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A lateral approach allows accurate and stable total elbow replacement in dogs

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OBJECTIVE
Evaluate whether total elbow replacement (TER) through a lateral approach is accurate and stable.

ANIMALS
12 skeletally mature large-breed dog cadavers were used.

METHODS
Limb alignment, elbow joint motion, and collateral ligament laxity were evaluated preoperatively. The order of surgery (left or right) and the approach (lateral or medial) were randomly selected for TER in each dog. The other approach was used in the contralateral elbow. Intraoperative technical difficulties, duration of surgery, and anatomic complications were recorded. Limb alignment, elbow joint motion, collateral ligament laxity, and prosthetic component alignment were evaluated after surgery. Data were collected from June 11 to 15, 2023.

RESULTS
The duration of surgery using a lateral or medial approach did not differ ($P = .499$). Anatomic complications were not observed. The lateral approach resulted in 8° more elbow extension ($P = .003$), 1.58° less lateral collateral ligament constraint ($P = .033$), 2.80° less medial collateral ligament constraint ($P = .002$), 4.38° less frontal plane constraint ($P = .004$), 8° greater humeral component inclination ($P = .033$), and 5.6° greater radioulnar component varus ($P = .001$) than the medial approach. Varus of the radius, mechanical axis deviation, limb supination, elbow flexion, mediolateral humeral component and craniocaudal radioulnar component orientation did not differ among joints operated using a lateral or medial approach. In normal cadaveric elbows, a lateral approach for TER appears feasible, producing equivalent limb alignment, joint laxity, and joint motion to normal elbows and to TER placed using a medial approach.

CLINICAL RELEVANCE
In dogs, TER can be performed using a lateral surgical approach.

Keywords: dog, elbow, total elbow replacement, surgical approach, osteoarthritis

Elbow osteoarthritis (OA) is a common cause of pain and disability in dogs that affected 8.9% to 70% of dogs in several studies.[1–3] Elbow OA most commonly results from elbow dysplasia, a developmental disease of the elbow joint.[4] Elbow joints with OA often remain undiagnosed until severe OA has developed.[5,6] Elbow OA often has a severe impact on affected dogs. In 1 study,[6] describing 616 diseased elbow joints in dogs, OA contributed to the decision to euthanize 41% of affected dogs.

Joint salvage procedures may be indicated to relieve debilitating discomfort in patients with OA where medical management or conventional surgical procedures have failed or are not tolerated.[7] Concerns about the unpredictability of the outcome of management of severe elbow OA prompted the development of several total elbow replacement (TER) prostheses, including the Iowa State Elbow in 2001,[8] the TATE Elbow in 2008,[9] and the SIRIUS Elbow in 2011.[10] The Iowa State Elbow prosthesis was historically introduced using a caudolateral

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approach and the TATE and SIRIUS prostheses were implanted using a medial approach.[4]

The TATE TER prosthesis has been placed using a medial approach[11] possibly because osteoarthritic changes are more severe on the medial aspect of the elbow[12] or because of the reluctance to disrupt the lateral collateral ligament during surgery, since that ligament is thought to be under tension due to the varus orientation of the antebrachium relative to the brachium.[13] Subjectively, the medial approach used to implant the TATE TER prosthesis has several drawbacks. Patient positioning is challenging because the chest and opposite forelimb interfere with access to the surgical site. In deep-chested dogs, exposing the distal portion of the humerus is difficult. It is not possible to fully evaluate limb alignment during surgery because observation and manipulation of the proximal portion of the humerus and shoulder of the operated limb are not possible. Also, the medial approach requires transection of the caudal branch of the ulnar nerve and sacrifice of the origin of the humeral head of the flexor carpi ulnaris. There may be advantages to implanting a TATE TER prosthesis using a lateral approach, including avoiding the potential interference of the chest or the opposite forelimb with the drill and mill during surgery. A lateral approach would also avoid iatrogenic disruption of the caudal branch of the ulnar nerve at the level of the medial epicondyle.

The purpose of the cadaveric study presented here was to investigate the accuracy and stability of a lateral approach to implant a TATE TER prosthesis in dog cadavers. Assessing the feasibility of the lateral approach included recording the duration of surgery, technical challenges encountered during surgery, potential lesions to nerves, and changes in collateral ligament laxity. Assessing accuracy included measuring limb alignment, joint motion, and prosthetic component alignment. We hypothesized that TER could be performed more rapidly, more precisely, and with more postoperative joint stability using a lateral approach compared to a medial approach. To test these hypotheses, an experimental study was conducted on a group of dog cadavers that underwent a medial and a lateral TER on opposite forelimbs.

Methods

Sample

The study relied on a sample of convenience. Canine cadavers were obtained from dogs unconditionally donated that had been euthanized or died for reasons unrelated to the study. The animals were obtained with signed consent from Nexus Veterinary Continuing Education. Dogs were excluded from the study if they were skeletally immature, weighed < 25 or > 35 kg, or had a chondrodystrophic conformation.[14] Data were collected from June 11 to 15, 2023, and analyzed from June 16, 2023 to January 15, 2024.

Preoperative planning

A CT scan was performed on all limbs to confirm the absence of orthopedic disease, injury, or deformity, to make a template of implant size and placement, and to design patient-specific cutting and drilling guides. The dogs were scanned in dorsal recumbency with the forelimb extended and elbows in a position corresponding to stance, without pronation/supination or varus/valgus stress. The CT images were acquired using a bone window with a slice thickness of 0.625 mm in helical acquisition with no pitch overlap (Somatom go.Up; Siemens Healthineers). Three-dimensional surface renderings of the left and right humerus, radius, and ulna were created using medical imaging software (Mimics Creative Suite; Materialise) and exported into surgical planning software (3-Matic; Materialise). Patient-specific drilling and cutting guides similar to guides designed for canine total knee replacement[15] were designed (Cartesian Medical) for the medial and lateral approach for each elbow **(Figure 1)**. Guides were printed in duplicate using steam-sterilizable biocompatible resin (BioMed Amber; Formlabs) in a stereolithography 3-D printer (Form 3B+; Formlabs).

