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# Clinical outcomes of canine total hip replacement utilizing a BFX lateral bolt femoral stem: 195 consecutive cases (2013–2019)

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**Abstract**

**Objective:** To evaluate the clinical outcomes of total hip replacements (THR) utilizing a BFX lateral bolt stem in dogs with coxofemoral joint disease.

**Study design:** Retrospective study.

**Sample population:** A total of 149 dogs representing 195 THR.

**Methods:** Consecutive THRs utilizing a BFX lateral bolt stem were studied. Preoperative, immediate postoperative, 1-, 2-, 3-, 4-, and 12-month postoperative radiographs were performed. All major and minor complications, revisions, outcomes, subsidence, canal flare index (CFI) were recorded.

**Results:** An intraoperative complication rate of 11.8% was observed. The postoperative complication rate was 13.6%, with 9.2% major and 4.4% minor complications. Complications included: postoperative femur fractures (3.6%), coxofemoral luxation (3.6%), stem failure (0.5%), septic loosening (0.5%), aseptic loosening (0.5%), and acetabular fracture (0.5%). Three dogs underwent prophylactic plating after subjective assessment of cortical thickness. Five of 195 (2.6%) cases underwent explant of their prostheses (median = 3 months). Mean stem subsidence at 1 month postoperatively was 1.22 ± 0.16 mm. An increased CFI was associated with postoperative femur fractures ($p < .05$). A total of 190 of 195 (97.4%) cases returned to normal function in the long-term follow-up period.

**Conclusion:** Use of the BFX lateral bolt stem resulted in minimal postoperative subsidence, a low femoral stem complication rate, and a high rate of achieving normal limb function.

**Clinical significance:** The BFX lateral bolt stem should be considered in canine THR as the femoral failure rate is low and the long-term success rate is high.

## 1 | INTRODUCTION

Total hip replacement (THR) is a procedure commonly performed to treat coxofemoral joint disease in humans and dogs. Total hip replacement can be used to treat severe coxofemoral pathology, including avascular necrosis of the femoral head,[1] capital physeal fractures,[2] chronic luxation,[3] and coxofemoral osteoarthritis secondary to canine hip dysplasia.[4–5] Complications of cementless THR include: femur fractures (6.8%–13.1%),[6–8] intraoperative femoral fissures (3.6%–21%),[6–10] stem migration (2.7%–8.1%),[6,9] and coxofemoral luxation (3%–13.5%).[10–11]

One commonly used cementless THR system (BFX, Biomedtrix) relies on initial press-fit of components into a prepared acetabular and femoral bone bed to allow for subsequent permanent bony ingrowth, otherwise known as osseointegration.[12] In order to allow for osseointegration, micromotion at the implant-bone interface should ideally be less than 20-μm.[13] Subsidence is defined as postoperative femoral stem distalization.[14] In humans, maximal stem subsidence is observed within the first 6–8 weeks of surgery.[15–16] Early weight-bearing compressive forces can result in subsidence, which may lead to fissures that propagate from the medial calcar of the femur. Femoral fractures have been associated with subsidence along with other risk factors such as osteopathies, iatrogenic fissures created during broaching, abnormal femoral conformation, low CFI, and stovepipe-shaped femurs.[7,17] Postoperative fracture complication rates range from 6.8% to 13.1% after the use of the BFX femoral stem.[6–8]

Various methods have been adopted to try to combat subsidence, including the use of cerclage to prevent fissure propagation,[18] a collared stem,[19] and the development of a stem with a lateral bolt (BFX lateral bolt, Biomedtrix). The BFX lateral bolt incorporates a bolt inserted through the lateral femoral cortex and engages the lateral aspect of the femoral stem.[20] In an ex vivo biomechanical study, the BFX lateral bolt enhanced stability and limited subsidence compared to the traditional BFX femoral stem under cyclical loading. Failure loads were 66% higher for BFX lateral bolt stems with failure occurring at supra-physiological loads.[20] Unlike the traditional BFX implant, the BFX lateral bolt more frequently resulted in distal spiral fractures that did not propagate from the medial calcar.[21] The BFX lateral bolt exhibited significantly higher torsional stiffness when compared to the collarless, collared, and short stem THR constructs.[21]

To date, there are limited clinical studies available in the veterinary literature assessing the BFX lateral bolt. A recent study demonstrated that use of the BFX lateral bolt led to less postoperative subsidence compared to the BFX collared and traditional BFX stems.[22] Based on previous studies, we postulated that the BFX lateral bolt could be successfully utilized in dogs undergoing THR surgery and would reduce previously observed subsidence-related stem complications.

## 2 | MATERIALS AND METHODS

### 2.1 | Inclusion criteria

Medical records of the first 205 consecutive cases (August 2013 through September 2019) utilizing a BFX lateral bolt were retrieved. Every dog undergoing a THR was implanted with a BFX lateral bolt stem if an appropriately sized implant was available. Dogs that received a discontinued generation of the BFX lateral bolt, or dogs for which the lateral bolt stem constituted a revision implant from a previous nonaugmented stem THR, were excluded. If the same dog had bilateral THR, each side was considered as an individual case and evaluated separately. Dogs were included with a minimum of 1 month of radiographic follow-up. Long-term follow-up was considered 1 year or greater. Owners who did not return for long-term re-evaluation were called and surveyed via telephone to inquire the dogs' function at home as part of routine postoperative follow-up. A brief follow-up inquiring how the dogs' function, and the owners' satisfaction level was performed; no scale was provided.

