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Three-Dimensional Computer-Assisted Surgical Planning and Use of Three-Dimensional Printing in the Repair of a Complex Articular Femoral Fracture in a Dog

Griselda Lam[1] Sun-Young Kim[1]

[1] Department of Small Animal Clinical Sciences, Michigan State University, East Lansing, Michigan, United States

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Address for correspondence Sun-Young Kim, DVM, DACVS, Department of Small Animal Clinical Sciences, Michigan State University, 736 Wilson Road, East Lansing, MI 48824, United States (e-mail: kimsunyo@cvm.msu.edu).

Abstract

Objective The main purpose of this study was to describe the use and benefits of 3-dimensional (3D) computer-assisted surgical planning (CASP) and printing in a complex articular fracture repair in a dog.

Study Design Case report.

Animals Client-owned dog.

Results One dog with a closed, severely comminuted, distal femoral supracondylar and bicondylar fracture underwent a preoperative computed tomography scan. Three-dimensional CASP was performed using computer-aided design software. Three-dimensional CASP allowed for visualization of the fracture fragments and virtual surgery, including reduction of the fragments and implant placement. A 3D model of the affected femur was printed and a bone plate was pre-contoured to the model. Intraoperative fracture reduction and stabilization were performed without complications. Postoperative radiographs revealed successful execution of the planned procedure. Subsequent radiographs and clinical examination indicated that bone healing was achieved with return to normal function of the limb. Three-dimensional CASP and the printed 3D model allowed for improved understanding of the anatomical relationship between fracture fragments, preoperative implant selection and contouring, and the ability to practice fracture reduction and implant placement preoperatively. The model was also used for client education, and to teach students and residents.

Conclusion Three-dimensional CASP and printed models are valuable tools in the preoperative planning of complex fracture repairs, educating clients and teaching students and residents.

Keywords
- dog
- articular fracture
- 3D printing
- 3D computer-assisted surgical planning
- virtual surgery

Introduction

Femoral fractures are frequently encountered in clinical small animal practice, accounting for 45% of all long bone fractures.[1,2] Trauma is a common cause of femoral fractures, such as vehicular accidents or falls from great heights. A small subset includes those fractures that affect the supracondylar and condylar regions, representing 8 to 10% of all femoral fractures.[1–4] These fractures pose unique challenges to veterinary surgeons due to the limited bone stock available for fixation and articular involvement, requiring anatomical reconstruction and rigid fixation via interfragmentary compression.[5] Therefore, a

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carefully constructed preoperative plan is critical for successful fixation.[6] Various pre-surgical planning techniques may be utilized based on orthogonal radiographs of the affected limb. However, severe displacement of fracture fragments in multiple dimensions can increase the difficulty of applying traditional planning techniques to comminuted articular fractures.

Computed tomography (CT) is a useful diagnostic modality that allows for further characterization of fracture configuration to assist with surgical planning, particularly when 3D rendering of images is performed. However, visualization of 3D images on a flat screen may not provide the veterinary surgeon with an adequate understanding of complex anatomical relationships,[7–9] such as in the case of severely comminuted fractures. Furthermore, although the 3D-rendered images can be manipulated, preoperative planning in the form of fragment reduction and selection of appropriate implants cannot be performed.

Three-dimensional (3D) printing or additive manufacturing, previously known as rapid prototyping, is becoming increasingly popular in veterinary medicine as a method of reproducing bone replicas for management of orthopaedic cases.[10–17] In addition, 3D computer-assisted surgical planning (CASP) has many clinical applications in reconstructive surgery in human and veterinary medicine.[9,14,18] To the authors' knowledge, there is no current literature reporting the use of 3D CASP and printing in the repair of an articular fracture in veterinary medicine. This report describes the process of 3D CASP and the use of a 3D printed model to facilitate complex articular femoral fracture repair in a dog.

