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Performance and Longevity of a Novel Intraosseous Device in a Goat (*Capra hircus*) Model

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We performed 2 studies to assess the function and longevity of a novel intraosseous catheter device. For study 1, 9 goats were assigned to 3 groups (intraosseous catheter in the proximal humerus, intraosseous catheter in the proximal tibia, or standard jugular catheter). Devices in the tibia remained in place for less time than did those in the humerus, and no goats exhibited radiographic evidence of resulting damage or structural change in surrounding bone. Positive bacterial cultures were found in all 9 goats at various time points. In study 2, 18 goats were assigned to 2 groups (intraosseous catheter in the wing of the ilium or proximal humerus). Samples for serial aerobic and anaerobic blood cultures and CBC were collected while devices remained in use. Clinical monitoring and removal criteria were identical those for study 1. Catheters in the ilium remained in place for less than 24 h on average, and those in the humerus remained in place for an average of 2.5 d. Several goats with proximal humeral catheters demonstrated moderate lameness after removal, and radiographic evidence of periosteal bone growth was noted in another goat. Bloodwork indicated mild elevations of WBC counts from baseline in some cases. Bacterial growth was found in samples from 4 of 18 goats at various time points. Our study indicated that intraosseous catheters may remain safely in place for more than 24 h, but animals should be monitored closely for negative side effects for several days after removal.

Intravenous administration of fluids and medication is a crucial component of emergency medical case management. However, venous access is often extremely difficult to obtain in severely compromised patients. A cutdown procedure can be time-consuming, difficult for those inexperienced with the technique, and ultimately unsuccessful in gaining intravenous access during severe hypovolemia. The spectrum of drugs that may be given endotracheally is limited, and their rate of distribution may be variable.[33,38,39] In addition, the endotracheal route is not a viable option for fluid replacement. When intravenous access is not readily achievable, intraosseous catheterization can serve as a reliable, life-saving alternative. This technique is used frequently in veterinary medicine, particularly in pediatric and exotic animal species. In veterinary medicine, the most common locations for intraosseous catheterization are the proximal humerus, proximal tibia, wing of the ischium, iliac crest, and proximal femur.[19,56] Although numerous studies have addressed the efficacy and potential applications of intraosseous catheters in several veterinary species, including dogs, swine, and goats,[5,12,18,30,45,46] data regarding the prolonged use of intraosseous catheters are limited. Removal of intraosseous catheters is recommended as soon as venous access is attainable. However, complications or other factors conceivably could arise that would necessitate unanticipated prolonged use of an intraosseous cannula.

Intraosseous cannulas have gained renewed interest for use in human emergency medicine. Although intraosseous access has been most commonly used in human pediatrics, recent attention has focused on its potential for use in adult emergency care and military special operations.[11,16,25,31,35] Several devices have been introduced for intraosseous catheterization, and at least one is approved by the Food and Drug Association for 24-h use in the human tibia and humerus.[25] Several studies have shown that the use of these devices and their correct placement are easily learned, regardless of the operator's experience level.[2,6,11,31,35] Our aim in the current study was to evaluate the extended safety and efficacy of intraosseous catheter systems for potential use in large animals.

Materials and Methods

Study 1. Nine domestic, mixed-breed goats (*Capra hircus*; age, 8 to 12 mo; weight, 27 to 40 kg) were determined to be healthy by physical examination (Texas A&M Veterinary Medical Park, College Station, TX). Conventional-status animals from the institution's teaching herd were used and had received routine deworming and vaccinations. All goats were housed in groups of 3 within approved laboratory animal facilities for the duration of the study and were maintained under a protocol approved by the Texas A&M Institutional Animal Care and Use Committee. Each goat was assigned to 1 of 3 groups for this initial pilot study (intraosseous device in the proximal tibia, intraosseous device in the proximal humerus, or jugular catheter). Catheters (25 mm) used in this study were labeled for use in human patients 40 kg or greater in weight. Thus, the 6 goats that most closely met the weight criteria were then randomly assigned to receive an indwelling device, either within the proximal tibia ($n = 3$) or proximal humerus ($n = 3$). The remaining 3 animals received a jugular catheter.

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Animals were fasted for 24 h, and xylazine (0.22 mg/kg IM; Butler Animal Supply, Dublin, OH) and ketamine (11 mg/kg IM; Fort Dodge, Fort Dodge, IA) were administered for induction of general anesthesia. Areas surrounding cannulation sites were clipped and prepared aseptically, and sterile technique was used for all device placements. After aseptic preparation of the skin and subcutaneous injection of lidocaine (2 mg; Sparhawk Laboratories, Lenexa, KS) immediately over the insertion point, intraosseous devices (EZ-IO, Vidacare, San Antonio, TX) were inserted according to the manufacturer's instructions. The catheters were inserted through the skin and into bone by using the high-powered drill supplied for the system. Tibial devices were applied medially by placing the needle perpendicular to the bone, approximately 1 in. below the tibial tuberosity (Figures 1 and 2). Devices in the humerus were placed longitudinally within the head of the humerus (Figures 3 and 4). For both sites, intramedullary placement was confirmed by firm seating and aspiration of blood and marrow contents. The catheter was capped after removal of the stylet, and baseline radiographs were obtained prior to anesthetic recovery. Tibial intraosseous devices were covered with a light wrap; wrapping humeral devices was not feasible because of their location. After preparation of the insertion site by clipping hair and using surgical scrub, jugular catheters were placed according to standard technique by using an 18-gauge, 2-in. vinyl intravenous catheter (Emergency Medical Products, Waukesha, WI). Once blood flow was confirmed by aspiration, the catheter was secured to the skin by using a small amount of skin glue (3M, St Paul, MN) and a 3-0 polydioxanone suture (Butler Animal Health, Dublin, OH).

