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Plate failure by bending following tibial fracture stabilization in 10 cats

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Objective: Describe the clinical findings and management of tibial fractures in cats in which plate osteosynthesis failed due to plate bending.

Study Design: Multicentre, retrospective clinical study.

Methods: Clinical histories and radiographs of 10 cats that suffered plate bending following plate or plate-rod fixation of tibial fractures were reviewed for signalment, fracture configuration and repair, post-operative and post-failure tibial alignment, ultimate treatment and outcome. Tibial alignment post-operatively and post-failure was compared using a paired T-test.

Results: Mean age was 5.3 years and mean body weight was 5.0kg. All ten cats sustained complete fracture of the tibia with an accompanying fracture to the fibula. Tibial fractures were generally oblique (4/10) or spiral (4/10) with mild comminution (8/10) and located in the middle (3/10) or distal (6/10) third of the tibia. Initial fracture stabilisation was with a plate (6/10) or plate-rod combination (4/10) with the plate applied to the medial tibial surface. Non-reduced, lateral tibial wedge fragments were present in 5 fractures. Mean time to implant failure was 24 days. Mean tibial valgus angle increased from 12.9° to 30.9° following bending of the plate ($p=<0.01$). Revision surgery was performed in 6/10 cats using orthogonal plating (4/10); stacked medial plates (1/10) or a combination of a stacked medial plate with an orthogonal cranial plate (1/10). Short-term outcome following revision surgery was favourable with improvement in tibial valgus in all 5 fractures with follow-up data ($p-<0.05$).

Conclusions: Bending of plates applied to stabilise tibial fractures in these 10 cats caused tibial valgus deformation. Implant failure was commonly associated with a reduced *cis*-cortex, but a non-reduced lateral tibial wedge fragment. Attention to plate and/or pin selection and application should be made to avoid stress overload of the plate. Revision using orthogonal plating or stacked medial plates was uniformly successful.

Introduction

There are few reports documenting outcome following tibial fracture repair in the cat. In a review of 66 cat tibial fracture repairs with known outcome 5% showed delayed healing, 14% healed as a malunion and 5% developed nonunion (Richardson & Thacher, 1993). The tibia is reported to be a common site of nonunion in the cat (Nolte *et al*, 2005). Fracture location in nonunion cases typically involves the distal tibia (McCartney & MacDonald, 2006; Witte *et al*, 2014). Detailed descriptions of implant failure following plate osteosynthesis of cat tibial fractures are limited. Richardson & Thacher, 1993, report malunion following open reduction and internal fixation of a cat's tibia with a plate, but further details were not given. Plate failure in 6 of 62 dog and cat fractures repaired using a polyaxial locking plate system is documented (Barnhart *et al*, 2013). These included 3 broken plates, 3 bent plates resulting in malunion and 1 bent plate associated with a nonunion. The femur was the predominant bone involved but a broken plate associated with a fractured tibia was reported but not described in detail (Barnhart *et al*, 2013). Malunion with valgus angulation has been reported following external coaptation of a cat mid-diaphyseal tibial fracture (Harari, 2002). Valgus deformation with plate bending two days following fixation of a closed spiral fracture of the tibia in the dog has also been reported (Schwandt & Montavon, 2005). Revision surgery with a plate-rod combination was successful in this case.

The objective of this retrospective study was to describe the features and management of plate failure by bending follow tibial fracture stabilization in 10 cats.

Material and Methods

The medical records from July 2007 to July 2013 of five veterinary orthopaedic referral institutions were searched to identify cats which sustained a bent plate following tibial fracture stabilisation.

Signalment and fracture description

The following parameters were documented for all cases: breed, sex, age, neuter status, and body weight. Cause of injury and time from tibial fracture to primary surgical stabilisation was recorded. Any concomitant injuries were noted. Fractures were classified using descriptive terms (transverse, oblique and spiral) defined previously (Piermattei *et al*, 2006).