Case Description

A 4-year-old, 32.6 kg, male neutered, Golden Retriever was presented to the Michigan State University Veterinary Medical Center for the evaluation of an acute onset non–weight-bearing right hindlimb lameness after jumping out of a second story window. On initial evaluation, the dog was quiet and alert with normal vital parameters. Orthopaedic examination revealed a non–weight-bearing right hindlimb lameness with crepitus present on palpation of the right distal femur. The results of haematology were within normal limits. Serum biochemical analysis revealed a mildly elevated aspartate transaminase and creatine kinase. Radiographs and CT images (GE Revolution EVO scanner, 0.63 mm slices, kVp = 120, mA = 193: GE Healthcare, Milwaukee, Wisconsin, United States) of the hindlimbs revealed a closed, severely comminuted, right distal femoral supracondylar and bicondylar fracture with articular involvement, as well as multifragmentary comminution of the caudolateral femoral metaphysis (►**Fig. 1**).

Three-Dimensional Computer-Assisted Surgical Planning and Printing

The CT images were converted to a 3D format using modelling software (Mimics Innovation Suite 19: Materialise NV, Leuven, Belgium). The fracture fragments were segmented virtually to create five main fragments: proximal femur, lateral condyle, medial condyle, trochlea, and medial metaphysis (►**Fig. 1C**, **D**). The virtual fragments were reduced with computer-aided design (CAD) software (Meshmixer 3.2: Autodesk, Inc, San Rafael, California, United States) by comparing them to a mirror image of the contralateral, unaffected femur. Following fracture reduction, various-sized cylinders (1.5, 2.7 and 4.0 mm in diameter) were applied to the virtual model to simulate screw placement (►**Fig. 2A**, **B**). A 3.5-mm reconstruction plate was applied virtually to the medial aspect of the distal femur (►**Fig. 2C**, **D**). Application of a lateral plate was not simulated as the surgeon had determined that a locking plate and monocortical screws were to be used. The virtually reduced femoral fracture, including the five main fragments, was printed using a stereolithography 3D printer (Form 2: Formlabs, Somerville, Massachusetts, United States). A 3.5-mm reconstruction plate (DePuy Synthes Inc., West Chester, Pennsylvania, United States) was pre-contoured to the distomedial aspect of the printed model to ensure that lag screws could be placed through the distal plate holes (►**Fig. 2E**). The plate was then steam sterilized.

Anaesthesia

The dog was sedated with fentanyl (3μg/kg intravenous [IV]) and dexmedetomidine (3 μg/kg IV). General anaesthesia was induced with propofol (1 mg/kg IV) and midazolam (0.2 mg/kg IV), followed by isoflurane and oxygen maintenance. Lactated Ringer's solution (10 mL/kg/h IV) and fentanyl (3–5 μg/kg/h continuous rate infusion [CRI] IV) were administered intraoperatively. The dog was treated with cefazolin (22 mg/kg IV every 90 minutes) and a single dose of carprofen (2.2 mg/kg subcutaneous [SQ]) perioperatively.

Surgery

Surgery was performed to stabilize the femoral fracture, as previously planned with 3D CASP and preoperative surgical rehearsal. The dog was placed in dorsal recumbency. A craniolateral surgical approach to the right distal femur was made, and a lateral parapatellar arthrotomy was performed[19] (►**Fig. 3A**). The cruciate ligaments, collateral ligaments and menisci were intact. The lateral condylar and trochlear fracture fragments were reduced and stabilized with a 1.5 mm positional screw (DePuy Synthes Inc., West Chester, Pennsylvania, United States). The medial condyle was then reduced to this unit and interfragmentary stabilization was achieved with a 4.0 mm cancellous screw (DePuy Synthes Inc., West Chester, Pennsylvania, United States) and washer (DePuy Synthes Inc., West Chester, Pennsylvania, United States) placed in a lag fashion (►**Fig. 3B**). Two 1.1 mm Kirschner wires (IMEX Veterinary Inc., Longview, Texas, United States) were placed in a mediolateral direction across the condyles and trochlea for temporary stabilization. The medial metaphyseal fragment was reduced to the proximal fragment. Compression of the two fragments resulted in collapse; therefore, the two fragments were stabilized with a 2.7 mm positional screw (DePuy Synthes Inc., West Chester, Pennsylvania, United States) and a 1.1 mm Kirschner wire (IMEX Veterinary Inc., Longview, Texas, United States). The two resulting composite fragments (lateral condyle + trochlea + medial condyle and proximal femur + medial metaphysis) were reduced and the pre-contoured 3.5-mm reconstruction plate was applied to the distomedial aspect of the femur, over