Approximately 3 mL blood was collected from a prepped, noncatheterized jugular vein of each goat for baseline aerobic and anerobic cultures. Samples were submitted to the Texas Veterinary Medical Diagnostic Laboratory (College Station, TX) in 20 mL pediatric soy tryptinase blood culture media (Becton Dickinson, Sparks, MD). The catheter was flushed with 3 mL heparin (American Pharmaceutical Partners, Shaumburg, IL) in 0.9% saline (Butler Animal Health, Dublin, OH; final concentration, 10 U/mL) according to manufacturer recommendations, the site was covered with a light wrap, and the goat was allowed to recover from anesthesia.

For the duration of study, personnel observed goats at least twice daily for overall condition, appetite, device-associated lameness, and any redness or swelling at the catheter sites. Each day, rectal temperatures were obtained, and all catheters were evaluated for patency and firm seating within the bone. Blood collection was performed every third day while catheters remained in place. The original intent was to collect blood through the intraosseous catheters for all samples. However, after the initial sample, we were unable to obtain sufficient volume for bloodwork and culture from many goats by this method. Therefore, for consistency, blood samples were collected from a freshly prepped, noncatheterized jugular vein. Loose or failed intraosseous devices were removed by study personnel, and catheters were submitted to the Texas Veterinary Medical Diagnostic Laboratory for aerobic and anaerobic culture. All goats with intraosseous catheters still in place at the time of failure also underwent a second anesthesia episode (0.22 mg/kg xylazine IM and 11 mg/kg IM ketamine) for their removal and follow-up radiographs. Goats were allowed to recover and were monitored until sternally recumbent.

Any catheters that did not flush easily due to clogging or poor positioning were removed immediately. Other criteria for removal included: temperature exceeding 39.5 °C (103.1 °F) for more than 24 h, pain or lameness associated with the device,

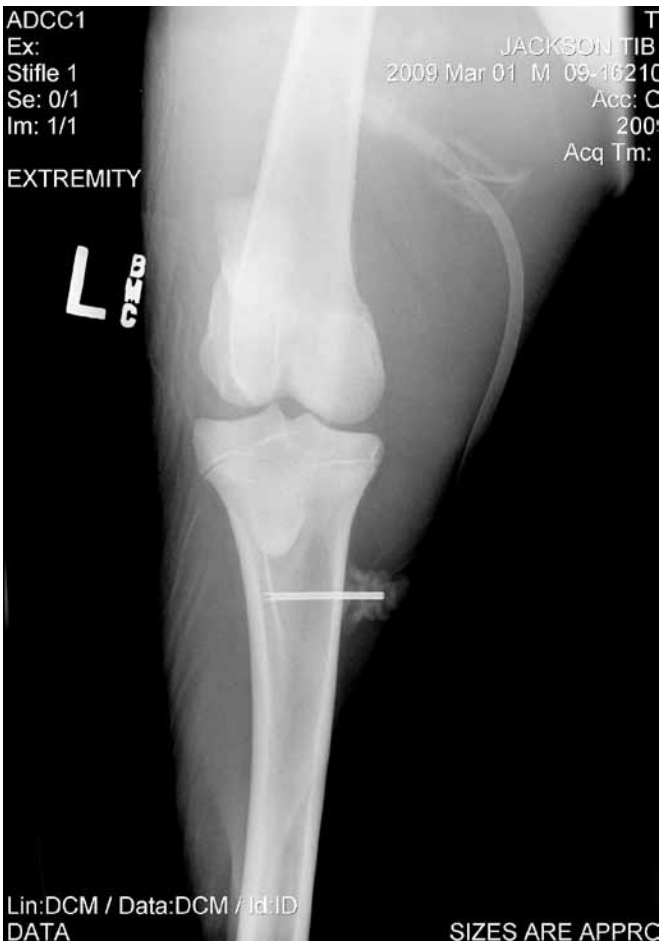

Figure 1. Radiographic view (caudal aspect) of proximal tibial intraosseous catheter placement.

Figure 2. Medial view of proximal tibial intraosseous catheter in left leg.

excessive redness, swelling, discharge around insertion sites, and inappetance, lethargy, or other behavioral changes. Goats displaying any of these clinical signs received appropriate daily antibiotics, including 2.2 mg/kg IM long-acting ceftiofur (Pfizer, New York, NY) or 2.5 mg/kg IM tulathromycin (Pfizer), or analgesia with phenylbutazone paste (4 mg/kg PO; Phoenix Pharmaceutical, St Joseph, MO) as needed or both analgesic and antibiotics, and all animals were placed on observation for 24