### 2.2 | Data retrieved

Information obtained from medical records included: breed, gender, bodyweight and condition (BCS), surgery date, indication for THR, laterality of procedure, and all clinical and radiographic follow-ups. Time frames for data collection, intra- and postoperative complications, management, and subjective outcome were recorded and classified as previously described for complications in orthopedic cases.[23] A modification was made to classify intra- and postoperative complications separately. An early postoperative complication occurred immediately postoperatively up to 3 months postoperatively. Short-term complications occurred between 3 and 6 months; mid-term between 6 and 12 months; and long-term at >12 months postoperatively. Minor complications did not require surgical intervention, whereas major complications did. Catastrophic complications caused permanent unacceptable function leading to death or euthanasia. Subjective outcomes were defined as: (1) normal function—restoration to full level of intended activities without evidence of lameness, pain, or necessity of non-steroidal anti-inflammatory drugs (NSAIDs); (2) acceptable function—restoration to intended activities from presurgical status but with intermittent pain or use of NSAIDs; and (3) unacceptable function—all other outcomes not allowing for return to intended activity.

### 2.3 | Surgical technique

Perioperative analgesia was provided by administration of a full-mu opioid along with an anxiolytic as needed. Antibiotics were administered intravenously at induction and repeated every 60 minutes throughout the procedure.

All THR surgeries were performed by American College of Veterinary Surgeon certified diplomates trained in the procedure using a craniolateral approach to the coxofemoral joint. Femoral stem size was predetermined using radiographic template measurements and adjusted, if necessary, intraoperatively. Final implant size was determined by a combination of preoperative digital templating and intraoperative assessment. Preparation of the acetabular bed was performed using standard techniques. Standard technique and instrumentation for BFX lateral bolt implantation was used as previously described.[20] If an intraoperative medial calcar fissure developed intraoperatively, one or two 16 or 18-gauge twist knot cerclage wires were placed circumferentially around the proximal femoral metaphysis prior to stem impaction.

Prophylactic plating was elected based on a combination of factors including: subjective radiographic assessment preoperatively, intraoperative assessment of the femur, and owner compliance with postoperative restrictions. To obtain exposure of the femoral shaft, the craniolateral approach was extended distally. A size 10 or 11 locking plate (ALPS, Kyon) was contoured to the lateral aspect of the femur. The third proximal-most hole was over-drilled to engage the lateral bolt, with the remainder secured using locking and cortical screws.

Postoperative radiographs confirmed implant position. Dogs were hospitalized for a minimum of 2 days postoperatively with opioid analgesia administered as needed. NSAIDs were recommended for 2 weeks, dependent on clinical progress. Oral antibiotic therapy was continued for 2 weeks postoperatively.

## 2.4 | Postoperative management

All dogs recovered in a cage with a nonslip surface and were allowed to weight-bear once completely awake. Dogs were supported using a sling under the abdomen to prevent splaying. After discharge, 2 months of confinement was recommended. Unrestricted activity was not allowed until after the third month. Controlled leash-walks with a sling used to control excessive lunging were advised. The length of walks was gradually increased with each recheck. No additional physical therapy was typically recommended or performed.

## 2.5 | Clinical evaluation

Dogs were re-evaluated postoperatively with follow-up examinations and radiographs recommended monthly for the first 4 months, at 12 months, then annually thereafter. The schedule was dependent on owner compliance. Subjective outcomes were determined by review of the dogs' medical records and phone follow-up.

## 2.6 | Radiographic evaluation

Radiographs were reviewed in DICOM viewing software (eFilm Workstation; Merge Healthcare) and imported into orthopedic templating software (Orthoplan; Sound-Eklin) for preoperative planning and stem position measurements. Radiographic projections were calibrated using a 25.4 mm sphere. Four radiographs were obtained, which included: an extended hip ventrodorsal projection of the pelvis, a lateral–lateral projection of the pelvis, a dorsal recumbent caudocranial projection of the femur, and a mediolateral projection of the femur. Radiographs were assessed for implant position, subsidence, femoral or acetabular fracture, luxation, loosening, or failure. All complications were recorded.

Using the caudocranial femoral projection, femoral stem position was measured as the distance from the proximal aspect of the greater trochanter to the impaction platform of the femoral stem. Subsidence was calculated as the difference between the stem position on the immediate postoperative radiographic projection and at one and 2 months postoperatively. CFI was evaluated on the caudocranial projection and calculated as a ratio of the endosteal width at the lesser trochanter divided by the endosteal width at the narrowest point of the femoral shaft.[15]

## 2.7 | Statistical analysis

The between and within dog variability of subsidence was quantified by means of a three-factor analysis of variance with the random factor of dogs and the fixed factors of leg and time. There was no evidence ($F$ test; $p = .44$) that between dog variability (0.72) was greater than within dog variability (0.65). Therefore, each individual leg rather than individual dog was considered as the experimental unit.