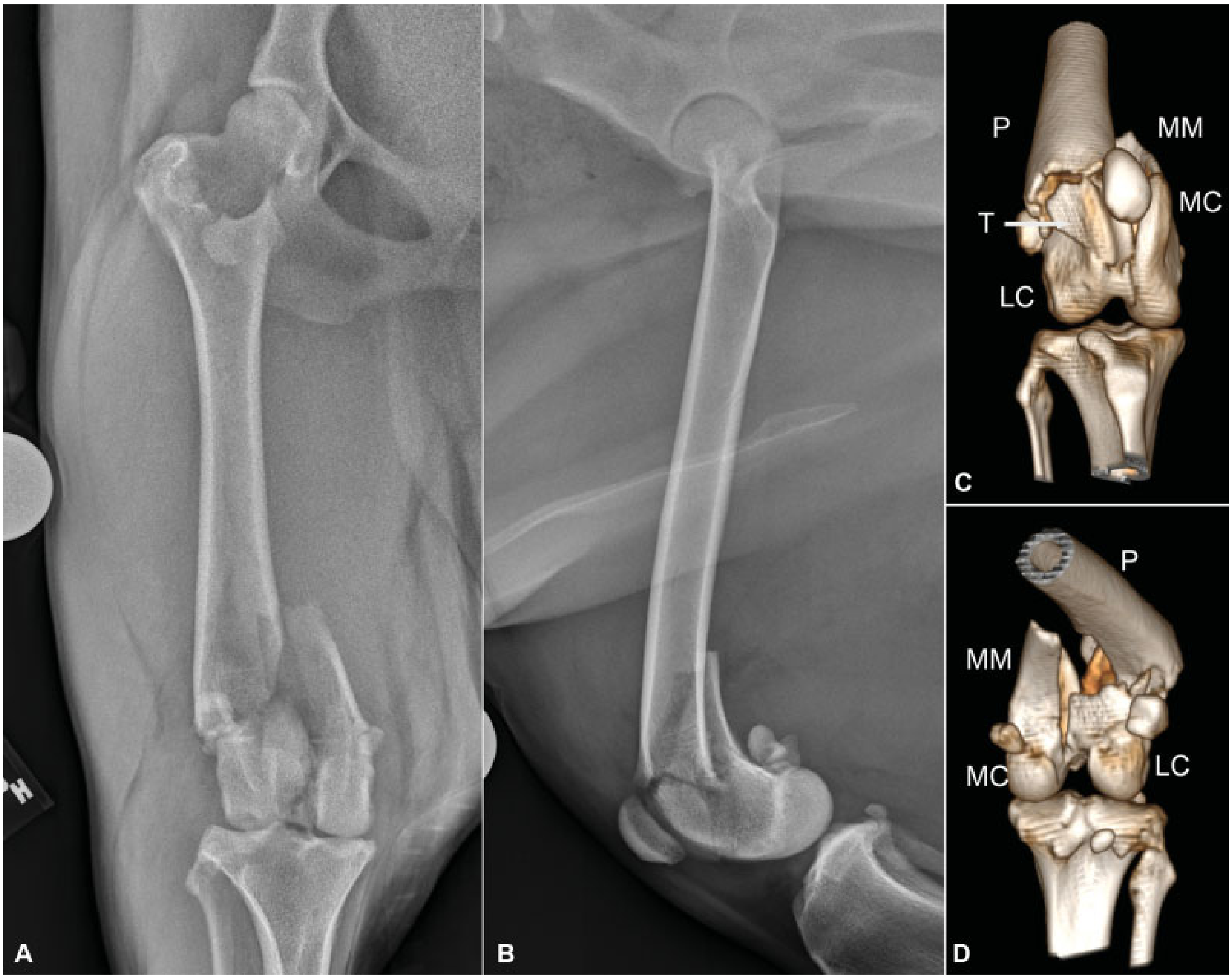

Fig. 1 Preoperative imaging of the left femur. (**A**) Craniocaudal radiograph. (**B**) Lateral radiograph. (**C**) Cranial view of CT rendered image. (**D**) Caudal view of CT rendered image. Abbreviations: CT, computed tomography; LC, lateral condyle; MC, medial condyle; MM, medial metaphysis; P, proximal femur; T, trochlea.

the temporary Kirschner wires. The Kirschner wires were replaced with 4.0-mm cancellous screws (DePuy Synthes Inc., West Chester, Pennsylvania, United States) placed in lag fashion through the two distal-most plate holes (►**Fig. 3C**). Two additional 3.5-mm bicortical screws (DePuy Synthes Inc., West Chester, Pennsylvania, United States) were placed in the two proximal-most holes of the reconstruction plate. A 2.7-mm String-of-Pearls plate (String-of-Pearls plate: Orthomed Ltd, Huddersfield, West Yorkshire, United Kingdom) was applied to the lateral aspect of the distal femur, and four 2.7-mm monocortical screws (DePuy Synthes Inc., West Chester, Pennsylvania, United States) were placed (►**Fig. 3D**). The surgical site was lavaged copiously with sterile saline, followed by routine closure. No intraoperative complications were encountered. Recovery from surgery was uneventful.

Postoperative Period