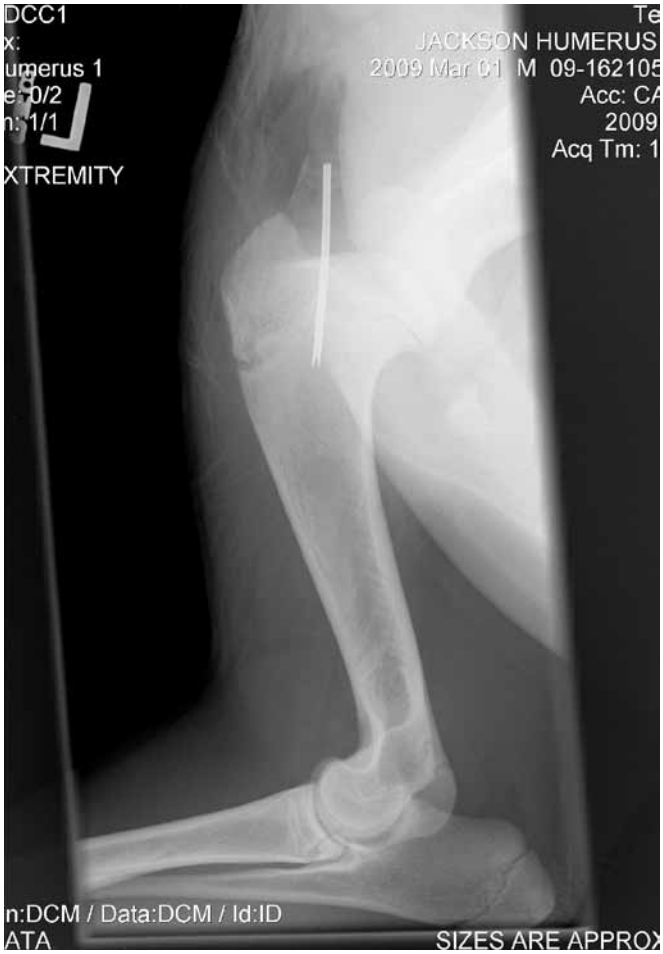

Figure 3. Radiographic view (lateromedial) of proximal humerus intraosseous catheter placement.

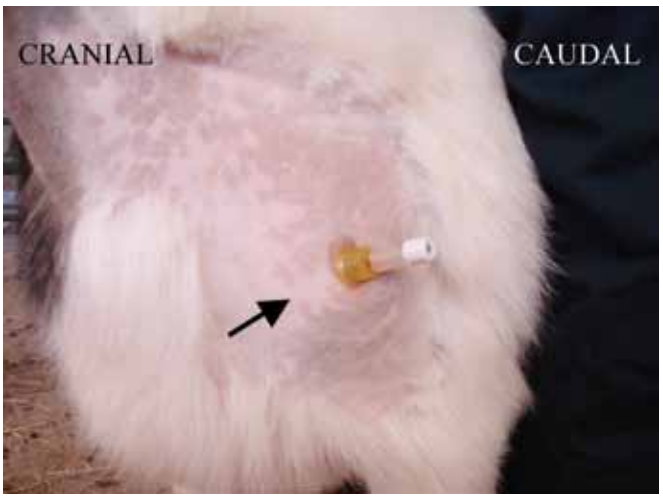

Figure 4. Lateral view of proximal humerus intraosseous catheter in the left leg. Arrow indicates the head of the humerus.

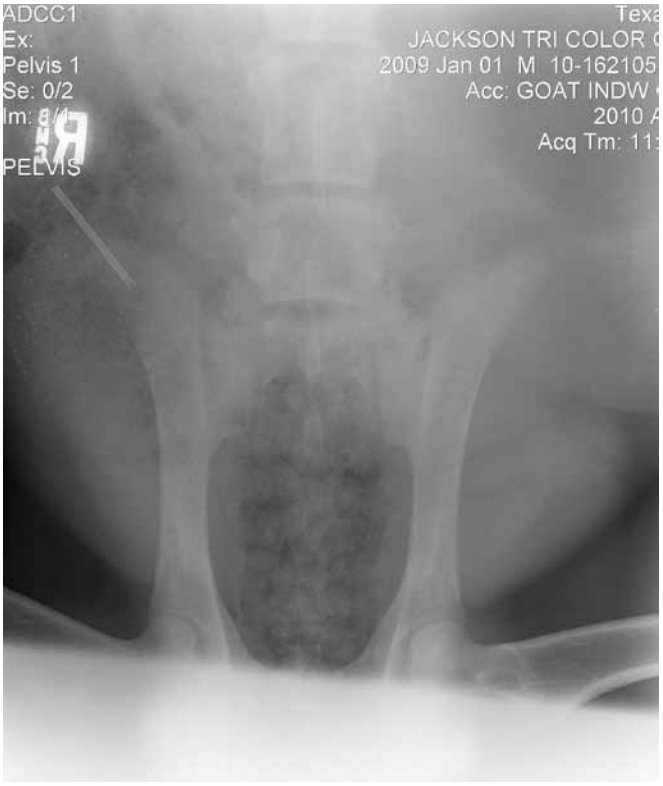

Figure 5. Radiographic view (ventrodorsal) of intraosseous catheter placed in the right ilium.

to 48 h. After confirmation of good health status, goats were returned to regular pasture housing.

Study 2. Eighteen adult, mixed-breed domestic goats (*Capra hircus*; age, 8 to 12 mo; weight, approximately 40 kg) were determined to be healthy by physical examination (Texas A&M Veterinary Medical Park, College Station, TX). Conventional-status animals from the institution's teaching herd were used for this study. After a recovery period of approximately 5 mo, 5 goats that had been used in study 1 were included in the second study; none of these 5 animals displayed any complications associated with the previous intraosseous catheter study during their recovery period. These 5 goats were selected based on weight, as they most closely met the manufacturer's guidelines. Goats receiving 45-mm catheters in the humerus were from a second institutional herd and, as for study 1, were selected based on weight. All goats were housed in groups of 3 within approved facilities for the duration of the study and were maintained under a protocol approved by the Texas A&M Institutional Animal Care and Use Committee. Each goat was assigned to 1 of 2 groups (25-mm intraosseous device in the wing of the ilium or 45-mm intraosseous device in the proximal humerus). These anatomic locations were selected in light of catheter performance and duration during study 1, during which catheters in the tibia were displaced soon after implantation. Catheters used in study 2 were labeled for use in human patients weighing at least 40 kg. Goats were assigned randomly to catheter site.