A total of 10 response variables (infection, subsidence, implant failure, explant, luxation, postoperative fracture, intraoperative fracture, nondisplaced fracture, intraoperative fissure, angle of lateral opening [ALO], return to normal function) and 21 factors were assessed (CFI, bodyweight, BCS, age, gender, castration status, breed [German Shepherd, Golden Retriever, Labrador, Mixed], side, anesthesia time, surgical time, femoral metrics: stem size, lateral bolt size, stem level, femoral anteversion, and cup-related metrics: angle of lateral opening, head size, and coronal retroversion). Data were assessed for normality using the Shapiro–Wilk test. Univariate comparisons of all combinations were performed using Fisher's exact test (categorical*categorical), Wilcoxon rank sum test (categorical*ordinal/continuous), or linear regression/

correlation (ordinal/categorical*ordinal/categorical) as appropriate. *p*-values were reported along with frequencies, mean/median/standard deviation, 25th and 75th quartiles, and $R^2$. Data were evaluated using a commercial statistical software package (NCSS Statistical Software, 2019; NCSS, LLC., available at: http://ncss.com/software/ncss). *p*-values <.05 were considered statistically significant.

## 3 | RESULTS

Of 205 cases evaluated, 10 dogs were removed from the study; records revealed eight cases utilized a discontinued generation of the BFX lateral bolt stem and two were revisions of a different manufacturer's stem. Therefore, 149 dogs representing 195 hips (92 left, 103 right) met the inclusion criteria for this study.

A total of 45 dogs underwent bilateral staged THRs; 105 underwent unilateral THRs. A total of 30 breeds were represented, including mixed breed (45), German Shepherd (35), Labrador (18), and Golden Retriever (15) (Table S1). Mean bodyweight was 32 kg (median, 31.5 kg; range, 13–76.6 kg) and mean BCS was 5.5. Mean age at surgery was 4.5 years (median 4.04, range 0.83–11 years). There were 77 males (72 castrated) and 69 females (68 spayed).

All dogs were presented for evaluation of pelvic limb lameness. The most common signs included lameness, bunny hopping gait, difficulty rising or jumping, and difficulty recovering from long periods of play or exercise. Reasons for surgery included coxofemoral osteoarthritis secondary to canine hip dysplasia ($n = 180$) and trauma ($n = 15$). Sequelae of trauma included luxation (craniodorsal = 3, caudoventral = 2), capital physeal fractures ($n = 8$), and luxation with concurrent femoral neck fracture ($n = 2$). Two dogs were previous amputees with severe hip dysplasia.

### 3.1 | Clinical follow-up

Physical and radiographic evaluations for the first 2 months were available for all but one dog that did not return after the first re-evaluation. A total of 11 (5.6%) were lost to radiographic follow-up after the second month. Three months of postoperative follow-up was available for 183/195 cases (93.8%). Long-term radiographic follow-up (>1 year) was available for 139/195 cases (67.8%). Mean radiographic follow-up for all THR was 1.4 ± 1.2 years (range 2–72 months). Overall, 190/195 cases (97.4%) returned to normal function, as defined by the owner's perception of outcome and lack of lameness and pain, with normal gait and function at rechecks. Unacceptable function was noted in 5/195 (2.6%) due to explant secondary to complications.

### 3.2 | Subsidence

Mean subsidence over the first month was 1.22 ± 0.16 mm. Increased bodyweight ($p = .0001$), BCS ($p = .001$), and stem size ($p = .02$), were strongly associated with subsidence at 1 month postoperatively. Canal flare index was not associated with subsidence (Table 1). No subsidence-related fractures or luxations were observed.

### 3.3 | Complications

#### 3.3.1 | Intraoperative complications

The intraoperative complication rate was 23/195 (11.8%). The majority of complications occurred during broaching. Medial calcar fissures were observed in 20/195 femurs (10.3%). Cerclage wires were placed around the proximal femur prior to implant impaction to restore hoop strength of the femur. No association was found between weight, BCS, age, or gender and the development of fissures. German Shepherd breed ($p = .01$), larger stem size ($p = .02$) and head size ($p = .01$) were associated with the development of intraoperative fissures.

Intraoperative fractures occurred in 3/195 cases (1.5%). Larger stem size ($p = .02$) and head size ($p = .01$) were associated with intraoperative fractures. One 10 month old dog with an incompletely closed physis developed a fracture of the greater trochanter during broaching of the femur and was repaired using a pin and tension band. One dog fractured the mid-diaphysis of the femur during broaching of the femoral canal. Another dog fractured the femoral diaphysis just distal to the BFX lateral bolt during reduction of the femoral head. Both fractures were repaired using ALPS bone plate and screws. All three dogs had a successful repair and recovery.

#### 3.3.2 | Minor postoperative complications

A 9/195 (4.6%) minor complication rate was observed. Five superficial surgical site infections were treated with a 2-week course of a second-generation cephalosporin. A seroma was noted in 1/195 cases (0.5%), which resolved with warm compresses. Sciatic neurapraxia was observed