Comminution was described as none, mild (3 fragments), moderate (4 or 5 fragments) or severe (>5 fragments) (Nolte *et al*, 2005). Degree of displacement was assessed as none, mild (>50% cortical contact between main fragments), or severe (no contact between bone fragments or overriding) (Nolte *et al*, 2005). Fracture location within the tibial diaphysis was approximated to the proximal, middle or distal thirds. The presence or absence of a fibular fracture was noted. Open fracture type was classified using the Gustilo-Anderson classification scheme (Gustilo & Anderson, 1976).

Fracture treatment description

The following variables were retrieved from clinical records or assessed from postoperative radiographs: plate type, plate position, implant dimensions, screw density, plate bridging ratio (PBR), plate span ratio (PSR) and working length of the plate (Pozzi *et al*, 2013) (Figure 1). For plate-rod combinations the percentage fill of the medullary canal at the isthmus of the tibia by the intramedullary rod (IMR) was recorded.

Fracture reduction and limb alignment

Postoperative radiographs were evaluated and any deviations from standard AO plate application technique and implant selection were noted. Tibial length was measured as the distance from the proximal tibial joint centre (PTJC) to the distal tibial joint centre (DTJC) on the craniocaudal (CC) radiograph (Radasch *et al*, 2008) (Figure 1). Fracture span was estimated by measuring the distance between the ends of major fracture segments and recorded as a percentage of tibial length (Figure 1). Fracture apposition was estimated by measuring the dispersion of the fracture fragments. The distance between the outermost fracture fragments on the CC and ML radiographic projections was subtracted from the mid-diaphyseal tibial diameter and expressed as a final percentage of the mid-diaphyseal diameter (Guiot & Déjardin, 2011). Apposition was recorded as good, adequate or un-acceptable when dispersion was <50%, 50 – 100% or >100% respectively.

Alignment in the frontal plane was assessed by calculation of the mechanical medial proximal tibial angle (mMPTA) and mechanical medial distal tibial angle (mMDTA) (Dismukes *et al*, 2007) (Figure 2). Using these values the tibial varus-valgus angle (TVA) was calculated as previously described where TVA = [mMPTA + mMDTA] – 180 (Guiot & Déjardin, 2011). Postoperative tibial plateau angle (TPA) was used as a measure of alignment in the sagittal plane (Guiot & Déjardin, 2011; Baroncelli *et al*, 2012). Assessment of TPA was made using the method described by Warzee (Warzee *et al*, 2001) (Figure 3).

Tibial torsion (TT) was assessed from the CC radiograph. With the frontal plane of the distal femur parallel to the imaging plane (i.e. the patella centred over the width of the distal femur and the fabellae (if present) bisected by their respective femoral cortices) the distal tibial orientation was assessed. The distance between the medial surface of the calcaneal tuber and distal intermediate ridge of the tibia on the CC projection was measured. This distance was divided by the distance between the most proximal points of the 2 arciform grooves of the cochlea tali of the tibia and multiplied by 100 to give percentage distal tibial rotation (DTR) (Dismukes *et al*, 2007; Swanson *et al*, 2012). Values greater than 50% were considered to denote excessive rotation of the limb (positional or TT). To standardise for limb position, TT malalignment (i.e. internal or external rotation of the distal tibial bone segment relative to the proximal tibial bone segment) was only recorded if DTR was greater than 50% and rotational deformation was noted in the clinical records. If these criteria were not satisfied, or if the frontal plane of the femur was not parallel to the imaging plane, TT was classified as ‘unable to assess’.

Plate failure

The time from primary surgical repair to detection of plate failure was recorded. The same criteria used to assess postoperative tibial alignment following fracture reduction were used to assess tibial alignment after plate failure. Postoperative and post-plate failure TVA and TPA values were compared using a paired T-test. The location of plate bending was recorded with reference to the proximal and distal screws closest to the fracture site. Medical histories were reviewed to attribute a lameness score to the cat at first presentation with the bent plate. Lameness was retrospectively graded as 0: no lameness; 1: subtle weight-bearing lameness; 2: obvious weight-bearing lameness; 3: intermittent non-weight bearing lameness; 4: consistent non-weight bearing lameness (Radasch *et al*, 2008). Where a lameness score was not possible a description of the presenting signs was summarised.