Methods for anesthesia, site preparation, and cannula placement were the same as those for study 1. Devices in the wing of the ilium were applied in the palpable dorsal crest, by placing the needle parallel to the long axis of the bone (Figure 5); radiographs were obtained to confirm correct placement. Humeral devices were placed longitudinally within the head of the humerus, as described in study 1. For both sites, intramedullary placement was confirmed by firm seating and aspiration of blood and marrow contents. Catheters were capped after removal of the stylet. Because study personnel had become proficient at inserting humeral devices during study 1, radiographs were not used to check their placement during study 2. Approximately 4 mL blood was collected from a prepped jugular vein of each goat for baseline aerobic and anaerobic cultures and CBC. Culture samples in 20 mL pediatric soy tryptinase media and blood samples were submitted to the Texas Veterinary Medi-

Table 1. Study 1: survival times, removal criteria, and culture results

Goat	Catheter type; site	Time to removal (h)	Removal criterion	Blood culture results		Catheter culture
				Day 0	Day 3	
163	Jugular	43	Nonpatent	*Bacillus* sp.; *Micrococcus* sp.; *Brachybacterium* or novel *Dermabacteracea*	Not done	Not done
166	Jugular	96	End study	No growth	Coagulase-negative *Staphylococcus*	Not done
161	Jugular	96	End study	No growth	*Bacillus* sp.	Not done
6600	25-mm intraosseous; tibia	18	Displaced	No growth	Not done	Not done
248	25-mm intraosseous; tibia	41	Nonpatent	*Bacillus* sp.; *Corynebacterium;* α-hemolytic *Streptococcus*	Not done	Not done
0100	25-mm intraosseous; tibia	96	Lameness	*Bacillus* sp.	*Bacillus* sp.	*Bacillus* sp.; mixed bacterial growth
0096	25-mm intraosseous; humerus	67	Displaced	*Bacillus* sp.	*Bacillus*	Not done
0250	25-mm intraosseous; humerus	83	Displaced	*Bacillus* sp.; coagulase-negative *Staphylococcus*	No growth	*Micromonospora chalcea*
0069	25-mm intraosseous; humerus	88	Displaced	*Bacillus* sp.	*Bacillus* sp.	*Bacillus cereus*

cal Diagnostic Laboratory. All other daily clinical monitoring, flushing, and criteria for removal were identical to those for study 1. Because study 1 revealed no evidence of bony change, postremoval radiographs during study 2 were obtained only for those goats showing evidence of lameness, swelling, or elevated temperature for more than 24 h after removal of devices. In addition, for 2 goats that showed persistent or intermittent lameness for more than 2 wk, samples for serum ELISA for caprine arthritis encephalitis virus were submitted to the Texas Veterinary Medical Diagnostic Laboratory.

Statistical analysis. Time to removal of intraosseous catheters placed in the wing of the ilium and proximal humerus (study 2) was analyzed by using Kaplan–Meier time-to-failure curves and compared by using the log-rank test. A P value less than 0.05 was considered statistically significant. All analyses were carried out by using Intercooled Stata software (version 11.0; Stata, College Station, TX).

Results

Study 1. *Proximal tibia.* Catheters in the tibia (n = 3) were well tolerated, although a few minor gait abnormalities due to the placement of bandage material were noted initially. The catheter removed at 18 h was completely displaced (Table 1). No samples for culture were collected from this catheter, given the high likelihood of environmental contamination beneath the bandage, thus preventing accurate sample assessment. The second catheter was removed at 41 h after insertion similarly was displaced under the bandage material and therefore was not submitted for culture. The final tibial catheter was removed after approximately 96 h, due to development of moderate lameness and mild pain on palpation near the catheter; however, the catheter was still patent and seated adequately at the time of removal. This same goat (no. 0100) showed mildly increased opacity within the stifle joint on postremoval radiographs. This goat received a long-acting intramuscular, broad-spectrum antibiotic at the time of catheter removal and had no further complications, including gait abnormalities after anesthetic recovery. The goat showed no further complications thereafter.

Proximal humerus. Catheters in the humerus (n = 3) were well tolerated, although external portions of devices began to deviate from the original angle of placement within 24 h after insertion. No immediate cause of the bending was noted during physical exams, but we surmise that the catheters underwent mild trauma due to the healthy, ambulatory nature of the animals in our study. Even though all external portions of the device progressively deviated (sometimes by as much as 90°) from the initial angle of placement, all catheters remained well seated in the bone and were patent for at least 3 d. None of these goats demonstrated lameness resulting from device placement, and all animals remained bright, alert, and active throughout the study. Catheters in the humerus were removed due to resistance to flushing at approximately 67, 83, and 88 h after (Table 1). At the time of cannula removal, all bending within the metal portion of the cannula was noted to occur at the exit site from the bone in a ventral direction, just at the level of the skin. Animal number 0069, whose catheter was removed at 88 h, developed mild swelling and purulent discharge at the insertion site at 24 h before catheter removal and received a single intramuscular dose of a long-acting broad-spectrum antibiotic. The goat was released to regular pasture housing without further incident.