Preoperative physical and radiographic assessment

Elbow flexion and extension were measured using a plastic goniometer and recorded.[16] Antebrachial supination was evaluated using a digital photograph acquired from the distal aspect of the forelimb with the elbow held at 90°.[17] Preoperative radiographs of the humerus, radius, and ulna were acquired (VetClarity Imaging; Movora). Radiographic views included a mediolateral view with the elbow flexed at 90° and craniocaudal views with an x-ray beam perpendicular to the humerus (1 view) and the radius (3 views, 1 without stress, and 2 stress views). For stress views, the humerus was fixed to a custom frame using a 4-mm metal pin placed across the diaphysis, and a medially or a laterally directed 2.2-kg force was applied at the distal aspect of the radius, respectively, to evaluate lateral and medial collateral ligament laxity, respectively. Frontal plane angulation of the radius relative to the humerus was measured as the angle between the mechanical axis of the humerus and radius **(Figure 2)**. The difference in varus between the neutral and lateral traction stress view was calculated as valgus (ie, medial collateral) laxity. The difference in varus between the medial traction stress view and neutral view was calculated as varus (ie, lateral collateral) laxity. Valgus and varus laxities were added to determine the frontal plane laxity. Mechanical axis deviation in the frontal plane was measured using a previously reported method on the craniocaudal view of the radius and on the 2 craniocaudal stress views.[13] Valgus laxity, varus laxity, and frontal plane laxity were similarly calculated. Radiographs of the elbow joints were evaluated for signs of OA. When present, OA was graded.[12]

Approach

For each dog, the side operated first and the selection of a medial or lateral approach for TER was randomized (Excel v. 16.83; Microsoft). The opposite approach was used for the opposite limb. For the lateral approach, an incision was made from

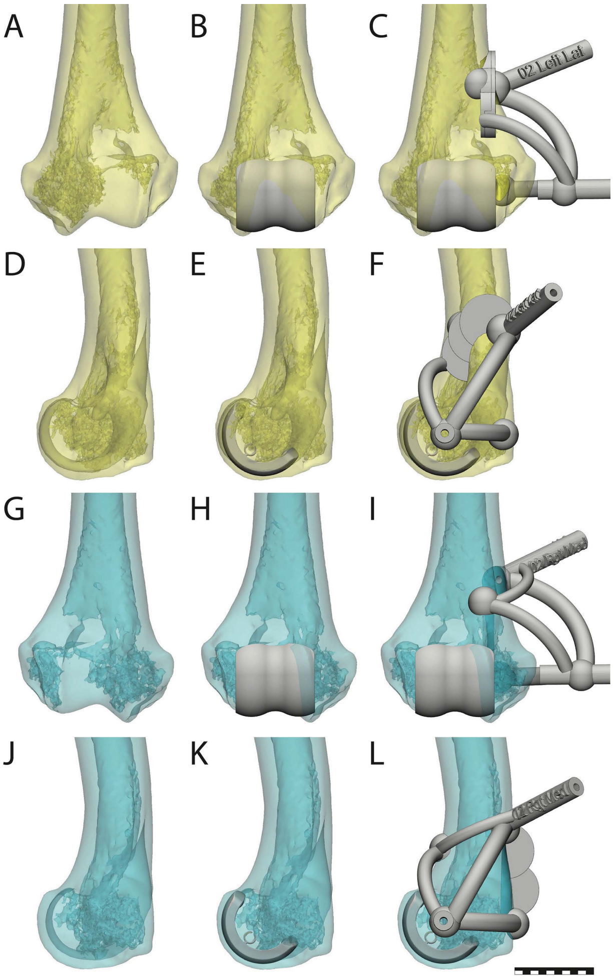

Figure 1—Craniocaudal and mediolateral or lateromedial representative 3-D reconstructed images derived from CT sequences of the forelimbs showing patient-specific guides used for a lateral (A to F) and medial (G to L) approach to the elbow joint. The origin of a Cartesian coordinate system is placed at the center of the humeral condyle. The humeral component of the TATE total elbow replacement (B, E, H, and K) and the cutting and drilling guides for the lateral (C and F) or medial (I and L) approach to the elbow joint are aligned with the coordinate system. The guides are placed so that a 2.0-mm drill bit is aligned with the long axis of the humeral condyle and the resulting osteotomy is tangential to the lateral (C) or medial (L) edge of the humeral prosthetic component. The shelf used to rest the saw blade is proximocranial for the lateral approach (F) and caudal for the medial approach (L). The guides are finalized by subtracting the humerus from the guide using a Boolean operation. Scale bar = 2 cm.