Final clinical outcome

Outcome following plate bending was described for each cat. If surgical revision was performed, the fixation method was recorded. Medical histories and radiographs were then reviewed to summarise the final outcome for each case at the last recorded examination.

Results

Ten cats sustained a bent plate following tibia fracture stabilisation (Table 1). Eight of the ten cats were male and all cats were neutered. Mean ± SD age at time of trauma was 5.3 ± 4.1 years (range 1 - 13 years) and mean body weight was 5.0 ± 1.2kg (range 3.7 - 6.8kg).

One cat had multiple orthopaedic injuries. All fractures were complete tibial fractures with accompanying fracture to the fibula (n=10). Tibial fracture pattern was either oblique (n=4), oblique and spiral (n=4) or transverse (n=2). Fracture comminution was mild (n=8), moderate (n=1) or severe (n=1). Moderate (n=2) or severe (n=6) fracture fragment displacement was seen. Pre-operative radiographs were unavailable for two cases. Isolated lateral wedge fragments (LWFs) were identified in five fractures. Radiographic evidence of fissure lines extending from the fracture site was seen in 5 cats. Fracture location was the distal third (n=6), middle third (n=3) or proximal third (n=1) of the tibial diaphysis. Mean fracture span was 16.2 ± 8.1% (range 6 – 32%) of tibia length. Fractures were grade 1 open (n=5) or closed (n=5). There were no grade 2 or grade 3 open fractures. Fracture treatment consisted of medial plating (n=6) or medial plating with an IMR (n=4) (Table 2). Additional cranio-caudally directed screws were placed in 3 cats during fracture reconstruction.

All surgeries were performed within 4 days of trauma. Four different plate types were used for fixation: 2.0mm Dynamic Compression Plates (DCP) (n=3), 2.4mm DCP (n=3), 2.0mm Limited Contact-Dynamic Compression Plates (LC-DCP) (n=2) and 2.0/2.7mm Veterinary Cuttable Plates (VCP) (n=2). Plate thickness was 1.5mm (n=7) or 2.0mm (n=3); mean plate width was 6.0mm (range 5.0-7.0mm). All plates and screws were constructed from 316L stainless steel. Screw sizes used for plate fixation were 2.0mm (n=8) and 2.4mm (n=2). 2.7mm screws were used as positional screws to maintain reduction in addition to plating in two cases. Intramedullary Kirschner wires were used (diameter: 1.6 mm (n=3) and 1.25 mm (n=1)) in four fractures. Mean IMR fill at the isthmus of the tibial medullary cavity was 33.2 ± 5.5% (range 28-41%). Plates were used in bridging (n=6) or neutralisation mode (n=4). For the two transverse fractures mean PBR was 0.48, mean PSR was 6.9, mean plate working length was 8.5% of tibial length and mean PSD 0.95. For oblique and spiral fractures with comminution (n=8) mean PBR was 0.76, mean PSR 4.1, mean plate working length 27.5% of tibial length and mean PSD 0.62. Unincorporated lateral wedge fragments were evident in all 4 fractures when reconstruction of the fracture had been attempted.

Calibrated contralateral tibial radiographs were available for 3 cases. Mean ± SD TVA and TPA for the unaffected limbs was 9.1° ± 1.9° and 23.0° ± 4.5° respectively. Post initial fracture repair tibial length was 95-99% of contralateral tibia length. Measurements of post-operative tibial alignment are shown in Table 3. In the frontal plane measurements for mMPTA and mMDTA for all initial fracture repairs fell within the reported reference range for this species (Swanson *et al*, 2012). Mean ± SD calculated TVA was 12.9 ± 4.4°. Mean postoperative TPA (22.6 ± 1.9°) was also within the reference range reported in normal cats (Schnabl *et al*, 2009). Postoperative radiographic rotational malalignment with external tibial torsion was apparent in two cases. Fracture apposition was good (n=9) or adequate (n=1) in the frontal plane and good (n=9) or adequate (n=1) in the sagittal plane. Postoperative management consisted of cage confinement until a review at 6-7 weeks (n=6). Details of postoperative management were unavailable for four cats.

