of the pin at the trans-cortex was significantly greater for the PSHA-coated pins, compared with the BMHA-coated pins.
The end insertional torque was not significantly different between the PSHA-coated (13,221.4 ± 6,065.7 Nmm) and uncoated pins (9,314.8 ± 2,888.1 Nmm). However, 3 of the 9 PSHA-coated pins were immovable after insertion, and a torque reading was impossible to achieve because of slippage of the chuck. Torque measurements > 20,000 Nmm were measured at the point of chuck slippage for these 3 pins. A value of 20,000 Nmm was used for these pins for statistical analysis. None of the uncoated pins became immovable following insertion.

The end insertional torque was not significantly different (P = 0.45) between the BMHA-coated pins and the uncoated pins. However, the end insertional torque was significantly (P = 0.006) greater for the PSHA-coated pins (10,380.0 ± 5,387.8 Nmm), compared with the BMHA-coated pins (5,123.3 ± 2,296.9 Nmm). One PSHA-coated pin in this group became immovable after insertion, and a torque reading was impossible to achieve because of slippage of the chuck.

Microstructural evaluation revealed no significant difference in the number of microfractures per sample in any group. The median number of microcracks per sample for the uncoated group was 2 (range, 0 to 4), compared with the PSHA-coated group, which had 1 (range, 0 to 3). The uncoated pins had a median of 2 (range, 0 to 2) microcracks/sample, compared with the BMHA-coated group, which had 2 (range, 0 to 4). The PSHA-coated group had 1 (range, 0 to 3) and the BMHA-coated group had 1 (range, 0 to 4) microcrack/bone sample. In addition to the microfractures ob-

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Table 1—Mean ± SE values for comparison of insertional characteristics of pairwise groups of uncoated (UC), PSHA-coated, and BMHA-coated transfixation pins into equine third metacarpal bone.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Stage</th>
<th>Location</th>
<th>Subgroup</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC vs PSHA</td>
<td>6.2-mm drill</td>
<td>Cis Temp</td>
<td>Plasma sprayed</td>
<td></td>
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<td></td>
<td></td>
<td>Trans Temp (hardware)</td>
<td>UC</td>
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<tr>
<td></td>
<td></td>
<td>Cis Temp</td>
<td>39.3 ± 3.0</td>
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<td></td>
<td></td>
<td>Trans Temp (hardware)</td>
<td>56.9 ± 2.6</td>
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<td></td>
<td>Pin</td>
<td>65.4 ± 8.0</td>
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<td></td>
<td></td>
<td>Trans Temp (hardware)</td>
<td>34.2 ± 3.4</td>
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<tr>
<td></td>
<td></td>
<td>Cis Temp</td>
<td>29.0 ± 8.4</td>
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<tr>
<td></td>
<td></td>
<td>Trans Temp (hardware)</td>
<td>70.9 ± 6.4</td>
<td>&lt; 0.001</td>
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<tr>
<td></td>
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<td>End-insertional torque</td>
<td>9,314.8 ± 2,888.1</td>
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<td></td>
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<td></td>
<td>13,221 ± 6,065.7</td>
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<tr>
<td>UC vs BMHA</td>
<td>6.2-mm drill</td>
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<td>Biomimetic</td>
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<td>Plasma sprayed</td>
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<td>Trans Temp (hardware)</td>
<td>56.0 ± 8.9</td>
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<td>Pin</td>
<td>36.8 ± 6.8</td>
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<td>Trans Temp (hardware)</td>
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<tr>
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<td>Cis Temp</td>
<td>31.7 ± 3.1</td>
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<td></td>
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<td>Trans Temp (hardware)</td>
<td>44.4 ± 10.5</td>
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<td>End-insertional torque</td>
<td>6.54 ± 2,870.5</td>
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<td></td>
<td>5,596.1 ± 2,101.9</td>
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<tr>
<td>PSHA vs BMHA</td>
<td>6.2-mm drill</td>
<td>Cis Temp</td>
<td>Biometric</td>
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<td>Trans Temp (hardware)</td>
<td>Plasma sprayed</td>
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<td>Cis Temp</td>
<td>33.2 ± 4.3</td>
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<td>Trans Temp (hardware)</td>
<td>56.0 ± 11.8</td>
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<td>Pin</td>
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<td>Trans Temp (hardware)</td>
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<tr>
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<td>Cis Temp</td>
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<td></td>
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<td>Trans Temp (hardware)</td>
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<td>End-insertional torque</td>
<td>58.3 ± 12.3</td>
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<td>10,380 ± 5,387.8</td>
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<td>5,123 ± 2,296.9</td>
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Cis Temp = Peak temperature of the cis-cortex (°C). Trans Temp = Peak temperature of the hardware or pins at the trans-cortex (°C). End-insertional torque = Torque required to turn the pins a half turn further following full insertion (Nmm).
served, there was 1 bone that grossly fractured during insertion of a PSHA-coated pin (Figure 3). The fracture radiated from the pinhole proximally along the dorso-lateral cortex approximately 2.5 cm.