the distal one-third of the humerus to the proximal one-third of the radius/ulna over the caudolateral aspect of the elbow, slightly caudal to the lateral epicondyle **(Figure 3)**. The fascia immediately cranial to the lateral head of the triceps brachii muscle was incised and retracted caudally. The radial nerve was identified at the proximal aspect of the incision. The origin of the extensor carpi radialis muscle was elevated from the lateral humeral epicondyle and separated from the common digital extensor at the cranial aspect of the lateral epicondyle. Dissection progressed through the joint capsule, elevating it en bloc, with the extensor carpi radialis muscle, exposing the radial head. The anconeus muscle was elevated from the caudal aspect of the humeral shaft. The incision was carried over from lateral epicondyle distally, just caudal to ulnaris lateralis. This exposed the proximal aspect of the ulnar shaft. The anconeus muscle was retracted caudally. A patient-specific drilling-cutting guide (PSI) was placed on the lateral aspect of the humeral condyle with 3 points of contact, cranioproximal, craniodistal, and caudodistal. The PSI location was compared to screen captures of a surface rendering of the PSI shown on a rendering of the humerus (Figure 1). The proximal aspect of the PSI was secured to the lateral cortex of the humeral shaft using a 2.0-mm drill bit. The drill bit reached the medial cortex without crossing it. A second 2.0-mm drill bit was drilled across the center of rotation of the humeral condyle. The elbow range of motion was assessed to verify that the transcondylar drill bit was coaxial with the elbow center of rotation. A lateral humeral epicondylar osteotomy was initiated from cranial, resting a saw blade on the PSI. The PSI was removed. The osteotomy was completed. The osteotomized epicondyle was elevated and retracted distally, exposing the joint capsule. The annular ligament was transected just cranial to the lateral collateral ligament against the radial head. The annular ligament attachment on the lateral coronoid process was released to allow adequate craniodistal retraction of the osteotomized lateral epicondyle. The anconeal process was osteotomized using an oscillating saw. The core post was placed in the condylar 2.0-mm hole. The 17-mm alignment plate was slid on the core post and maximally medialized, without placing torque on the tissues or subluxating the elbow joint. A drill sleeve was inserted in the proximal plate hole to place the proximal humeral pin. The caudal cortex of the humeral shaft was identified to center the pin and align the guide with the humeral shaft. A 2.8-mm drill bit was used through the drill sleeve to drill a bicortical pilot hole. A 7/64-inch (2.78-mm) positive profile pin was placed in the humeral shaft. The drill sleeve was secured to the alignment plate and to the positive profile pin using the 2 set screws. The procedure was repeated for the second humeral pin. The elbow was flexed using manual pressure so that the drill sleeve was centered over the radial head. Care was taken not to induce pronation/supination or varus/valgus angulation. A negative profile 3/32-inch (2.38-mm) pin was drilled through the drill sleeve at the craniocaudal midpoint of the radial head. The procedure was repeated for the caudal ulnar and cranial ulnar posts. Stability of the alignment plate was tested manually. If necessary, a slight varus or valgus deviation of the antebrachium was corrected before milling by loosening the radius and ulnar sleeve set screws, correcting the malalignment, and tightening the screws. A 3-cm-long window was created in the flexor carpi ulnaris fascia over the proximal third of the ulnar diaphysis. The flexor carpi ulnaris was retracted medially. A 2.0-mm drill