Minor short-term complications were reported in three cases all of which resolved with conservative treatment. Case 8 required a repeat surgery to correct a torsional malalignment four days following initial surgery. The plate in this case was removed, re-contoured and reapplied to correct the external rotation of the distal fragment. Tibial plates failed by plastic deformation in all 10 cases (Table 4). Radiographic evidence of plate breakage or screw loosening was not identified. Bending of the plates occurred immediately distal to the proximal screw closest to the fracture line (n=4), approximately midway between the proximal and distal screws closest to the fracture (n=5) and in case 8 the plate bent approximately one third of the distance between the proximal and distal screws closest to the fracture.

Mean ± SD time to failure was 24 ± 19 days (range 2 – 56 days). For two cases there were reported episodes of jumping out of the window (n=1) or unrestricted access to the garden (n=1) prior to plate bending. For 8 cases there was no known traumatic incident associated with bending of the plate. Abnormal stance was noted in 8/10 cats with clinical evidence of tibial valgus noted in 4/10 cats. Cats were attributed a lameness score of 1/4 (n=6) at time of first presentation after tibial plate bending. A lameness score for 4/10 cats could not be assigned due to insufficient detail in the clinical notes. Mean ± SD mMPTA and mMDTA after plate failure was 97.3 ± 2.7° and 113.6 ± 6.3° respectively. Eight measurements of mMPTA and 4 measurements for mMDTA were greater than the reported reference range in the cat (Swanson *et al*, 2012). Mean ± SD TVA was 30.9 ± 6.5°. Post failure TVA was significantly elevated from the primary surgery postoperative TVA measurement confirming tibial valgus resulting from bending of the tibial plate ($t(9)=2.26$, $p<0.01$). Mean ± SD TPA was 22.7 ± 3.0° with no difference apparent from immediate postoperative TPA measurements ($p=0.84$). There was no evidence of torsional malalignment following plate bending in seven cases. Rotational alignment was unable to be assessed in two cases and in one case external TT of the distal limb was present.

Six of the ten cats had revision surgery following plate failure. Three cats were managed conservatively due to financial constraints and an owner perception that their cat was coping sufficiently well (n=2) or for unknown reasons (n=1). Case 9 was taken to a different veterinary clinic where the cat was sedated and the implant manually straightened *in-situ*.

Further follow up data was unavailable for this case. Of the six cats managed surgically treatment was with: application of an additional orthogonal plate to the cranial aspect of the tibia (n=4); application of stacked plates on the medial aspect of the tibia (n=1); or a combination of stacked medial plates with an orthogonal cranial plate (n=1). Outcome was unavailable for the conservatively managed cats (n=3). Five of six cats that underwent revision surgery had outcome data with a mean follow-up of 8.3 weeks (range 6-12 weeks). TVA was improved for all 5 revision cases where alignment was able to be assessed (t(4) = 2.8, p=<0.05). Revision surgery mean ± SD TVA and TPA was 12.2 ± 3.5° and 20.6 ± 0.9° respectively. Case 5 had mild tibial valgus with mMPTA above the normal reference range and a TVA of 18°. No evidence for torsional malalignment was seen except for case 8 although this could not be distinguished from radiographic positioning versus true TT. Cats that underwent revision surgery were reported to have no lameness (n=6) and no gross abnormalities of limb alignment (n=6).