Postoperative right femoral radiographs revealed appropriate alignment and positioning of the implants (►**Fig. 4A**, **D**), with similar results compared with those achieved with 3D CASP. In the immediate postoperative period, analgesia was provided with fentanyl (3–4 µg/kg/h CRI) for the first 24 hours, followed by tramadol therapy (3 mg/kg per os [PO] q8–12h). Metoclopramide (2 mg/kg/day CRI) therapy was initiated due to regurgitation. Cefazolin administration (22 mg/kg IV q12h) was continued until discharge. The dog was discharged 2 days following surgery with instructions to the owner to administer carprofen (2.2 mg/kg PO q12h for 10 days), tramadol (3 mg/kg PO q8–12h for 10 days), cephalexin (22 mg/kg PO q12h for 14 days), metoclopramide (0.3 mg/kg PO q8h for 5 days) and trazodone (3 mg/kg PO q8–12h for 14 days).

The dog was re-evaluated at the Michigan State University Veterinary Medical Center 6 weeks following surgery. Orthopaedic examination revealed a mild, weight-bearing right hindlimb lameness and moderate muscle atrophy of the right hindlimb. Radiographs revealed stable implants and normal bone remodelling (►**Fig. 4B**, **E**). Goniometric measurements of the right stifle were obtained as previously described,[20] which revealed a mildly reduced extension angle (155°) and moderately reduced flexion angle (60°) compared with the contralateral stifle (extension angle—160°, flexion angle—40°).