**TABLE 1** Association between multiple factors and response variables. A *p*-value <.05 was considered significant

| **Stem size** | | | | |
|---|---|---|---|---|
| | **Median** | **25th percentile** | **75th percentile** | |
| No fissure | 8 | 7 | 9 | $p = .02$ |
| Fissure | 9 | 7.3 | 10 | |
| **Stem length** | | | | |
| | **Median** | **25th percentile** | **75th percentile** | |
| No fissure | 71.5 | 65.6 | 78.3 | $p = .01$ |
| Fissure | 79.2 | 69.4 | 87.5 | |
| **Stem level** | | | | |
| | **Median** | **25th percentile** | **75th percentile** | |
| No fissure | 11.5 | 9 | 14 | $p = .008$ |
| Fissure | 13.7 | 11.7 | 16.8 | |
| **Age** | | | | |
| | **Median** | **25th percentile** | **75th percentile** | |
| No fracture | 3.4 | 1.4 | 7.1 | $p = .01$ |
| Fracture | 7.3 | 4.2 | 10.6 | |
| **Stem size** | | | | |
| | **Median** | **25th percentile** | **75th percentile** | |
| No fracture | 8 | 7 | 9 | $p = .04$ |
| Fracture | 9 | 9 | 10 | |
| **CFI** | | | | |
| | **Median** | **25th percentile** | **75th percentile** | |
| No fracture | 1.9 | 1.7 | 2.00 | $p = .019$ |
| Fracture | 2.1 | 1.9 | 2.30 | |
| **Subsidence** | | | | |
| | | $R^2$ | | ***p*-value** |
| Weight | | 0.15 | | .0001 |
| BCS | | 0.06 | | .001 |
| Stem size | | 0.03 | | .03 |
| Canal flare index | | 0.0003 | | .81 |

Abbreviations: BCS, bodyweight and condition; CFI, canal flare index.

immediately postoperatively in 1/195 (0.5%), which resolved by 2 weeks postoperatively. An exuberant periosteal reaction along the femoral diaphysis was observed in 2/195 (1%) at 1 month postoperatively, consistent with a nondisplaced femoral fissure. These healed with strict rest (Figure 1).

One dog with a minor complication (surgical site infection) developed a major complication (femur fracture). The dog underwent revision surgery 5 months postoperatively due to septic loosening of the acetabular cup. No other dogs with a minor complication developed major complications.

### 3.3.3 | Major postoperative complications

Major complications were observed in 18/195 (9.2%) cases, including: femoral fractures (7/195, 3.6%), coxofemoral luxations (7/195, 3.6%), dorsal acetabular rim fracture (1/195, 0.5%), aseptic loosening of the acetabular cup (1/195, 0.5%), septic loosening of the acetabular cup (1/195, 0.5%), and femoral stem failure (1/195, 0.5%). Revision surgeries were successful in 13/18 (72.2%) without additional complications while 5/18 (27.8%) resulted in explant of the THR (median 90 days, range 61–910 days) (Table S2). One explant was secondary to

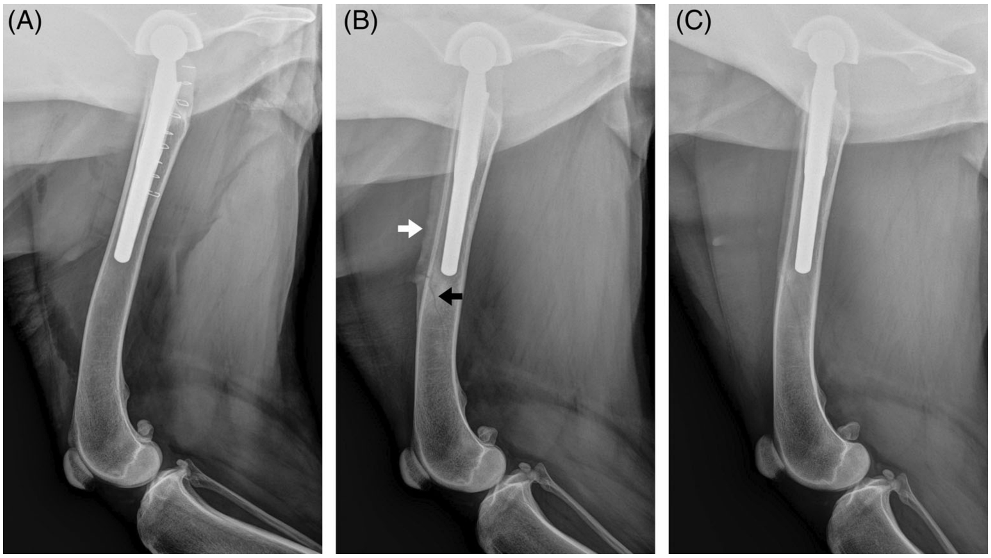


FIGURE 1 Radiographic projections of a postoperative nondisplaced femoral fissure. (A) Postoperative mediolateral projection showing appropriate implant placement with mild recurvatum tilt of the stem and no visible femoral fissure. (B) One month postoperatively with visible femoral fissure (black arrow) and minimal displacement just distal to the femoral stem. An exuberant periosteal reaction was observed (white arrow). Strict rest was recommended. (C) Three month postoperative radiographic projection showing remodeling of the periosteal reaction

femoral complications; four were related to complications involving the acetabular cup.

In the 3 months postoperatively, 14/18 complications (77.8%) occurred, including seven femoral fractures (median 4 days, range 2–12 days), six luxations (median 22 days, range 2–67 days), and a dorsal acetabular rim fracture at 30 days postoperatively. Two cases with intraoperative fissures developed postoperative fractures. Fractures were categorized based on the Vancouver classification as previously described;[24] five were classified as type B1, and two as type C. No fractures involved the medial calcar or the area of ingrowth of the femoral stems. Fractures were repaired using a locking plate system (ALPS) (Figure 2). Surgical revision was successful in 6/7 dogs. One dog failed primary fracture repair and underwent explant. Univariate analysis revealed the only factor associated with postoperative fractures was increased age ($p = .01$). In dogs with luxation, repositioning of the cup was successful in 5/6 (83.3%) dogs. One developed an avulsion fracture of the dorsal acetabular rim during cup removal, resulting in an explant. One dog fractured the acetabular rim fracture 30 days postoperatively, which resulted in explant.