Jugular catheters. The jugular catheter of 1 of the 3 goats in this experimental group was removed after 43 h due to kinking of the catheter in the vessel and subsequent inability to flush effectively. The other 2 jugular catheters remained patent until removal, which was coincident with removal of the remaining intraosseous devices at day 4 of the study (Table 1). All goats were returned to pasture and were free of adverse sequelae thereafter.

Radiographs. Radiographs of all animals assigned to intraosseous groups were taken immediately after device placement and after manual removal or unintentional displacement of the devices. All radiographs obtained at device insertion confirmed appropriate placement and lack of damage to surrounding bone. Images obtained after removal or dislocation of the devices revealed healthy bone in most goats, with no evidence of fractures or other damage acquired during use of the devices. A single goat with a tibial catheter, goat no. 0100, showed mildly

Table 2. Study 2: survival times, removal criteria, and culture results

Goat	Catheter type; site	Time to removal (h)	Removal criteria	Blood cultures			Catheter culture
				Day 0	Day 2	Day 4	
87	45-mm intraosseous; humerus	22	Nonpatent	No growth	Not done	Not done	No growth
7	45-mm intraosseous; humerus	31	Lameness, swelling	No growth	Not done	Not done	Not done
29	45-mm intraosseous; humerus	46	Nonpatent	No growth	Not done	Not done	*Bacillus cereus*; α-hemolytic *Streptococcus*
124	45-mm intraosseous; humerus	46	Nonpatent, displacement	No growth	Not done	Not done	*Bacillus* sp.; coagulase-negative *Staphylococcus*
132	45-mm intraosseous; humerus	48	Nonpatent	No growth	Not done	Not done	*Enterococcus* sp.
34	45-mm intraosseous; humerus	94	Nonpatent, displacement	No growth	*Bacillus* sp.	Not done	Not done
137	45-mm intraosseous; humerus	95	Lameness	No growth	No growth	Not done	*Staphylococcus aureus*; α-hemolytic *Streptococcus*
131	45-mm intraosseous; humerus	100	Lameness	No growth	*Bacillus* sp.	Gram-positive rod	*Enterococcus* sp.
88	45-mm intraosseous; humerus	100	Lameness	No growth	*Bacillus* sp.	No growth	Gram-negative nonfermenter; α-hemolytic *Streptococcus*
0100	25-mm intraosseous; illium	16	Complete displacement	No growth	Not done	Not done	Not done
299	25-mm intraosseous; illium	16	Complete displacement	No growth	Not done	Not done	Not done
0099	25-mm intraosseous; illium	16	Nonpatent	No growth	Not done	Not done	Not done
298	25-mm intraosseous; illium	19	Complete displacement	No growth	Not done	Not done	Not done
0069	25-mm intraosseous; illium	19	Complete displacement	No growth	Not done	Not done	Not done
248	25-mm intraosseous; illium	22	Complete displacement	No growth	Not done	Not done	Not done
0096	25-mm intraosseous; illium	27	Complete displacement	No growth	Not done	Not done	Not done
175	25-mm intraosseous; illium	30	Complete displacement	No growth	Not done	Not done	Not done
250	25-mm intraosseous; illium	43	Complete displacement	No growth	Not done	Not done	Not done

increased opacity within the stifle joint; this same animal recovered fully after catheter removal due to lameness (Table 1).

Culture. The results of baseline blood cultures and catheters submitted for culture after removal for study 1 are summarized in Table 1. Goat 163 yielded a single colony of a branching, gram-positive rod-shaped organism of unknown significance. Supplemental gene sequencing identified this organism as belonging within the genera *Brachyacterium* or as a novel *Dermabacteracea* species. The bacterial isolates obtained from the blood and catheter cultures are found routinely in large-animal environments and were not considered to be significant pathogens. No anaerobic or obligate anaerobic growth was noted among samples at any time point.

Study 2. *Wing of the ilium.* Catheters (25 mm) placed in the crest of the ilium (n = 9) were well tolerated by all animals. However, 8 of the 9 devices became displaced within the first 24 h (Table 2). The last catheter became displaced and was removed after approximately 43 h (goat 250). No animals in this group showed lameness, swelling, or other clinical signs associated with the devices. CBC analysis yielded no significant abnormal values from any goat in this experimental group.

Proximal humerus. As in study 1, catheters were placed in the proximal humerus in a total of 9 animals, but a longer 45-mm catheter length was used. The catheters in the humerus were well tolerated but began to deviate from the original angle of placement within the first 24 h. Most of the catheters remained patent for several days, with removal at approximately 22, 31, 46, 46, 48, 94, 95, 100, and 100 h (Table 2).

Compared with the 25-mm needles used in study 1, the 45-mm catheters appeared slightly more resistant to bending but seemed to cause more soft-tissue swelling around the insertion site after removal. In addition, 4 of the 45-mm catheters were removed due to mild to moderate lameness (goats 137, 131, 34, and 88; Table 2). No localized areas of joint or bone pain were identified on palpation, although mild discomfort at catheter sites was noted. These 4 goats received appropriate antibiotics and analgesics.