Nine weeks postoperatively, the dog was re-evaluated again. Orthopaedic examination revealed an intermittent, mild,

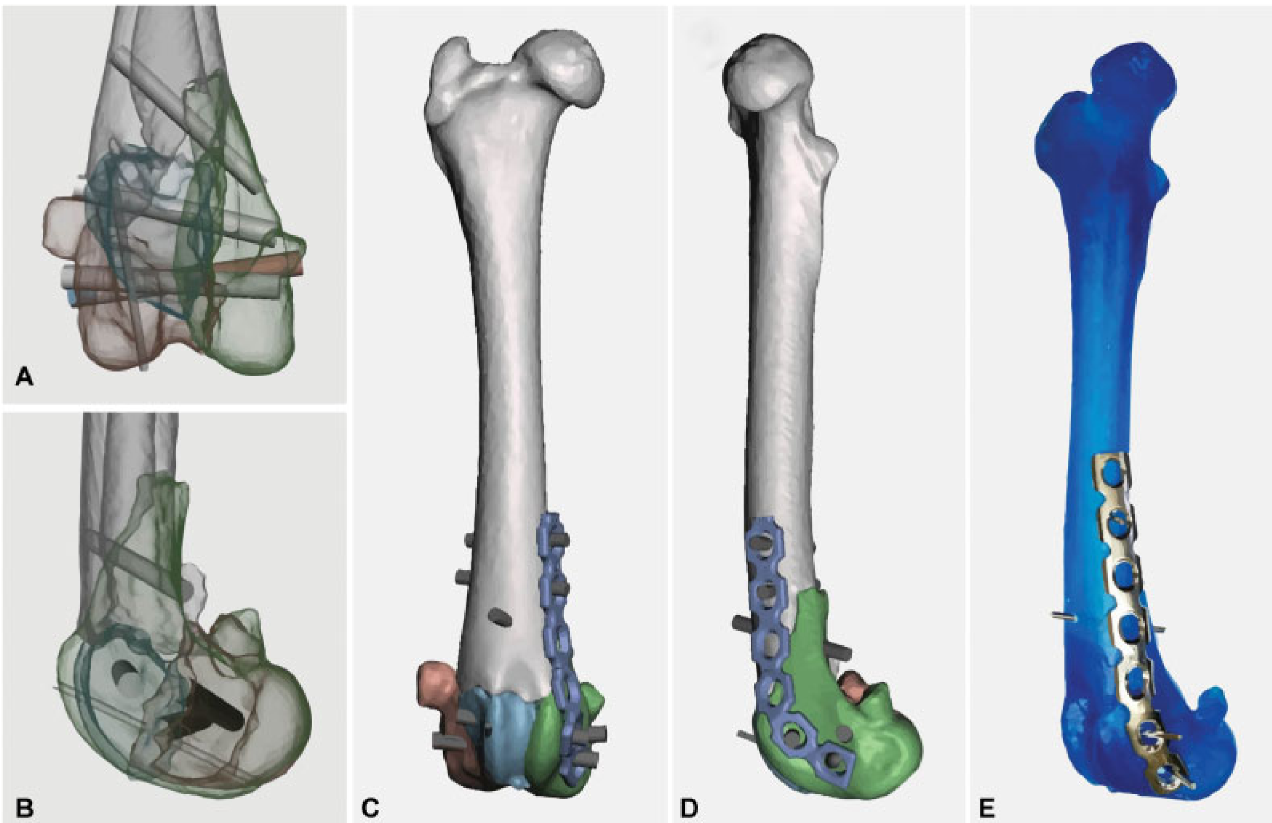

Fig. 2 (**A–D**) Images from computer-aided design software with simulation of screw (via cylinders) and reconstruction plate placement. (**E**) Three-dimensional printed model with pre-contoured reconstruction plate applied to the medial aspect of the distal femur.