In the short-term period, 2/18 complications occurred (11.1%). One dog with excessive proximal femoral valgus sustained a luxation at 120 days postoperatively (Figure 3). Visible dorsal polyethylene wear of the acetabular cup was evident during revision surgery. Owners declined revision and elected for explant of the prosthesis. Septic loosening of the acetabular cup was observed in 1/195 (0.5%). This dog initially developed a superficial SSI, which resolved with oral antibiotic therapy. A femoral fracture was observed 12 days postoperatively; fracture reduction and repair were uneventful. A weight-bearing lameness developed 5 months following fracture repair. Radiographs revealed lucency surrounding the acetabular cup. The acetabular cup was removed and cultured a *Pseudomonas* infection. Tobramycin-impregnated polymethylmethacrylate (PMMA) beads were placed into the acetabular bone bed along with oral treatment with marbofloxacin based on the culture. Cup revision was staged for 1 month later. The dog continued to have moderate weight-bearing lameness, but died from splenic hemangiosarcoma 4 months postoperatively.

In the mid-term period, 1/18 complications was observed (5.6%). The #6 femoral stem fractured at 9 months postoperatively. The dog had a chronic femoral neck fracture with bone loss of the medial calcar and marked sclerosis of the proximal femur (Figure 4A). The implant was undersized and positioned slightly more varus due to the malformation and sclerotic bone, and implanted more distal into the femoral canal due to the fracture defect in the medial calcar bone (Figure 4B). Due to increased lateral translation, a 9+ head/neck and an iliofemoral suture anchor was placed. The dog did well initially but became acutely lame 9 months postoperatively. Radiographs revealed a fracture through the path of the lateral bolt (Figure 4C,D). A revision was performed using a craniolateral approach combined with a cranial, caudolateral, and transverse distal osteotomy of the proximal femur to bivalve the bone facilitating

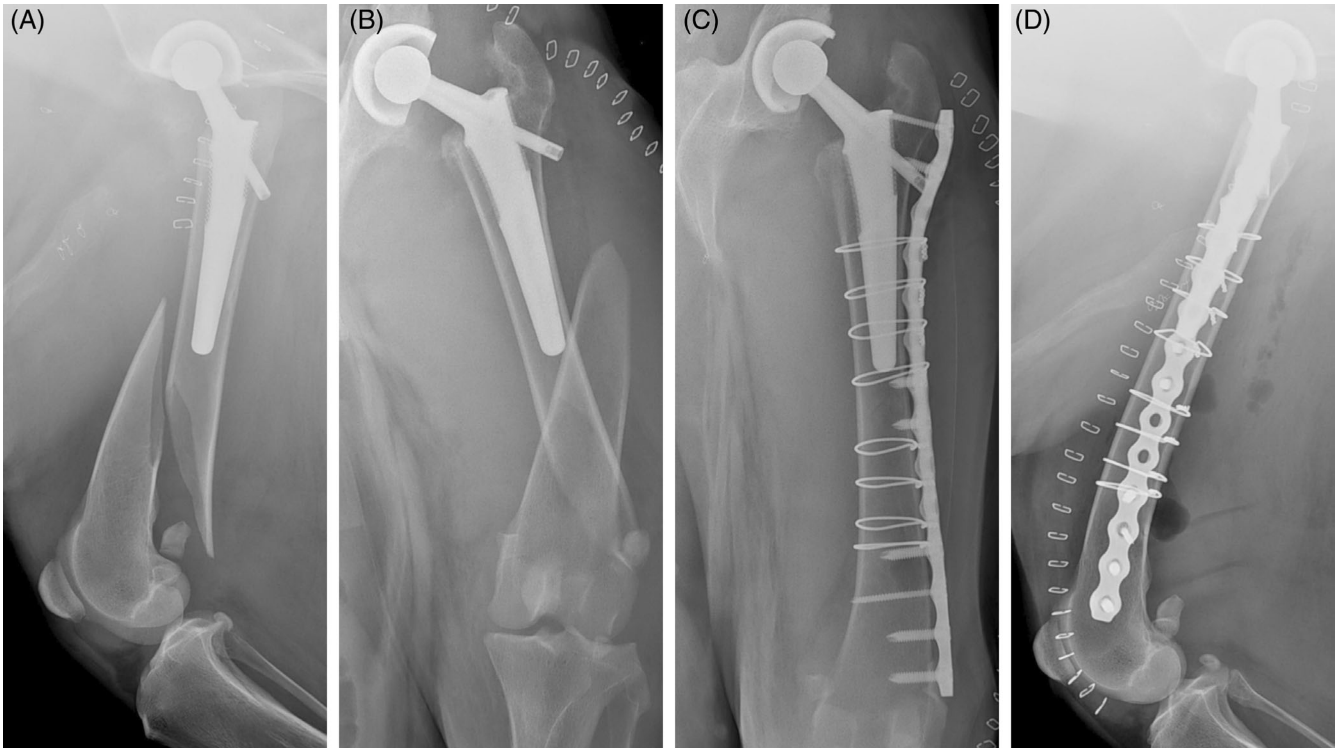


FIGURE 2 Radiographic projections of a postoperative femoral fracture and subsequent repair. (A, B) Mediolateral and caudocranial radiographic projection of a dog with a mid-diaphyseal femoral fracture after jumping off a bed 4 days postoperatively. (C, D) Caudocranial and mediolateral radiographic projection of the dog after revision. A size-11 advanced locking plate system (ALPS) plate was secured on the lateral aspect of the femur