Gross qualitative evaluation of both hydroxyapatite coatings did not reveal any damage. Furthermore, scanning electron microscopic evaluation of 1 sample of each coating revealed that both coatings remained intact with no evidence of cracking or loss of the coating (Figures 4 and 5).

Discussion

The heat generated and the insertional torque required by the BMHA-coated pins were comparable to uncoated large animal transfixation pins, and these pins appear to be a feasible prospect for further in vivo evaluation in the third metacarpal bone of adult horses. However, the PSHA coating evaluated in this study was not feasible for use in the third metacarpal bone with currently available large animal transfixation pins and insertion hardware because of the large increase in the amount of heat generated during insertion and the excessive torque required to insert the pins.

The addition of the PSHA coating to large animal transfixation pins resulted in temperatures that exceeded those known to cause thermal damage to osteocytes.\textsuperscript{11,12} Thermal bone damage at the time of pin insertion would lead to bone resorption at the BPI and possible ring sequestration. Ultimately, failure of osteointegration would be inevitable because subsequent resorption of thermally damaged bone and pin loosening would be expected to occur at the BPI instead of bone formation.\textsuperscript{4} In addition, the amount of torque required to insert the PSHA-coated pins was greater than limits of the standard pin-driving equipment used for the study in 4 of 18 of these pins, resulting in a pin that was immovable following insertion. This situation would be unacceptable clinically, especially if osteointegration occurred, because removing the pins would be difficult, if not impossible. Although we did not detect an increase in the amount of bone microdamage in the PSHA coating group, in one of these pins, a gross cortical fracture occurred during pin insertion. This too would be unacceptable clinically. We suspect that the increased temperature generation, higher insertional torque, and 1 case of gross bone fracture associated with the PSHA-coated pins were attributable to the increase in radial preload\textsuperscript{13} that resulted from addition of the PSHA coating to currently available hardware. Another factor that may have contributed to temperature generation during insertion of the PSHA-coated pins was the roughness of the coating. Although we did not measure the roughness of each coating or the uncoated pins, differences between the materials may account for some of the temperature differences detected.

Biomimetic hydroxyapatite–coated large animal transfixation pins were similar to uncoated transfixation pins in this study when temperature, insertion torque, and bone microdamage were evaluated. The BMHA coating is a nanoapatite coating that is formed from a physiologic aqueous solution at a physiologic temperature. The coating is similar to the apatite in bone in terms of chemical composition, crystalline structure, and mechanism of formation.\textsuperscript{16,20} From the results of the present study, it appears feasible to insert BMHA-coated transfixation pins in the third metacarpal bone of an adult horse without creating excessive mechanical or thermal bone damage. Further studies are needed to determine the extent of osteointegration associated with the BMHA-coated pins in equine bone in vivo.

Uncoated pins were chosen as a paired comparison for the feasibility of both coatings because these are currently used clinically in the horse. Plasma-sprayed and solution-precipitated coating techniques were evaluated in this study because they are commonly used in human orthopedics for implant coatings.\textsuperscript{16,27} Currently, PSHA is commercially used on external fixation pins, dental implants, and joint replacement implants in humans. Solution-induced hydroxyapatite is used primarily for joint replacement implants. We chose to compare both types of coating in the present study because these coatings differ in properties such as thickness, crystallinity, surface roughness, and porosity.\textsuperscript{18,19} The BMHA coating is an alternative type of solution-precipitated hydroxyapatite coating that mimics the crystalline structure of bone.\textsuperscript{18}

A surface thermocouple was used to measure the temperature at the trans-cortex, instead of an implantable thermocouple, to enable consistent readings. In a pilot test, placement of an implantable thermocouple in the trans-cortex resulted in inconsistent distances between the subsequent pinhole and the thermocouple because of slight play in the drilling jig track and vice holding the drill. This resulted in variable temperature recordings. For this reason, a surface thermocouple was used to measure the temperature of the hardware and pins as they exited the trans-cortex. The custom jig was used in this study to mimic the clinical setting while controlling as many drilling variables as possible.

We are unaware of any studies that have used insertion torque for evaluating pin stability in horses. This method of torque measurement was adapted from previous studies\textsuperscript{16,21} in other species. The torque measurements reported here may serve as initial reference values for future studies. The torque value for the PSHA-coated pins that became too tight to complete a reading
was set at 20,000 Nmm because this was the minimum value measured before chuck slippage occurred. All values measured prior to chuck slippage were at least 20,000 Nmm, so this is a conservative value that represents the lowest value of torque that could have been measured for these pins.