Radiographs were obtained from the 4 goats with signs of discomfort or lameness for more than 72 h (goats 29, 131, 137, and 134). Images from 2 of these goats (nos. 131 and 134) were free of significant bony changes. Goat 137 had a small bony defect at the site of insertion. CBC data showed normal WBC counts, and serum ELISA testing for caprine arthritis encephalitis virus was negative. Follow-up radiographs approximately 2 wk later showed good healing of the area and resolution of soft tissue swelling, and the goat recovered fully.

The fourth goat (no. 29) showed minimal improvement with clinical therapy. This goat's catheter was removed on day 2 because of nonpatency. Approximately 2 d later, the goat developed a fever, swelling in the shoulder area, and became lame. Antibiotics were administered, and the fever resolved, but approximately 1 wk after catheter removal, an abscess developed dorsal to the original catheter insertion site. The abscess was drained and flushed, and culture showed growth of *Arcanobacterium pyogenes* and *Staphylococcus aureus*. The goat was treated procaine penicillin G (25,000 units/kg IM daily for 5 d; Agripharm Products, Westlake, TX). Radiographs were suggestive of possible infectious periostitis and osteomyelitis; CBC analysis at that time showed a normal WBC count, and temperature remained normal. Serum ELISA testing for caprine arthritis encephalitis virus was negative. An additional 5 d of antibiotic therapy was administered, along with low-dose dexamethazone (0.1 mg/kg IM). The goat was monitored for several weeks and then euthanized when lameness did not resolve. Gross necropsy findings indicated that this goat's intraosseous catheter may have entered the joint cavity during placement.

Statistics. Time-to-removal of intraosseous catheters placed in the wing of the ilium or proximal humerus was analyzed by using Kaplan–Meier time-to-failure curves and compared by using the log-rank test (Figure 6). Time to failure was significantly ($P = 0.0008$) longer for intraosseous catheters placed in the proximal humerus than the wing of the ilium.

Radiographs. Follow-up radiographs of 4 of the 9 goats that received 45-mm catheters in the humerus had evidence of soft tissue swelling around the insertion site (goats 29, 34, 131, and 137); this swelling had been was visible or palpable during examination. In addition, goat 137 showed a small bony defect at the insertion site that healed well radiographically in the following weeks. Goat 29 demonstrated persistent lameness, despite antibiotic and analgesic therapy, and follow-up radiographs indicated development of early-stage periostitis and osteomyelitis (Figure 7).

Culture. In study 2, all baseline cultures were negative (Table 2). Because no catheters in the ilium remained past 24 h, additional blood cultures were not submitted for these animals. In addition, no ilial catheters were submitted for culture because of self-displacement and the high likelihood of excessive environmental contamination.

Among the 9 goats with humeral catheters, 4 blood cultures were submitted on day 2 of the study, and 3 of these (goats 34, 88, and 131) showed growth of *Bacillus* species. In the 2 samples that were submitted on day 4, goat 131 showed growth of a gram-positive rod, and goat 88 had no growth. However, goats having positive blood or catheter cultures (or both) were not necessarily those who appeared lame at any point in the study; because the converse also was true, bacterial growth likely was due to environmental contamination during collection. Catheters from the humerus submitted over the course of the experiment showed growth of *Bacillus cereus*, α-hemolytic *Streptococcus*, *Staphylococcus aureus*, and *Enterococcus* spp. Neither of the bacteria cultured from the abscess of the goat that also radiographic evidence of osteomyelitis (goat 29) were present in blood or catheter culture. Growth noted on blood cultures likely was due to environmental or skin contaminants acquired during the blood collection procedure or removal of intraosseous devices.

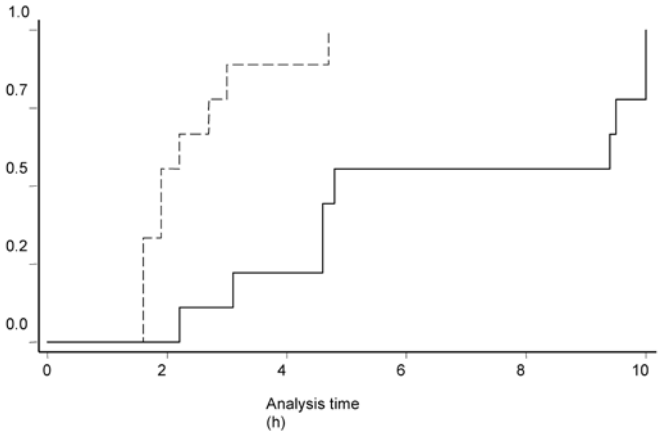

Figure 6. Kaplan–Meier failure functions for 45-mm interosseous catheters placed in the humerus ($n = 9$; solid line) and 25-mm intraosseous catheters placed in the wing of the ilium ($n = 9$; dotted line) during study 2. Data were visualized by using Kaplan–Meier time-to-failure curves and compared by using the log-rank test. Time to failure was significantly ($P = 0.0008$) longer for intraosseous catheters placed in the proximal humerus than the wing of the ilium.