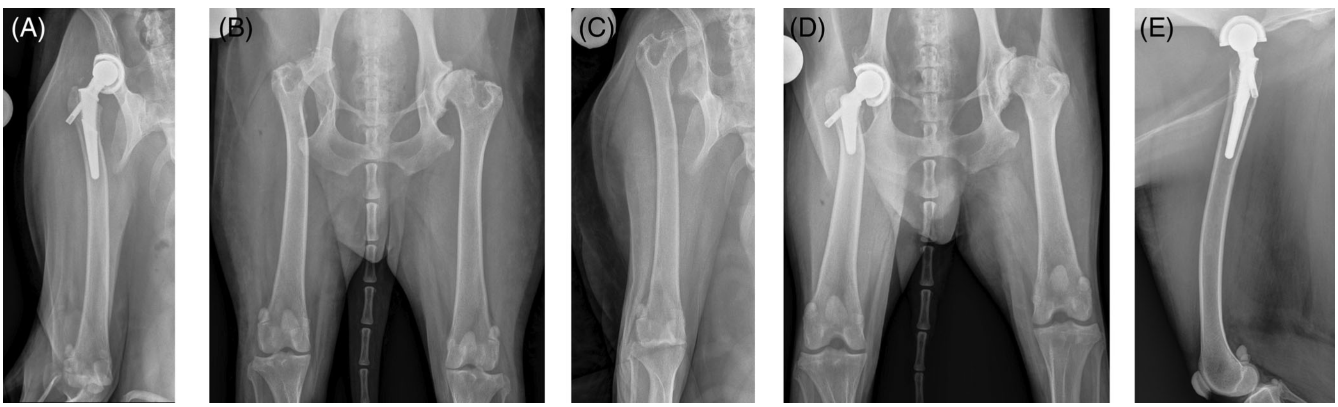


FIGURE 3 Dog with previous femoral head fracture and proximal femoral valgus. (A, B) Caudocranial and ventrodorsal radiographic projections revealing a previous chronic femoral head fracture and unknown trauma leading to proximal femoral valgus. (C, D) Caudocranial and ventrodorsal postoperative radiographic projections with the acetabular and femoral prosthesis; note the severe proximal femoral valgus in the ventrodorsal projection. (E) Mediolateral radiographic projection revealing appropriate implant placement with an angle of lateral opening (ALO) of 48°, coronal retroversion of 21°, and femoral anteversion of 18°

explant of the femoral stem (Figure 4E–G). A new #7 BFX lateral bolt was inserted. The neck length was reduced. Recovery was uneventful and postoperative evaluations showed normal radiographic healing and excellent clinical function at 31 months post-revision.

There was one long-term complication at 910 days postoperatively (1/18, 5.6%) involving aseptic loosening of the acetabular cup; culture was negative. The acetabular bone was significantly resorbed and the owners elected explant of the prosthesis.