The difference in the thickness of the coatings used in this study could account for several of the observed results. The PSHA coating was 30 to 60 μm, whereas the BMHA coating was only 3 to 8 μm thick. This added thickness increases the radial preload\(^2\) of the pins by increasing the overall diameter. The additional preload increases the amount of friction on the pin during insertion and ultimately the insertional torque. The increase in radial preload and friction during insertion would also be expected to increase the temperature generated during pin insertion, as detected in this study. A change in radial preload was a known consequence of using coatings with currently available hardware; however, the extent of the effect this would have on insertional properties was not known prior to this study. Potentially, pin hardware could be redesigned to accommodate for the added thickness of the PSHA coating. With the expectation of osteointegration to add stability, redesigning pins with a lower radial preload may be desirable.

Although it is recommended to place large animal transfixation pins in the distal portion of the third metacarpal bone for construction of a transfixation cast when treating phalangeal fractures,\(^{1,2}\) we used the mid-diaphyseal location for testing during this study. The mid-diaphysis of the equine third metacarpal bone may be the most challenging location in horses to place transcortical pins without creating excessive heat in the process. We felt that a consistent and stringent test of the coatings could be achieved by use of this location, leaving no doubt as to their feasibility following testing.

Osteointegration can be measured biomechanically by comparing the insertion and extraction torque of a transfixation pin in vivo.\(^9\) An increase in extraction torque suggests that osteointegration has taken place during the period of implantation. With the use of an uncoated pin, extraction torque decreases relative to the insertion torque over a period of time because of bone resorption and fibrous tissue deposition at the BPI.\(^{31}\) When hydroxyapatite-coated pins are used in vivo, osteointegration becomes evident within 4 weeks, as indicated by increased extraction torques and results of histologic examination of the BPI.\(^{38}\)

Transfixation casts have improved the success of treating unstable phalangeal fractures in horses; however, complications associated with their use still cause concerns. Pin complications are intimately related to bone resorption at the BPI and pin loosening. Hydroxyapatite coating of transfixation pins may decrease the amount of resorption and promote osteointegration in equine bone. The findings of this study suggested that PSHA coating of currently available large animal transfixation pins is not feasible because of the amount of heat generated and the degree of torque needed at insertion. However, the insertional properties of BMHA-coated transfixation pins were comparable to uncoated pins; specifically, the generated heat, amount of torque required for insertion, and amount of damage observed at the BPI were similar between these groups. Before these pins can be used clinically, further studies evaluating the in vivo properties in equine bone need to be performed to assess the ability of BMHA-coated pins to osteointegrate and the ease of these pins to be removed at the appropriate time during fracture healing.

\(\text{a. Centerface large animal transfixation pin, 1/4" shank, 5/16" thread, provided by Imex Veterinary Inc, Longview, Tex.}
\(\text{b. Plasma-sprayed hydroxyapatite coating, 30- to 60-μm thickness, Bio-coat Inc, Southfield, Mich.}
\(\text{c. Solution-based biomimetic hydroxyapatite coating, 3- to 8-μm thickness, provided by Dr. Panjian Li, DePuy, Warsaw, Ind.}
\(\text{d. Maxi driver, 3M, Saint Paul, Minn.}
\(\text{e. Masterflex console drive fluid pump, Cole Parmer Instruments, Vernon Hills, Ill.}
\(\text{f. Implantable thermocouple type K, Omega Engineering Inc, Stamford, Conn.}
\(\text{g. 0.2 X 175-mm drill bit, provided by Imex Veterinary Inc, Longview, Tex.}
\(\text{h. Temperature surface probe type K, Omega Engineering Inc, Stamford, Conn.}
\(\text{i. Tap for Centerface large animal transfixation pin, 1/4" shank, 5/16" thread, provided by Imex Veterinary Inc, Longview, Tex.}
\(\text{j. Electrotork Electronic Torque Wrench, Snap-On Inc, Kenosha, Wis.}
\(\text{k. Adapt-A-Drive, Milwaukee Electric Inc, Brookfield, Wis.}
\(\text{l. Jacobs 3/8" hand chuck, Jacobs Chuck Manufacturing Co, Clemson, SC.}
\(\text{m. Esakti macro cutting device, Esakti Technologies, Oklahoma City, Okla.}
\(\text{n. Purdue Life Science Microscopy Facility, West Lafayette, Ind.}
\(\text{o. STATA, version 9.2, StataCorp, College Station, Tex.}

**References**

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