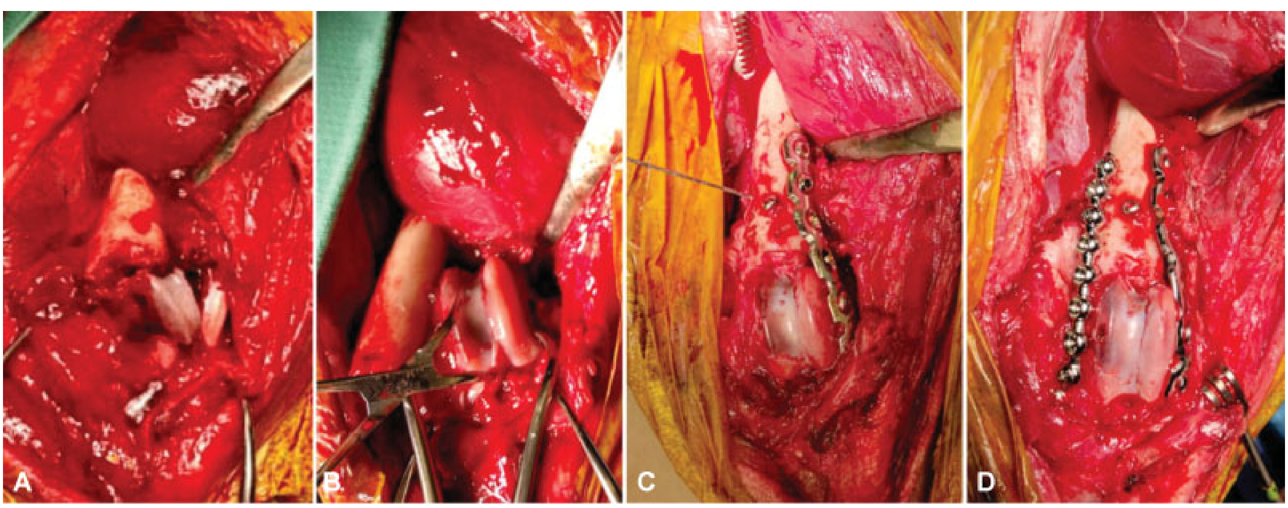

Fig. 3 Intraoperative images obtained (**A**) prior to reduction, (**B**) following reduction in lateral condylar and trochlear fragment to medial condyle, (**C**) application of screws and reconstruction plate and (**D**) following placement of all implants.

weight-bearing right hindlimb lameness with improvement in the degree of muscle atrophy. Goniometry revealed normal extension (160°) and mildly reduced flexion (50°) of the right stifle.

A final re-examination conducted at 8 months postoperatively revealed no lameness present at a walk or trot. Radiographs revealed unchanged implants and complete bone healing (►**Fig. 4C**, **F**). Bilateral muscle symmetry was present at the level of the proximal thigh (33-cm circumference). Goniometry revealed normal extension (160°) and flexion (42°) of the right stifle.

Discussion

This report describes the successful clinical application of 3D CASP and printing in the repair of a comminuted articular fracture in a dog. In this clinical case, the 3D printed replica was instrumental in providing the surgeon with a custom