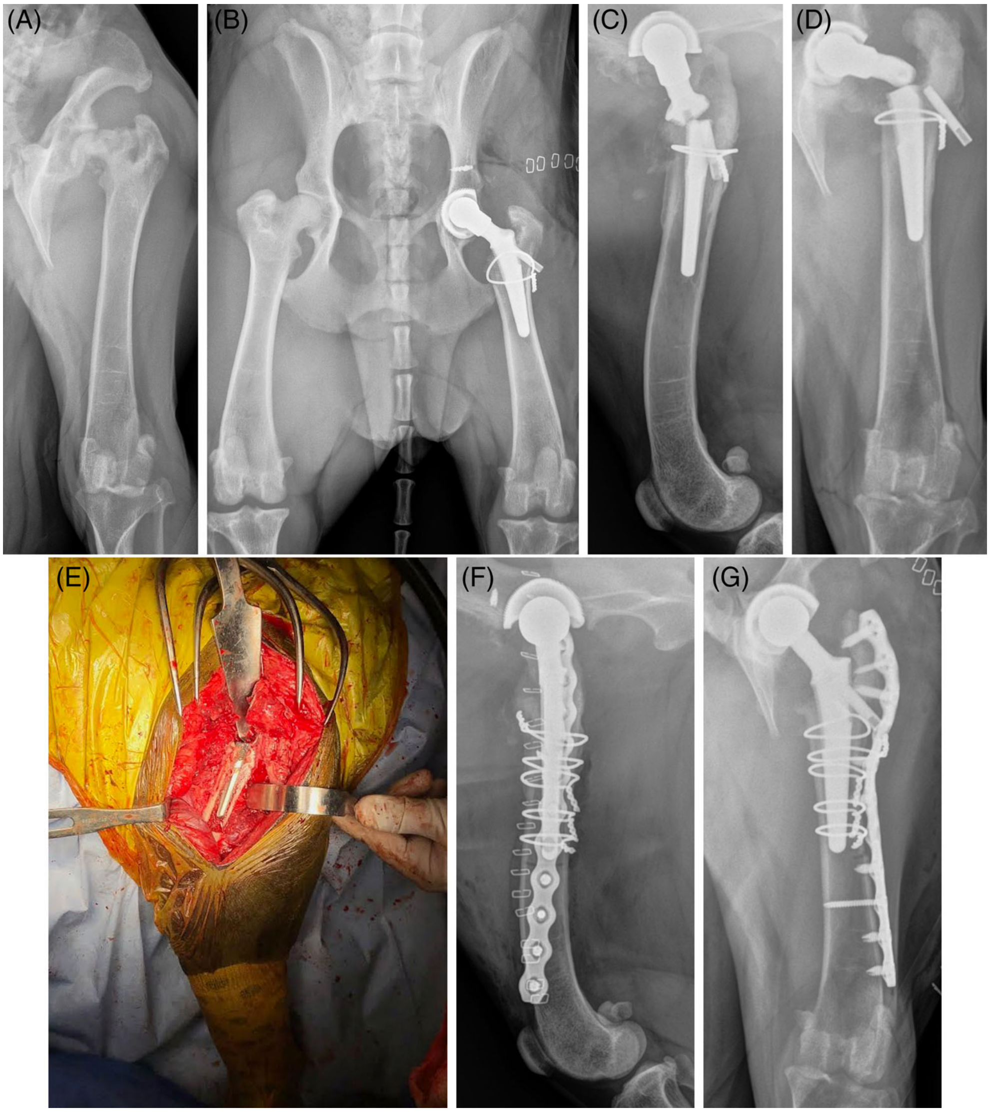


**FIGURE 4** (A) Caudocranial radiographic projection of a case with a chronic femoral head and neck fracture with marked sclerosis and a chronic fracture extending distal to the lesser trochanter. (B) Immediately postoperative ventrodorsal radiographic projection from initial surgery; note the undersized implant and more distal placement of the femoral stem. (C, D) Mediolateral view and caudocranial view of a dog at 9 months postoperatively with a fracture through the path of the lateral bolt. (E) Revision with a craniolateral approach to the left hip combined with cranial, caudal, and distal osteotomy to allow for appropriate exposure and removal of the femoral stem. (F, G) Immediately postoperative mediolateral and caudocranial radiographic projections following revision surgery. The dog returned to normal function and is doing very well at 31 months post-revision

### 3.4 | Prophylactic plating

Three dogs underwent prophylactic plating in this study due to suspected increased risk of a postoperative fracture. The subjective decision to plate was determined by the preoperative radiographic assessment of cortical bone thickness, along with the ability of the owner to restrict the dog postoperatively. All three dogs treated with prophylactic plating achieved an excellent outcome with no postoperative complications.

## 4 | DISCUSSION

This is one of the first studies detailing the short- and long-term clinical outcomes of THRs utilizing a BFX lateral bolt. The success rate was high, with 190/195 (97.4%) of the THRs returning to normal function as defined by restoration to full level of intended athletic activities without evidence of lameness, pain, or necessity of NSAIDs.

Townsend and colleagues reported that cases with subsidence >3 mm in the postoperative period were 45.3-times more likely to develop postoperative stem complications as compared to those with <3 mm of subsidence.[25] The mean subsidence of 1.22 mm detected in our study is comparable to the subsidence reported by Mitchell and colleagues comparing short-term radiographic outcomes after THR with the BFX lateral bolt to those of BFX and BFX collared stems.[22] Previous studies showed that the BFX lateral bolt decreases subsidence compared to the BFX and collared stems, but the effect over time was unknown. In our study, the majority of the detected subsidence occurred in the first month postoperatively and was minimal thereafter. When installing the BFX lateral bolt, a cannulated drill bit is used to enlarge the lateral femoral cortical hole for placement of the lateral bolt. This hole is larger than the lateral bolt and may be enlarged by an awl, thus the lateral bolt can migrate distally by 1–2 mm prior to contacting the cortical rim of the drilled hole in the lateral cortex.

Previously, Ganz and colleagues observed that dogs with a CFI <1.8 may be at risk for postoperative femur fractures.[7] Mitchell and colleagues found no association with CFI and postoperative complications.[22] In our study, femur fractures were associated with a higher CFI ($p = .019$). A type I error was suspected due to the low number of fracture complications. Canal flare index can also be variable depending on the level of width measurements[26] and stem positioning.[27] Interobserver variability has not been assessed when measuring CFI and may explain the differences found across studies. Due to the variability observed, CFI may not be not an accurate predictor of postoperative complications. A study with a larger population of femur fractures and CFI may be indicated.

Femoral fissures during broaching were the most common intraoperative complication. The German Shepherd breed was associated with intraoperative fissures, but was not associated with post- or intraoperative fractures. Previously, German Shepherds were candidates for cemented THR due to their thin cortices that may increase their risk of fissure or fracture. When an intraoperative fissure was identified, one or two twist cerclage wires were applied in an attempt to restore hoop strength prior to impaction of the femoral stem. Of the dogs who developed an intraoperative fissure and a femur fracture, one twist cerclage was applied to one femur, and two twist cerclage wires were applied to the second. Both dogs with an intraoperative fissure that later developed a femur fracture showed no subsidence of the femoral stem at the time of the fracture. Previous studies show that double loop cerclage helps restore hoop strength and increases the force necessary for fractures secondary to subsidence to occur, which may be an indication to utilize double loop cerclage in the future.[18]