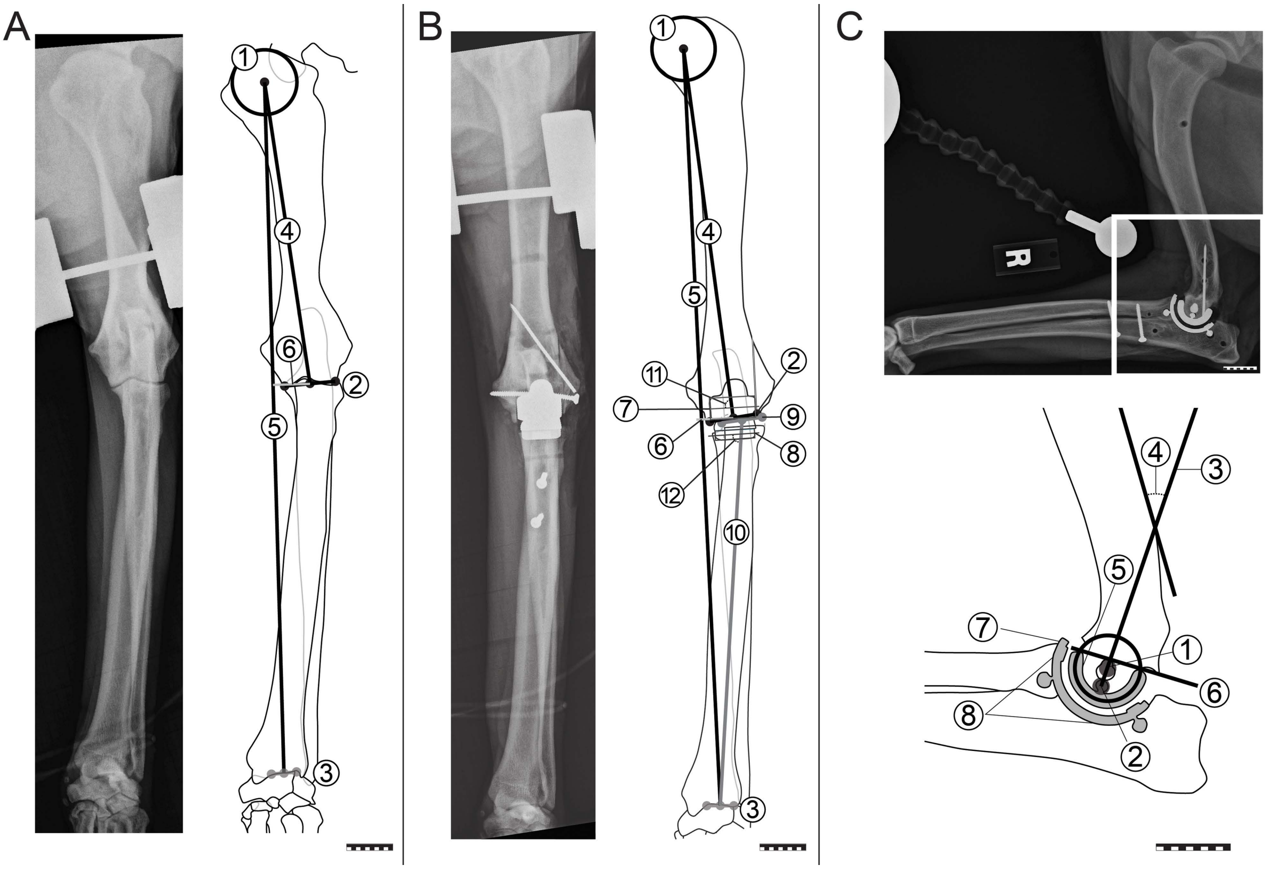

Figure 2—Craniocaudal (A and B) and mediolateral radiographic views (C) and corresponding illustrations before and after total elbow replacement. Before surgery (A), the elbow mechanical axis deviation is calculated by fitting a circle to humeral head (1), drawing lines along the distal aspect of the humeral condyle (2) and the distal radial articular surface (3), drawing the long axis of the humerus (4) as the line joining the center of circle (1) and the midpoint of line (2) and the long axis of the forelimb (5) as the line joining the center of circle (1) and the midpoint of line (3). Elbow medial axis deviation is the shortest distance between line (5) and the midpoint of line (2).[13] Antebrachial varus was measured as the angle between the long axis of the humerus (4) and radius (10). Elbow mechanical axis deviation and antebrachial varus are similarly measured after total elbow replacement (B). The orientation of the humeral prosthetic component in the frontal plane is the angle (11) formed by line (4) and a perpendicular to the transverse axis of the humeral component (line 7). The orientation of the radioulnar component in the frontal plane is the angle (12) formed by a perpendicular to the transverse axis of the radioulnar component (8) and the long axis of the radius (line 10), drawn as the line joining the midpoint of a line drawn across the proximal radial articular surface (9) and the midpoint of (3). On the mediolateral view (C), inclination of the humeral component (6) was the angle (4) formed by the line (3) joining the center of the humeral component (1) and the center of the humeral expansion post (2) and the caudal aspect of the humeral shaft. Inclination of the radioulnar component was the distance between the proximal axis of the radioulnar component and the proximal aspect of the radial head (7). Bone implant gaps were measured in 5 zones along the humeral (5) and radioulnar (8) components. Scale bars = 2 cm.

bit was used to drill 2 holes 15-mm apart across the diaphysis of the ulna and radius in a caudomedial to craniolateral direction. Two 2.7-mm self-tapping cortical screws were placed to achieve radioulnar stabilization. The drill plate was placed on the alignment plate and used to drill a 3.5-mm hole in the humeral condyle and two 4.5-mm holes in the radius and ulna. The milling arm was placed on the core post with the 7.0-mm milling bit. The milling distance was set with the drill collar by using a trial implant and subtracting approximately 2 mm from its mediolateral width. Milling was started cranially by plunging the mill to a depth of 2 to 3 mm, bringing the mill up, rotating the milling arm by approximately half of the mill diameter, and repeating the operation along the entire curvature of the milled area. The process was repeated 4 or 5 times at increasing depth. The milled bone bed was lavaged. Milling was repeated with an 8.0-mm milling bit using the sweeping technique. The location of the milled bed relative to the medial aspect of the medial coronoid process was evaluated. The trial implant was placed and its depth relative to the humeral condylar surface and the caudal ulnar surface was evaluated. Milling depth was adjusted so that the lateral surface of the trial implant after insertion was located 0.5 mm medial to the osteotomized humeral condyle surface. The ridge breaker was used to connect the expansion post holes to the milled surfaces. The practice 17-mm TATE cartridge TER implant was impacted. In a clinical case, expansion bolts would be inserted until flush with the humeral, radial, and ulnar posts. Practice implants have no expansion bolts.

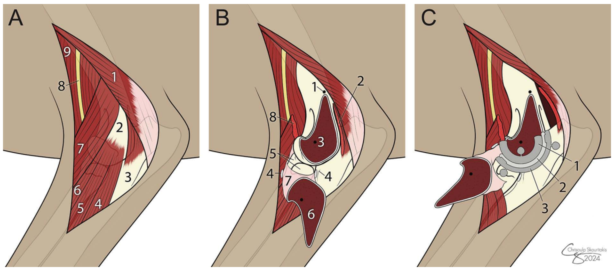

Figure 3—The lateral approach to the elbow for implantation of a TATE total elbow replacement prosthesis includes a lateral skin and fascial incision (A) that exposes the distal third of the brachium and proximal aspect of the antebrachium. The lateral head of the triceps (1) is retracted caudally. The distal portion of the humerus (2) and proximal aspect of the ulna (3) are exposed. The ulnaris lateralis (4), lateral (5) and common (6) digital extensors, extensor carpi radialis (7) muscles, radial nerve (8), and brachialis muscle (9) are visualized. Site preparation (B) includes the elevation and retraction of the extensor carpi radialis (8) and anconeus muscles (2). A guide (not shown), affixed to the humerus using 2 drill bits (1 and 3), has been used to osteotomize the lateral epicondyle (6). The annular ligament is transected at its cranial and caudal aspects (4). The epicondylar fragment is retracted distally, reflecting the joint capsule (7) and exposing the radial head. The humeral (1) and radioulnar (3) components are implanted simultaneously (C). A polyethylene liner covers the radioulnar component (2).