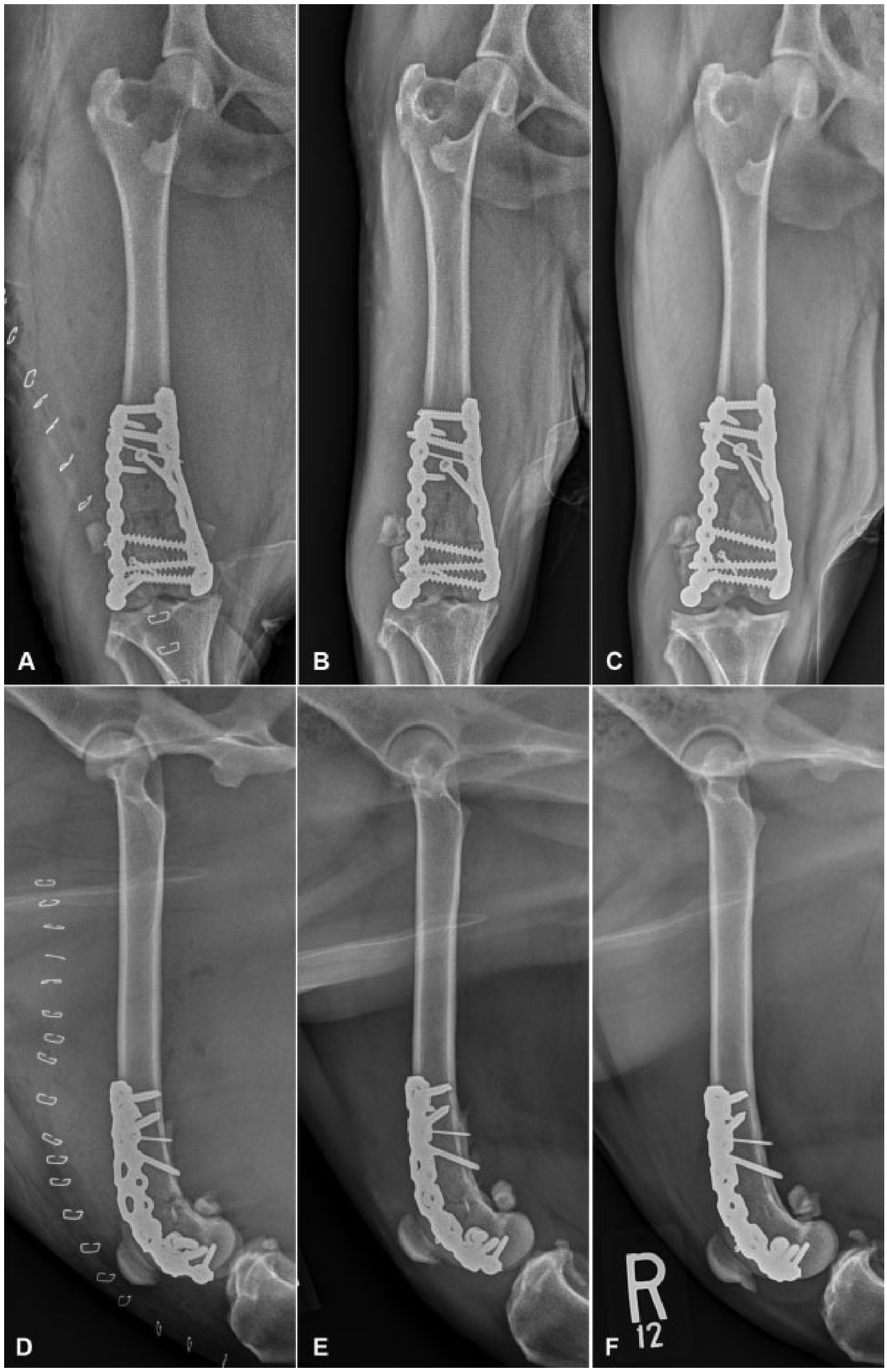

Fig. 4 Postoperative radiographs of the left femur. (**A**) Immediate postoperative craniocaudal and (**D**) lateral radiographs. (**B**) Six-week postoperative craniocaudal and (**E**) lateral radiographs. (**C**) Eight-month postoperative craniocaudal and (**F**) lateral radiographs.

model depicting the anatomic relationship between fracture fragments. According to AO principles,[6] different techniques may be utilized in the preoperative planning stage. The direct overlay technique involves reduction in fracture segments after tracing them individually on pieces of paper. Another technique uses a mirror image of the contralateral (normal) bone as a template for fracture reduction. The drawing of fracture lines directly onto a cadaveric bone specimen from a similar-sized animal to facilitate selection and pre-contouring of implants can also be performed. Due to the complex degree of displacement and rotation present, it was nearly impossible to trace the shape of the fracture fragments accurately based on two-dimensional (2D) views, such as orthogonal radiographs. Instead, CAD software was used to manipulate each CT-derived fracture fragment in 3D space. Direct fracture reduction in 3D fragments remained difficult due to overlapping of the segments; therefore, the technique in which the contralateral femur is used as a template for reduction was performed in this case. As with 2D planning, 3D CASP allowed for simulated placement of key implants, such as interfragmentary lag screws, but in multiple planes. In addition, contouring and placement of a reconstruction plate were performed virtually with the CAD software, allowing the surgeon to determine the length, size and placement of the implant preoperatively. The printed 3D model was used to facilitate pre-contouring of the plate selected through 3D CASP. It is estimated that pre-contouring of the plate and increased surgeon confidence due to pre-operative rehearsal of the procedure reduce surgical time by 15 to 20 minutes.[14] There were no intraoperative delays or complications noted. However, direct comparisons cannot be drawn between this procedure and a similar procedure performed without the use of preoperative 3D CASP.