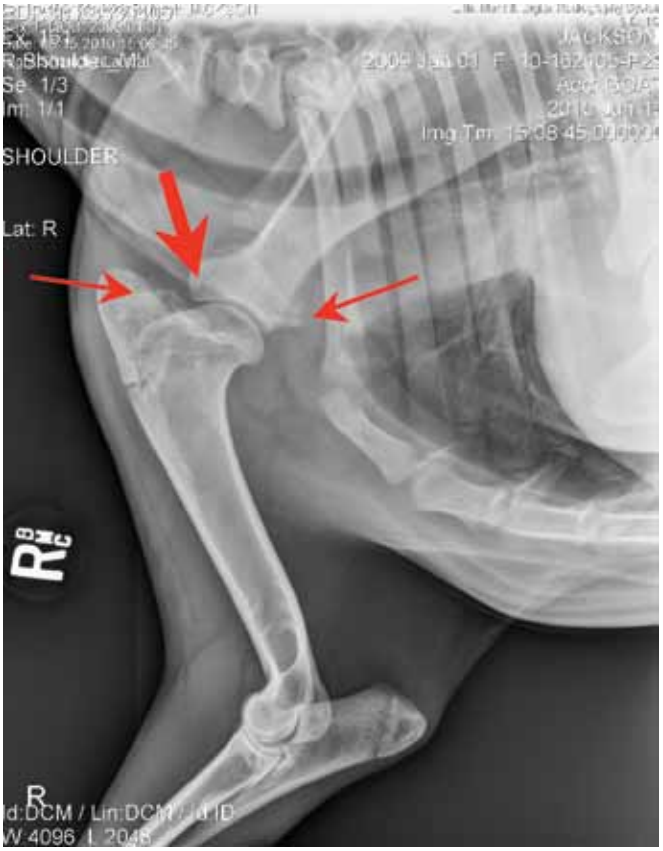

Figure 7. Radiograph (goat no. 29) showing periosteal new bone and sclerosis around the glenoid and supraglenoid tubercles and greater tubercle of the humerus (small arrows) as well as a lucency within the cranial glenoid–coracoid process (large arrow). Findings were suggestive of possible infectious periostitis and osteomyelitis.

Discussion

In study 1, the intraosseous devices generally were well tolerated by the goats, and the humeral and tibial catheters were functionally similar to jugular catheters. Most remained functional for several days with few complications or notable long-term health effects, with the exception of one goat. Most of the goats from the intraosseous groups had no radiographic evidence of damage or structural change within the surrounding bone, again with the exception of one animal that showed a mildly increased opacity in the stifle joint. All other devices remaining in after the first day during study 1 were removed solely due to external deviation significant enough to affect overall patency.

In study 2, both humeral and ilial intraosseous devices were well-tolerated, but the time to failure was significantly different ($P = 0.0008$) between the 2 groups. Catheters in the ilium became displaced much more quickly than did those at all other locations, potentially making this location less useful. Due to the mechanical trauma and bending that was noted with the sites in study 1, we hypothesized that catheters in the ilium might be subjected to less mechanical force during normal movements, thereby remaining patent and in place longer. Contrary to our expectations, 25-mm ilial catheters were less resilient than other intraosseous devices, possibly because of a thinner cortex in which to seat the catheter. Although a 45-mm needle potentially could be used in the wing of the ilium, initial placement would be complicated due to the narrow space and angle of the marrow cavity, increasing the likelihood of the catheter passing through the opposite cortex and functioning poorly. Based on our results, the wing of the ilium is not a favorable placement site for intraosseous catheters in ambulatory animals. The ilium might be an option for recumbent patients, despite the increased risk of catheter displacement during movement or rotation of the animal.

Goats that received 45-mm humeral catheters in study 2 had a higher incidence of associated lameness and swelling (including one case of osteomyelitis). Radiographs confirmed lack of bony change and fracture in nearly all of the goats; swelling was predominantly soft-tissue and confined to the area immediately over the insertion site. Except for one animal, most goats with swelling and lameness had catheters in place for approximately 4 d. Eight of the 9 goats in this group ultimately did well clinically, and no long-term complications emerged after resolution of the adverse signs. The remaining goat developed an abscess and subsequent periostitis and osteomyelitis, which are rare side effects also associated with the use of intraosseous catheters in humans.[40,41] The definitive reason for the increased swelling and clinical signs in this group of goats is unknown, but the longer needle (45 mm in study 2 compared with 25 mm in study 1) potentially could cause more soft tissue disturbance on insertion at the angle used. Furthermore, because most swelling was noted after removal of the catheters, the increase noted may be partially attributable to the fact that removal of the 45-mm needles required considerably more effort due to their deeper seating in bone. Although the 45-mm humeral catheters may be used, possible side effects should be considered.

In the current study, intraosseous devices placed in the humerus appeared to remain functional and in place longer than did those in the tibia or wing of the ilium, and all intraosseous catheters were comparable to jugular catheters in terms of initial usefulness for injectable agents in an ambulatory animal. In human medicine, both manually placed needles and drill-type automatic intraosseous devices similar to the ones used here are frequently used in the tibia,[15,41] and have been used with good results in animal models under surgical anesthesia.[14,21,29,42,53,54] Studies in animal models (using other brands of intraosseous devices) have demonstrated adequate flow rates by using the tibia and malleolus but that higher rates are attainable with the humerus and femur.[54] Because the goats in our study were healthy, active, and housed in small groups, external portions of the intraosseous catheters likely were subjected to more movement and trauma than might occur in clinical situations. In addition, the thicker cortex of the humerus in the goats may have provided greater physical stability than did the thinner cortex of the tibia. Furthermore, the approximate 45° exit angle of the cap in a humeral catheter was such that it likely could withstand torque and forces better than might the caps of tibial device caps, which exit the skin at a 90° angle medially. However, all devices that remained in place were comparable in terms of initial function and likely could be used with ease for administration of fluids and medications in emergency clinical situations. Although the healthy status of the goats might be viewed as a limitation of the current study, most of the intraosseous devices placed within long bones remained quite functional.