The pins and milling plate were removed. The range of motion of the elbow joint was evaluated to confirm the absence of impingement. Impinging bone was removed with rongeurs as needed. The epicondylar segment was reduced and stabilized with a 2.7-mm self-tapping cortical screw that was partially (90%) tightened. An antirotational 0.062-inch (1.55-mm) Kirschner wire was placed in the distal lateral epicondylar crest and the transcondylar screw was fully tightened. The annular ligament with the cranial portion of the joint capsule was sutured to the remaining cranial portion of the annular ligament that was attached to the lateral collateral ligament. The extensor carpi radialis just proximal to the joint was attached to the common digital extensor at their origin on the lateral epicondyle. The proximal extensor carpi radialis was sutured to the anconeus muscle using 2-0 PDS in a simple continuous pattern. Distally, the ulnaris lateralis and flexor carpi ulnaris fascia was sutured. The brachial fascia was closed using 2-0 PDS in a simple continuous pattern.

The medial approach, implant placement, and closure were performed as described previously.[11] Limbs were examined for the presence of iatrogenic injuries, including transection of the radial or ulnar nerve.

Postoperative evaluation

Elbow flexion and extension and antebrachial supination were measured using the methods used before surgery. Five radiographic views identical to the views acquired before surgery were acquired. On the neutral and stress craniocaudal radiographic views of the humerus, varus orientation of the radius relative to the humerus, deviation of the mechanical axis, and the corresponding laxities under stress were calculated using the methods described above and recorded. The mediolateral position of the humeral component relative to the center of the condyle was measured. The orientation of the humeral component relative to the long axis of the humerus was measured using a previously reported method and recorded (Figure 2).[9] On the craniocaudal radiographic view of the radius, the orientation of the radioulnar component relative to the long axis of the radius was measured and recorded.[9] On the mediolateral radiographic view, the orientation of the humeral component relative to the caudal aspect of the distal humeral diaphysis (humeral component inclination) and the position of the radioulnar component relative to the radial head (radioulnar component inclination) were measured and recorded. Implant-bone contact was evaluated using zonal analysis on the mediolateral view. The maximal width of implant-bone gaps was measured and recorded cranial (zone 1) and caudal to the humeral expansion post (zone 2), cranial to the radial expansion post (zone 3), between the radial and ulnar expansion posts (zone 4), and caudal to the ulnar expansion post (zone 5). Bone protruding cranial or caudal to the humeral component on the mediolateral view was measured and recorded.

Statistical analysis

Analyses were done using statistical software (SAS version 9.4; SAS Institute). Normality was evaluated using the Shapiro-Wilk test. Data were considered normally distributed when $W > 0.90$ and $P > .05$. Data that were not normally distributed are reported as median (range). The duration of surgery followed a logarithmic distribution. Duration of surgery data were log transformed before ANOVA. Other data that were not normally distributed were rank transformed before ANOVA. The effect of TER (preoperative or postoperative) and the approach (medial or lateral) were evaluated using repeated measures ANOVA. Regression analysis was used to evaluate the relationship of joint motion/laxity and implant orientation, stratified by approach. The slope of regression lines for medial and lateral approaches was compared. Significance was set at $P < .05$.

Results

Twelve dogs were included in the study. The median dog weight was 27.4 kg (range, 25.0 to 35.0 kg). One dog had moderate elbow OA, with a score of 27/54 in the left elbow and 22/54 in the right. Other dogs had no OA. The median duration of surgery was 39 minutes and 30 seconds (range, 32 minutes and 22 seconds to 60 minutes and 24 seconds) for the lateral approach and 40 minutes and 41 seconds (32 minutes and 20 seconds to 80 minutes and 7 seconds) for the medial approach. These durations did not differ statistically ($P = .499$) and followed logarithmic curves whose asymptotes suggested that, with experience, the duration of surgery in cadavers would be approximately 30 minutes for both approaches **(Figure 4)**.

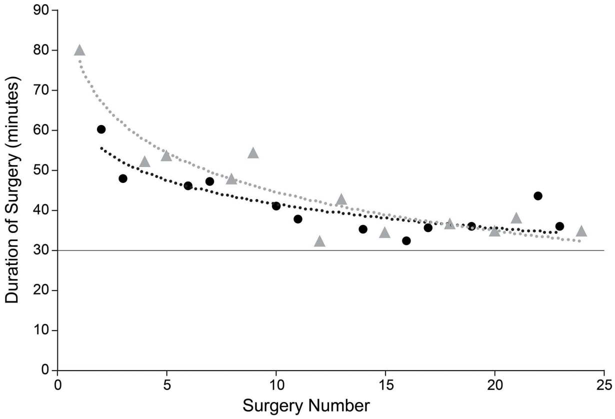

Figure 4—Linear regression plots showing the duration of 24 total elbow replacement surgeries performed using a lateral (n = 12, black circles) or medial approach (12, gray triangles). For both, logarithmic regression lines show a decrease in surgery duration with repeated procedures. The asymptotes of these regression lines suggest that, with experience, total elbow replacement performed using a lateral or a medial approach would take approximately 30 minutes to complete.

Several intraoperative technical difficulties were encountered. During the lateral approach, 1 core post was directed too caudally and was redrilled. Another core post subjectively appeared excessively cranial but was not corrected. One epicondylar osteotomy had different planes for cuts made from the cranial and the caudal aspect of the humerus. No corrective action was required. Motion between the radius and ulna was detected in 1 dog before milling. Motion was eliminated using pointed reduction forceps. In 1 dog, the retaining clip separated from the implant before final impaction. Impaction was completed without the retaining clip. During the medial approach, 1 cutting guide was placed too distally and was repositioned. One osteotomy had partial cuts in 2 planes seemingly because the chest interfered with the drill alignment. The bone appeared stable, and no action was taken. In 1 dog, the radial pin securing the milling plate was too cranial and required replacement after increased flexion of the elbow. The technical difficulties did not appear to negatively influence implant placement.