Previously, femoral fractures appeared to propagate from the femoral osteotomy at the medial calcar, making repair difficult due to disruption at the site of osseointegration in the proximal femur.[7,20] The BFX lateral bolt has been shown to be more resistant to subsidence than the traditional BFX stem.[20,22] The BFX lateral bolt likely provides more stability and resistance to subsidence, therefore preventing femoral fractures that propagate from the medial calcar. All postoperative femur fractures were mid-diaphyseal, long oblique or spiral fractures (type B1 or type C) located distal to the ingrowth area of the stem or distal to the stem. All femoral stems were subjectively assessed to be stable at the time of revision surgery for femoral fracture reduction and stabilization. Type B2 or B3 fractures involving the medial calcar or proximal femoral metaphysis were not observed. Based on the authors' experience, the fracture configurations encountered were more easily repaired compared to previous fractures that propagated from the medial calcar. The 3.4% postoperative femoral fracture rate identified in this study is low as compared to previous reports utilizing the traditional BFX stem and is more comparable to that of the cemented THR.[17]

Postoperative femoral fractures were strongly associated with increased age, similar to the finding previously reported by Ganz et al.[7] Interestingly, dogs with postoperative femur fractures did not exhibit progressive subsidence, indicating that the fractures observed likely did not propagate as a fissure from the medial calcar. Two type C Vancouver femur fractures were observed in this study, one of which was associated with 4 mm of subsidence. During femoral canal preparation, the tip of the broach or the femoral stem during insertion may impinge on the cortex of the femoral diaphysis, weakening the cortex. Fractures may propagate from the weakened femoral diaphysis at the tip of the stem and could have accounted for a portion of the cause of the femur fractures. Without more advanced imaging, it is unclear whether the femur fracture propagated from impingement or a fissure that was not visualized at the time of surgery. Overall, the dogs with femur fracture repair healed without additional complications and returned to normal function without any lameness post repair.

In human literature, a low cortical thickness index has been shown to be associated with a greater risk of fracture.[28] This index is useful for the prediction of osteopenia and osteoporosis in humans but has not been assessed in dogs.[29] The three dogs that underwent prophylactic plating were subjectively assessed to have a low cortical wall thickness; noncompliance was also suspected based on their history. Thus, prophylactic plating was performed to try to maximize their outcome. Cortical thickness, in combination with owner compliance and intraoperative assessment of bone quality may provide a grading scale to better guide surgical recommendations such as prophylactic plating to reduce the risk of a postoperative fracture.

Luxations can occur secondary to intrinsic (cup and femoral stem positioning),[30] or extrinsic interference (such as osteophytes allowing the femoral head to be levered out of the cup, impingement from the caudal pillar), excessive lateral translation or general soft tissue laxity,[31] and femoral deformities. The mid-term luxation at 120 days occurred in a dog with proximal femoral valgus. At the time of revision, dorsal polyethylene wear and deformation of the acetabular cup were observed.

Proximal femoral valgus may increase loading to the lateral aspect of the dorsal rim of the cup, which likely contributed to the late luxation. Revision of a fully osseointegrated cup also increases the risk of disruption or fracture of the dorsal acetabular rim. During the revision of the cup, the dorsal acetabular rim was iatrogenically damaged due to an avulsion fracture during removal and explant was elected. Otherwise, revisions of luxations were successful in 6/7 dogs (85.7%).

There was one femoral implant failure utilizing a #6 stem. The dog was an athletic 25 kg Pitbull with a chronic femoral neck fracture that extended distal to the lesser trochanter. Due to the distal chronic fracture and sclerotic bone, an undersized prosthesis was placed but mispositioned in slight varus. It was also more distal than desired and required an extra-long neck. The probable failure mechanism was a stress riser leading to metal fatigue and implant failure. Four other femoral stem failures have been recorded based on the authors' communications with Biomedtrix. All were #6 femoral stems that were potentially undersized in athletic dogs; further surgical details are not available.

Limitations encountered in this study include its retrospective nature and the lack of objective postoperative force-plate analysis to assess improvement of limb function. The retrospective nature of the study prevents the strict standardization of perioperative protocols and follow-up. The level of owner compliance in the postoperative follow-up protocol was very good, despite a small amount of owner compliance variability. The radiographic and clinical follow-up varied in a small number of dogs due to a variety of factors, most notably financial reasons.

In conclusion, the use of the BFX lateral bolt resulted in minimal postoperative subsidence, a low femoral stem complication rate, and a high rate of return to normal function. Revision surgery was successfully performed in the majority of dogs that experienced major complications, resulting in salvage of the THR without the need for prosthesis explant. Further investigation is needed to determine the effect of revision surgery and the risk of septic complications. Four of five explants were related to cup complications while only one was due to a femoral stem complication. The BFX lateral bolt resulted in minimal postoperative subsidence and no fractures involving the medial calcar of the femur. Although femoral fractures did occur, from the authors' experience, the fracture configurations that resulted were more easily stabilized compared to past fracture configurations which originated from the medial calcar and propagated distally. The BFX lateral bolt should be considered for THR surgery, including in dogs previously considered at higher risk for postoperative femur fractures.

## AUTHOR CONTRIBUTIONS

Kwok J, MS, VMD: Study design, data acquisition, analysis, and interpretation, revision. Wendelburg K, DVM, DACVS: Study design, data interpretation, revision. Hauptman, JG, DVM, MS, DACVS: Statistical analysis.

## CONFLICT OF INTEREST

The authors declare no other conflicts of interest related to this study.

## DISCLOSURE

Kirk Wendelburg, DVM, DACVS, owns the patent for the BFX lateral bolt and receives royalties from BioMedtrix.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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