Intraosseous catheters would likely be an alternative emergency, bridging method in compromised, hypovolemic, and possibly recumbent animals. In such cases, these devices would be exceptionally useful and provide a rapid means of fluid, blood, or drug administration until venous access could be acquired at a later time. Proximal humeral devices in our study lasted 3 to 4 d, and one tibial device lasted 4 d prior to removal. In a recumbent or ill animal, these catheters likely would remain patent even longer, because they would not experience the movement and trauma associated with healthy animals. Although our study indicated that catheters generally can remain in place safely for longer than the currently approved 24 h, we noted more side effects as duration increased.

All goats remained bright, alert, and active throughout the study. Although baseline and postplacement blood cultures and catheter cultures of some animals did show growth, the bacterial species isolated are ubiquitous in soil and farm animals. Whereas 2 goats in study 1 received antibiotics after catheter removal as a precaution for swelling or associated lameness, all of the remaining 7 animals remained healthy and active with no clinical sequelae regardless of whether positive cultures were obtained. In comparison, 4 of the 18 animals in study 2 were treated with antibiotics after developing mild lameness or swelling. Again, the clinical signs did not show a particular correlation with CBC changes or culture growth results. Although close monitoring of any ill or immunocompromised patients that have jugular or intraosseous catheters is advisable, the positive cultures results in the current study likely were due to skin and environmental contaminants acquired during blood collection and device removal. Additional studies are needed to confirm this interpretation of the data.

Because of the preliminary nature of the current study, the number of animals used was small. However, we determined that with proper placement and management, these intraosseous devices may be left in place for greater than 24 h (which the device is currently approved for during use in human medicine) with few complications. Different anatomical locations may potentially provide similar stability, but perhaps be subject to less force by the animal's body weight during normal activity, or in a recumbent animal.

The drills needed to insert intraosseous catheters are easy to use correctly after only brief instruction. They are portable and generally take less than 1 min to prepare and insert with a 96%

to 100% successful placement rate.[6,31] Previous studies in human medicine have shown that most nurses, medical students, physicians, and first-responders placed intraosseous devices successfully and quickly after a short training session.[11,16] This training approach could easily be extended to technicians and veterinarians in clinical, research, and teaching facilities.

Agents administered into the intraosseous space are first absorbed into venous sinusoids and then travel rapidly into the central venous channel and systemic circulation,[48,49] reaching the heart within 10 s. Many drugs, including glucose, lidocaine, calcium chloride, and epinephrine, reach a peak effect within 30 to 45 s.[33,44] An added benefit of the intraosseous system is that these sinuses, unlike many peripheral veins, remain open during shock or hypovolemic situations.[23,50] In most cases, medications and anesthetics administered at an intravenous dose by the intraosseous route have equal distribution and effect.[4,9,26,28,37,42,45,52,53] Some antibiotics, such as ceftriexone, may reach slightly lower, but generally comparable, serum levels when given intraosseously instead of intravenously.[37] This difference may need to be considered if a loading dose of antibiotic is desired, as in cases of suspected sepsis or meningitis. In such situations, the highest manufacturer-recommended dose may be warranted during intraosseous administration. Fluids and blood transfusions are equally effective when given intraosseously or intravenously.[36,43]

Contraindications to the use of intraosseous catheters include infection, injury, and cellulitis over the insertion point and damage or fracture of the bone intended for use.[13] Intraosseous devices are not recommended for patients known to be bacteremic. Although most fluids and medications can be given intraosseously, very alkaline or hypertonic solutions should be diluted prior to administration to help avoid medullary damage and subsequent development of osteomyelitis.[15] In addition, several cases of osteomyelitis in children developed after intraosseous delivery of hypertonic solutions, including 5% sodium chloride, which can cause marrow necrosis and damage to the endosteum.[3,30] Sodium bicarbonate injections may cause mild inflammatory changes within the surrounding bone marrow cells[45,47] and minor increases in skeletal turnover.[24] Dextran 70 can also cause minor disruption of the medullary cavity. Many of these clinical cases of osteomyelitis were documented in the late 1940s; the current percentage of osteomyelitis due to intraosseous catheter use in human patients is thought to be less than 0.6% of all cases,[41] likely due to improvements in aseptic technique and antibiotic administration. The potential for fat and bone marrow pulmonary emboli is also a concern after aggressive intraosseous infusion.[17,32] However, emboli can be found in patients with or without damage to bone, and in most cases, these risks are outweighed by the many benefits of intraosseous cannulation in emergency situations. Complication rates are relatively low, although the devices should be monitored closely. Punctures in the opposite cortex and extravasation of fluids may result in decreased efficacy, pain, and compartmental syndrome after placement or with multiple attempts at cannulation.[8,27,40] Unintentional displacement is considered one of the most common complications associated with intraosseous catheters.

In summary, intraosseous catheter devices are simple to use, portable, quickly placed, require minimal training to use, and have immense potential for use within many different veterinary settings when intravenous access is not immediately available. The automatic drill devices are useful in larger or adult bones, for which manual placement of catheters may be difficult and time-consuming. Several studies have shown no long-term, negative sequelae in swine,[10,24,51,53] and our initial study in a goat model further supports these previous findings. The device we used in the current study can be placed with or without local anesthesia, saving valuable time and resources. Although venous access remains the 'gold standard' for emergency drug and fluid administration, intraosseous devices provide a valuable alternative bridging technique for quick administration of potentially life-saving fluids and therapeutics.

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