Preoperatively, the orientation, motion, collateral ligament laxity, and mechanical axis deviation of the limbs that underwent TER with a lateral and medial approach did not differ statistically (*P* ranging from .336 to 1.000; **Table 1**). When a lateral approach was used, TER led to a 5° loss of extension (*P* = .006) and an 11° loss of flexion (*P* < .001). Surgery did

Table 1—Mean ± SD prosthetic component orientation and elbow joint laxity after total elbow replacement performed using a lateral or medial approach in 12 dogs weighing 25 to 35 kg.

Parameter	Lateral approach	Medial approach
Preoperative measurements		
Flexion (°)	25 ± 6	24 ± 6
Extension (°)	166 ± 3	166 ± 2
Supination (°)	5.0 ± 2.6	4.5 ± 3.1
Varus angulation, neutral‡ (°)	7.14 ± 5.46	7.28 ± 5.40
Varus angulation (minimal), valgus stress‡ (°)	1.86 ± 4.93	2.56 ± 4.69
Varus angulation (maximal), varus stress‡ (°)	10.83 ± 6.05	10.99 ± 6.61
Frontal plane laxity† (°)	8.98 ± 2.30	8.43 ± 3.32
Mechanical axis deviation, neutral* (%)	3.31 ± 1.56	3.21 ± 2.48
Mechanical axis deviation, valgus stress* (%)	1.18 ± 1.80	1.29 ± 1.92
Mechanical axis deviation, varus stress* (%)	4.95 ± 2.33	4.60 ± 2.67
Frontal plane total medial axis deviation† (%)	3.76 ± 1.18	3.31 ± 1.35
Postoperative measurements		
Flexion (°)	36 ± 7	33 ± 7
Extension (°)	161 ± 5[a]	153 ± 7[b]
Supination (°)	6.8 ± 6.0	7.1 ± 3.4
Varus angulation, neutral‡ (°)	6.95 ± 4.00	5.58 ± 5.28
Varus angulation (minimal), valgus stress‡ (°)	1.69 ± 4.50	3.11 ± 5.82
Varus angulation (maximal), varus stress‡ (°)	11.95 ± 4.56	9.00 ± 7.06
Frontal plane laxity† (°)	10.26 ± 3.88[a]	5.88 ± 2.78[b]
Mechanical axis deviation, neutral* (%)	3.07 ± 1.77	2.74 ± 2.89
Mechanical axis deviation, valgus stress* (%)	0.89 ± 2.04	1.33 ± 2.54
Mechanical axis deviation, varus stress* (%)	5.31 ± 2.02[a]	3.91 ± 3.04[b]
Frontal plane total medial axis deviation† (%)	4.43 ± 1.72[a]	2.58 ± 1.19[b]
ML humeral component position¶ (mm)	−1.05 ± 1.56[a]	0.59 ± 1.31[b]
ML humeral component orientation‡ (°)	2.7 ± 2.2	1.7 ± 3.4
CC humeral component orientation (°)	37 ± 12[a]	29 ± 5[b]
ML radioulnar component orientation‡ (°)	7.4 ± 4.3[a]	1.8 ± 2.4[b]
CC radioulnar component orientation (mm)	−1.8 ± 2.4	−2.4 ± 2.5

CC = Craniocaudal (ie, in the sagittal plane). ML = Mediolateral (ie, in the frontal plane).

*Measured using the method described by Goodrich et al[13] and reported as a percentage. †The sum of valgus (medial collateral ligament) and varus (lateral collateral ligament) laxity. ‡Positive numbers represent varus. ¶Deviation from center, positive numbers represent medial deviation.

[a,b]Within a row, mean values with different superscript letters differ statistically among approaches (*P* < .05).

not lead to statistically significant changes among other parameters of limb orientation and joint laxity. Median bone-implant contact (range) was 0.3 mm (0.0 to 0.7 mm) in zone 1, 0.0 mm (0.0 to 0.4 mm) in zone 2, 0.0 mm (0.0 to 0.7 mm) in zone 3, 0.0 mm (0.0 to 1.2 mm) in zone 4, and 0.4 mm (0.0 to 0.9 mm) in zone 5. Median protruding bone (range) was 0.0 mm (0.0 to 5.4 mm) cranial to the humeral component and 5.8 mm (0.0 to 9.7 mm) caudal to the humeral component. When a medial approach was used, TER led to a 13° loss of extension ($P < .001$), a 9° loss of flexion ($P < .001$), a 2.6° increase in supination ($P = .049$), a 48% decrease in medial collateral ligament laxity ($P = .009$), and a 26% decrease in medial mechanical axis deviation ($P = .021$). Surgery did not lead to changes among other parameters of limb orientation and joint laxity. Median bone-implant contact (range) was 0.0 mm (0.0 to 0.7 mm) in zone 1, 0.1 mm (0.0 to 0.8 mm) in zone 2, 0.0 mm (0.0 to 0.4 mm) in zone 3, 0.1 mm (0.0 to 0.4 mm) in zone 4, and 0.1 mm (0.0 to 1.1 mm) in zone 5. Median protruding bone (range) was 0.0 mm (0.0 to 3.6 mm) cranial to the humeral component and 0.0 mm (0.0 to 5.5 mm) caudal to the humeral component. Compared to the medial approach, the lateral approach resulted in 8° more elbow extension ($P = .003$) and preserved preoperative frontal plane laxity (10.26°), while the medial approach decreased frontal plane laxity (5.88°, $P = .004$). The lateral approach also led to a humeral component that was 1.6 mm more lateral relative to the center of the humeral condyle ($P < .011$) and more inclined (craniodorsally oriented) by 8° ($P = .033$) and to a radioulnar component that had 5.6° greater varus ($P = .001$) than those placed using a medial approach. When both approaches were combined, TER led to a loss of flexion ($P < .001$) and extension ($P < .001$), an increase in supination ($P = .023$), and a decrease in medial collateral ligament laxity ($P = .046$).