Discussion

Initial tibial fracture location and configuration in this study was consistent with that previously reported in the cat with spiral, oblique and comminuted fractures of the middle and distal third of the diaphysis predominating (Boone *et al*, 1986; Richardson & Thacher, 1993; Zaal, 1996; Brunnberg, 2003; Guiot & Déjardin, 2011). Radiographic evidence of fissure lines extending from the fracture site was seen in 5 cats. Implant failure, by plate bending, caused tibial valgus deformation in all ten cats. The exact stress distribution under axial compression in the cat tibia is unknown. The human tibia under axial loading creates tensile strain in the craniomedial portion of the tibia and compressive strains in the remainder of the bone (Eckenman *et al*, 1998). All initial fracture repairs in this study were performed with medial plating with or without an IMR. Loading direction has a profound effect on plate stiffness. Medial plating of the tibia provides greater stiffness in the sagittal plane than the frontal plane (Figure 1). Stiffness of the plate in the frontal plane is proportional to the cube of the plate thickness. Due to cat size and narrow distal tibia, plates recommended for cat tibia fracture stabilisation are small (See Table 5). They are proportionally less stiff than plates used for larger animals. The low area moment of inertia (AMI) of the plate construct in the frontal plane and tensile strain in the medial portion of the tibia under axial loading could explain the tibial valgus deformation when plate bending occurred in these cases.

Plate deformation occurs due to a plate strain environment that exceeds the bending moment of the plate. The time to this failure will depend on the interplay of strain magnitude above the yield point of the plate and the number of load cycles (Hulse & Hyman, 1991. Muir *et al*, 1995). A plate under high strain would be expected to fatigue after a smaller number of load cycles than a plate under a lower strain environment. The range in time from fracture fixation to plate bending in this study was 2 to 48 days. This variation was likely due to differences in the AMI of the plate construct as well as the unique load conditions applied to each plate. Patient factors, including body weight and activity, also vary the magnitude, direction and duration of applied forces to the plate. Mean body weight of cats in this study was 5.0kg and three cats weighed more than 6.5kg. All owners of cats in this study were instructed to provide cage confinement until a review at 6-8 weeks. Despite this two cats were known to have unrestricted activity during the initial convalescent period.   It is possible for these cases plate bending was due to a single catastrophic event associated with overloading of the plate. However, for the majority of cases implant failure by plate bending was proposed to occur by cyclic fatigue.

The mechanical environment at the fracture site has a profound impact on plate strain. Five cats had tibial fractures with isolated lateral wedge fragments. Following fixation with medial plating these defects in the lateral, compressive, side of the tibia remained. Failure to reconstruct the transcortex negates load sharing between the plate and bony column and exaggerates the bending moment acting on the plate. The bending moment applied to an implant under axial compression is proportional to the eccentricity of the axial load vector with respect to the centroid of the load transfer cross section. That is to say when load sharing with the bone is not achieved the plate undergoes an increased bending moment as well as an increased load. Plate strain on axial loading is concentrated through the plate spanning the fracture gap (Maxwell *et al*, 2009). This stress riser effect is increased at plate holes due to the reduced AMI of the construct at this point. For several fractures a long plate working length was used to bridge a short fracture gap. Increasing the working length of the plate aims to reduce plate strain by allowing deformations to be accommodated over a longer length of the plate. However, all initial fracture fixations in this case series utilized conventional plating systems. These plates rely on friction between the plate and the bone and attempts to bridge a short fracture span with a long plate working length using a conventional friction plate may not reduce plate strain at the fracture gap (Maxwell *et al*, 2009). A short fracture span generates a region of high interfragmentary strain. The fracture span of seven initial fracture configurations in this case series was less than 15% of tibial length.

Four of the initial fracture repairs in this study utilised a plate-rod construct. IMR size in the cat tibia is limited by both the cat's size and by the distal narrowing of the medullary cavity. Clinical findings from biomechanical testing of canine femora show combination of an IMR that occupies 30%, 40% and 50% of the marrow cavity with a bone plate reduce internal plate strain by 19%, 44% and 61% respectively (Hulse *et al*, 2000). The authors recommend the use of a rod which occupies 35%-40% of the diameter of the medullary cavity. Three of the four cases of fracture repair with a plate-rod construct in this study utilized an IMR that, at the isthmus of the tibia, was below 35% diameter of the medullary cavity. By using an increased diameter IMR, internal plate strain could have been reduced in these cases and may have increased the fatigue life of the plate sufficiently to allow fracture healing. Care should be taken when extrapolating recommendations of IMR size from the canine femora study to the cat tibia. AMI for a cylindrical object is calculated from the fourth power of the radius. Small diameter K-wires are proportionally less stiff and may not provide for a comparable protection of plate strain as that provided by the larger diameter Steinmann pins. Further biomechanical testing of the small K-wire-plate constructs used in cats is warranted before a recommendation of implant size can be made.