Intraoperatively, interfragmentary compression of the various fracture fragments was achieved via placement of screws in lag fashion. To achieve superior compression, lag screws were placed in a medial to lateral direction due to the limited bone stock present medially compared with laterally. Screws were also preferentially placed through plate holes to provide a better lag effect. Following placement of the medial reconstruction plate and associated lag screws, a lateral locking plate was applied to distribute bending forces between the two plates. This plate was not virtually applied during 3D CASP and pre-contoured preoperatively, as precise contouring of locking plates is not critical to implant stability. Also, since monocortical screws were placed rather than lag screws through the plate holes, the plate position on the bone surface was of less importance.

The use of a 3D printed model can also facilitate client education and communication. The 3D printed bone replica enhanced the client's understanding of the treatment plan, potential complications and financial cost associated with moving forward with surgery. Indeed, the visual and tactile feedback from a 3D model has been shown in human medicine to improve patient understanding of anatomical details compared with 2D or 3D reconstructed imaging.[9]

Acquiring a thorough knowledge of surgical anatomy is an essential objective for all surgical residents and veterinary students. The utility of 3D printing in human surgical training has been demonstrated in various disciplines.[21–24] To this end, the 3D printed bone replica in this case served as a tool with which residents could simulate the surgical procedure, allowing for subjectively improved understanding of the patient-specific anatomy. However, objective outcomes to measure the utility of this modality in augmenting knowledge were not used. This may be an area of interest for future studies investigating the utility of 3D CASP and printing.

The primary drawbacks to 3D CASP and printing are the associated costs and time. A 3D model typically takes at least 18 to 24 hours to print, depending on the size of the replica.[14] Stereolithography is a 3D printing technology where epoxy resin or liquid photopolymer is exposed to a low-power ultraviolet laser.[9] Although stereolithography is capable of yielding resolutions up to 25 µm,[9] a lower resolution was used in this report (100 µm) to reduce printing time. Since CT images were obtained using thin slices with a thickness of 630 µm, the resolution of the printed 3D bone replica was still six times finer than that of the CT images, and is likely to be an appropriate resolution when it comes to the fabrication of small models. This is supported by a study that evaluated the accuracy and repeatability of CT-derived bone models produced by low-end and high-end 3D printers.[25] The cost and time associated with 3D printing was further reduced in this report by performing 3D CASP beforehand. Three-dimensional CASP allowed the surgeon to focus on the region of interest (distal femur) and reduce the 3D volume to be printed, therefore reducing the amount of resin used. Overall, the 3D bone replica took 5 hours to print with an associated cost of about US$10.

Conclusion

Three-dimensional CASP and printing is a rapidly emerging technique with a variety of benefits, such as preoperative surgical planning, client education and training of residents and students. Three-dimensional CASP and the clinical use of 3D printed models in articular fracture repair have yet to be documented in veterinary literature, probably because standard planning procedures are sufficient in the majority of cases. However, in cases of complicated articular fractures, careful surgical planning using 3D CAD software and 3D printing may be indicated to reduce operating time and improve the success rate of the procedure.

Author Contribution
Both authors contributed to conception of study, study design and acquisition of data and data analysis and interpretation. Both authors also drafted, revised and approved the submitted manuscript.

Conflict of Interest
None declared.

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