For TER implanted using a lateral approach, placing the radioulnar component more cranially relative to the radial head by 2 mm led to an approximately 1% increase in lateral deviation of the mechanical axis ($P = .005$, $R^2 = 0.569$) and a 1% decrease in varus laxity ($P = .005$, $R^2 = 0.561$). Other changes in prosthetic component orientation were not significantly associated with changes in limb alignment or collateral ligament laxity for the lateral and medial approaches. The slopes of the regression lines for the influence of radioulnar component varus ($P = .012$) and inclination ($P = .049$) on lateral collateral ligament laxity differed among the lateral and medial approaches. Other regression lines evaluating the influence of humeral and radioulnar component orientation on limb alignment and joint stability did not differ among the medial and lateral approaches.

Discussion

No anatomic injury was observed and no statistically significant increase in collateral ligament laxity was observed after TER using a lateral or a medial approach. We rejected the hypothesis that the lateral approach results in statistically significant increased collateral ligament stability. Interestingly, however, medial collateral ligament laxity decreased because of the medial approach. Based on the surgeon's experience, the proximity of the milling plate and humeral condyle is key to milling accuracy because deflection of the milling bit appears more likely when the plate is elevated from the bone bed. The placement of the milling plate in proximity to the bone requires the retraction of the osteotomized epicondyle distally and cranially. Also, the pressure exerted on the milling plate tends to compress the antebrachial muscles, potentially leading to a deflection of the antebrachium since the joint temporarily has no collateral ligament support. Subjectively, the antebrachial muscles interfered less with the placement of the milling plate on the lateral aspect of the elbow than on its medial aspect. This is likely because antebrachial flexor muscles are approximately 20% bulkier than antebrachial extensors and because the largest extensor muscle, the extensor carpi radialis, is elevated from the humerus and retracted cranially during surgery, while the flexor muscles remain inserted on the medial epicondylar fragment.[18] During the medial approach, pressure on the milling plate may have led to a slight increase in the joint gap. In turn, that gap may have led to a decrease in the amount of bone removed on the medial aspect of the joint, leading to a slight radioulnar component misalignment and increased medial compartment tension. Increased medial compartment tension is the likely cause of the decreased medial collateral ligament laxity that was observed after implant placement using a medial approach. It is also possible that a change in position of the osteotomized epicondylar fragment led to increased tension in the medial collateral ligament. This seems unlikely, since the osteotomy and reattachment techniques were identical for the medial and lateral epicondyle, and thus, changes in collateral ligament tension from osteotomy and reattachment would likely be similar on the medial and lateral aspects of the elbow joint.

Based on the absence of anatomic injury to nerves and collateral ligaments, we concluded that the lateral approach was safe. This finding was expected since a lateral approach to the elbow is widely used to manage distal humeral and proximal ulnar fractures, to reduce radial head luxation, and to perform ulnar ostectomies.[19–21] A lateral approach to the elbow was also used to implant the Iowa Elbow prosthesis.[22] Because of the absence of interference from the chest or the opposite forelimb when a lateral approach to the elbow is used, it is possible that the procedure would be more precise. However, since patient-specific guides were used to align the core post, the precision of drilling the core post across the condyle from its medial or lateral aspect could not be evaluated. In 1 study[23] evaluating safe corridors for the placement across the humeral condyle, drilling from medial to lateral carried a higher risk of penetrating the articular surface than drilling from lateral to medial. Subjectively in the current study, using a lateral approach rather than a medial approach facilitated tissue dissection and facilitated the placement of the radioulnar screws. In human TER, several lateral, posterior (caudal), and medial approaches are used. In 1 report,[24] a lateral approach was recommended to avoid the tenotomy of the triceps tendon that is required when performing a posterior approach. One study[25] reported that the strength of the triceps muscle was maintained when TER was performed through a lateral approach. A systematic view of TER reported similar success rates when a lateral, posterolateral, or posterior approach was used.[26] Some authors[27] recommend a posterior approach to the elbow to minimize the risk of ulnar nerve injury, since these injuries are a common complication of TER in humans. In 1 study[28] of 126 TER, approximately 10% of patients (n = 13 of 126) had ulnar nerve symptoms, most often sensory (12 of 126) but also motor (2 of 126). In an anatomic study[29] of the human elbow, cutaneous nerve injuries were deemed less likely after a posterior approach than a medial or a lateral approach. Nerve preservation is also a concern during canine TATE TER. With a lateral approach, the surgeon should be mindful of avoiding traction or damage to the radial nerve. With a medial approach, the ulnar nerve should be identified, retracted, protected, and possibly transposed.