The tibia is a common site of nonunion in the cat (Nolte *et al*, 2005). This is due, at least in part, to the biological environment of the fracture. 5/10 cats in this case series had a grade 1 open fracture. This is consistent with a review of 80 cat tibia fractures that identified 46% as open fractures (Richardson & Thacher, 1993). In humans, the most common site for nonunion is the distal tibia (Boyd, 1961). Human tibial fractures are commonly open and are susceptible to stripping of the periosteum (Court-Brown & McBirnie, 1995). This, together with the limited soft tissues surrounding the middle and distal tibia, can limit extraosseous vascular support during fracture healing (Trueta, 1974). Particular to cats is a proposed lack of diffuse arborisation of the intramedullary arterial circulation to the middle and distal tibia (Dugat *et al*, 2011). This may further limit the vascular response during tibia fracture healing. A delayed or nonunion will extend the time period before load is shared between the callus and the implant construct. Anatomic reduction and interfragmentary compression to promote primary (direct) bone healing with load sharing between the bone column and implants was not possible for any of the 10 fractures in this study. Fracture healing must be assumed to have been occurring by secondary (indirect) healing. Healing of cortical bone in the cat tibia, following plate fixation, has been reported at 12.5 weeks (Richardson & Thacher, 1993). Mean time to plate bending in this study was 24 days. Implant failure can occur as a result of mechanical or biological processes or both (Hulse & Hyman, 1991). The time period to plate bending in these cases suggest mechanical, rather than biological, factors had a greater influence on fixation failure.

Management of implant failure by plate bending in the cat tibia has not been reported. Revision surgery using orthogonal plating or stacked medial plates was uniformly successful in this study. Both techniques were found easy to perform. Orthogonal plating with a medial and cranial plate has been described for the management of cat distal tibial fractures (Fitzpatrick, 2013). Orthogonal plating provides greater stiffness to lateromedial bending and fails at a higher axial compressive load than single plating or plate-rod constructs (Glyde et *al,* 2011). Stacked VCPs create a superior construct with respect to bending stiffness and cyclic fatigue when compared to comparably sized DCP, LC-DCP or VCP constructs (Fructer & Holmberg, 1991; Hammel *et al*, 2006). With advances in plate osteosynthesis, including locking plate technology, a greater variety of plate sizes and types are now available to the veterinary orthopaedist. When considering implants for clinical stabilisation of cat tibial fractures, the biology and mechanics associated with healing needs to be considered. Attention to plate and/or pin selection and application should be made to avoid stress overload of the plate. Further ex-vivo biomechanical testing of the cat tibia is indicated to determine appropriate implants that provide a suitable microstrain environment to stimulate bone healing but avoid fixation failure by plate bending. None of the 10 cases of plate bending in this study showed radiographic evidence of screw loosening or pullout. This is consistent with the ex-vivo biomechanical testing of VCP plates by Hammel *at al*, 2006 where no implants failed by screw pullout, breakage or loosening. The strength of plates with 2.4mm screws was not significantly different from those of comparable plates with 2.0mm screws (Hammel et al, 2006). This could give greater credence to the use of a smaller screw size when performing plate osteosynthesis in the cat tibia and may be especially relevant in orthogonal plating.

The longer the bone the greater the magnitude of the bending moment caused by the application of a force. Further study as to the relative length and diameter of the cat tibia is justified to determine if this bone is subjected to particularly high bending moments. High tensile and compressive stresses could contribute both to implant failure by plate bending and the higher incidence of nonunion seen in this bone.

The retrospective nature of the study and the small number of cases reported are the major limitations of this study. Collating data from more institutions over a longer period would be an appropriate way to increase the case numbers observed and reported. Comparing these cases to a control group of cat tibia fractures that had not failed may allow identification of risk factors for plate bending. This was beyond the scope of this study. Notwithstanding these limitations, this study reports the type of deformation of the plate following bending and reports the successful management of this complication.

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