In the current study, the lateral approach was effective. The duration of surgery when TER was performed using a lateral approach did not differ statistically from a medial approach. We therefore rejected the hypothesis that TER was more rapid when using a lateral approach than a medial approach. The lead surgeon in all TER (LPG), had extensive clinical and research experience using the medial approach but had limited experience using the lateral approach. This difference in experience may have introduced a bias toward the medial approach. With repetition, the TER performed using either a lateral or a medial approach became more rapid, even though the investigators were experienced in TER before the study. The changes in surgery duration over time suggest that, with repetition and experience, TER can be performed using a lateral or a medial approach in approximately 30 minutes in cadavers. This suggests that cadaveric training is useful to decrease the duration of surgery. However, changes in surgery duration with repetition may not happen during live surgery on clinical patients because preexisting pathology and hemorrhage complicate the procedure.

The precision of prosthesis implantation appeared similarly accurate with both approaches. We therefore rejected the hypothesis that the lateral approach leads to a more precise prosthetic position in TER. Implant-bone gaps for the humeral and radioulnar components were absent or were minimal for implants placed using the lateral and medial approaches, except three 1.0- to 1.2-mm wide gaps in the central or caudal zone of the radioulnar component, indicating that all components fit well in their bone preparation. This suggests that the milling process resulted in satisfactory bone bed preparation in all cases, particularly considering that the prosthetic components used in this cadaveric study were practice implants, featuring alignment fins rather than the expansion posts found in clinical implants. The purpose of the use of expansion posts is to optimize bone-implant contact, decrease implant-bone motion, and increase the likelihood of bone ingrowth into the prosthetic components in the early postoperative period. Since this was a short-term study and since all implants remained stable during the study, the use of practice implants instead of clinical implants likely did not influence the findings of the study.

No statistically significant changes in limb alignment within the frontal plane (ie, varus or deviation of the mechanical axis) or the transverse plane (ie, change in supination) were observed after the lateral approach. The medial approach did not lead to a change in limb alignment within the frontal plane, but it led to a statistically significant increase in antebrachial supination. That change was small (< 3°) and, therefore, would have no clinical impact. Both the lateral and medial approaches led to statistically significant losses in elbow flexion and extension, albeit the loss of extension was less with the lateral approach (5°) than with the medial approach (13°). A loss of flexion of approximately 10° would likely have no clinical impact. However, a loss of extension of 10° may interfere with limb use.[30]

A difference of 8° in humeral component inclination (alignment in the sagittal plane) between implants placed using a lateral or medial approach was observed. However, no difference in radioulnar component inclination between implants placed using a lateral or medial approach was observed. The placement of the humeral component with more inclination when using the lateral approach indicates that during the lateral approach, the alignment plate was affixed to the humerus with a deviation of its axis toward flexion. The lateral supracondylar ridge slopes toward its cranial aspect, potentially impeding the placement of the fixation pins in the frontal plane bisecting the humeral anatomic axis and leading to placement of the fixation pins caudal to the humeral anatomic axis. A proximal and caudal tilt of the alignment plate leads to a distal and cranial tilt of the plate, increasing inclination of the humeral component. This issue may be related to the fact that the alignment plate was designed for a medial approach, where the humeral surface does not slope cranially. Inclination of the radioulnar component, however, is independently set by aligning the cranial aspect of the radial head with a mark on the milling plate. Therefore, a cranial tilt of the alignment plate may not lead to increased inclination of the radioulnar component. Because a slightly more inclined implant would have a lower profile on the caudal aspect of the condyle, the difference in humeral component alignment in the sagittal plane was the likely cause of increased preservation of elbow extension after TER using a lateral approach. Suboptimal component placement has also been shown to negatively impact functional and clinical outcomes after TER in humans.[31] Other studies[32,33] of human TER confirmed that accurate reconstruction of the center of rotation of the elbow was associated with improved durability and decreased complications. However, 1 review[9] of 33 TATE TER in dogs did not identify an association between implant alignment and clinical outcome. However, long-term data were limited in that study. In human total joint replacement, the precision of implantation has been shown to influence bearing surface stresses, implant-related complications, the need for revision surgery, working life expectancy of the implant, and clinical outcomes.[34,35] In 1 study[36] evaluating total knee replacement in humans, a 3° error in varus positioning of the tibial component may have led to accelerated liner wear. Similarly in dogs, changes in stifle joint loading were identified when the tibial component of a total knee implant was misaligned by 3°.[37]

Patient-specific drilling and sawing guides were used in the current study to increase the consistency of implant placement. The guides facilitated the placement of the core post along the center of rotation of the humeral condyle and the epicondylar osteotomy. The guides were designed to "snap" in place. The snap-fit effect is the use of small undercuts to lock the guide in place with small pressure onto specific anatomic locations, increasing guide stability.[38,39]

Guide placement was satisfactory for most surgeries, with 3 exceptions for 2 lateral guides and 1 medial guide. The contact surface of these guides could possibly be optimized to facilitate their placement. Patient-specific guides have been shown to increase the accuracy of implantation of total joint components in humans and in dogs,[15,40] as well as increase the accuracy of a wide range of other surgical procedures.[38] Because of their increased precision, in dogs, patient-specific guides are rapidly becoming the dominant procedures for total joint replacement other than total hip replacement.

This study had limitations. Most elbow joints did not have OA. The influence of articular fibrosis and osteophytes on the accuracy and stability of a lateral or medial approach is not known. While the duration of surgery was recorded, the time required to perform each of the surgical steps was not recorded. A more specific assessment of surgery duration would provide information that could facilitate surgeon training or prompt refinements in the procedure. Also, since this study was limited to TATE TER implants, the findings of the current study should be cautiously extrapolated to other TER systems.

From the findings of this study, we concluded that the use of a lateral approach to implant a TER prosthesis was safe and effective: limb alignment was maintained, joint motion was minimally impacted, and collateral ligament strength was unchanged.

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