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Effect of cranial tibial artery laceration on radiographic bone healing and perioperative complications in dogs undergoing tibial plateau leveling osteotomy

Francesco Ferrari[a], Roberto Tamburro[b], Maurizio Longo[a], Federica Alessandra Brioschi[a], Luigi Auletta[a,*], Damiano Stefanello[a]

[a] Department of Veterinary Medicine and Animal Sciences (DIVAS), University of Milano, via dell'Università 6, 29600 Lodi, Italy
[b] Department of Veterinary Medicine, University of Teramo, Località Piano d'Accio, 64100 Teramo, Italy

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ABSTRACT

During tibial plateau leveling osteotomy (TPLO), the laceration of the cranial tibial artery (LCTA) may occur, and the ligation of the cranial tibial artery might lead to impaired blood supply to the osteotomy site. The present case-control study aimed to evaluate the effect of LCTA on TPLO healing and the occurrence of perioperative complications. The incidence and predisposing factors to LCTA were also investigated.

Fourteen cases experiencing LCTA were retrospectively enrolled from medical records of two veterinary teaching hospitals (LCTA group), whereas 28 randomly selected TPLOs that did not experience LCTA were included in the control group. Signalment data, proximal tibial epiphysis conformation, osteotomy features, perioperative complications, and bone healing were compared between the two groups. Bone healing was evaluated using the modified radiographic union scale for tibial fracture and the visual analog scale.

The mean incidence was 9.6%. Bodyweight was significantly higher in the LCTA group compared to the control group ($P = 0.009$). Dogs belonging to the LCTA groups were significantly younger ($P = 0.01$). Intraoperative hypotension was significantly overreported in the LCTA group ($P = 0.0001$). None of the other variables differed significantly between the two groups.

Dogs' size seems to be a predisposing factor, with dogs weighing >15 kg having 22 times more chance of experiencing LCTA. Due to the well-developed collateral blood supply of the canine hindlimb, LCTA and the closure of the cranial tibial artery did not appear to delay the radiographic bone healing or affect the incidence of perioperative complications.

1. Introduction

The popliteal artery sits behind the stifle in the popliteal fossa and bifurcates into the cranial and caudal tibial arteries nearby the distal border of the popliteus muscle in the space between tibia and fibula trough the interosseus membrane (Bezuidenhout, 2013). The cranial tibial artery passes caudal to the stifle joint between the tibial condyles, close to the caudal tibial cortex in a lateral and distal direction (Bezuidenhout, 2013; Moles and Glyde, 2009; Mullins et al., 2020). During its path, cranial tibial artery crosses underneath the muscle fibularis longus to gain the deep surface of the long digital extensor muscle. Cranial tibial artery supplies almost the entire blood supply of the cranial tibial and lateral digital extensor muscles, and it gives an epiphyseal vessel to the tibia (Bezuidenhout, 2013; Cieciora et al., 2022; Moles and Glyde, 2009; Mullins et al., 2020).

The laceration of the cranial tibial artery (LCTA) is an intraoperative complication described in up to 3.9% of dogs during tibial plateau leveling osteotomy (TPLO) (Montano et al., 2023; Pacchiana et al., 2003; Pages et al., 2022; Priddy 2nd et al., 2003; Stauffer et al., 2006). It was initially reported with an incidence of <1% during the muscle envelope elevation from the tibia for gauze positioning to protect the caudal soft tissues during TPLO (Pacchiana et al., 2003; Priddy 2nd et al., 2003; Stauffer et al., 2006). Recent publications reported an LCTA incidence of 3.6% (Pages et al., 2022) and 3.9% (Montano et al., 2023)

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* Corresponding author at: Department of Veterinary Medicine and Animal Sciences (DIVAS), University of Milano, 29600 Lodi, Italy.
E-mail addresses: francesco.ferrari@unimi.it (F. Ferrari), rtamburro@unite.it (R. Tamburro), maurizio.longo@unimi.it (M. Longo), federica.brioschi@unimi.it (F.A. Brioschi), luigi.auletta@unimi.it (L. Auletta), damiano.stefanello@unimi.it (D. Stefanello).

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as direct damage by the blade during the radial osteotomy in its exit point on the caudal tibial cortex (Matres-Lorenzo et al., 2018; Roses et al., 2022). The LCTA leads to a severe hemorrhage, which is difficult to control due to the involvement of several arterial branches, arising from the cranial tibial artery at the level of the caudolateral aspect of the tibia, distal to the cranialmost aspect of the tibial tuberosity (Moles and Glyde, 2009). The lateral position of the cranial tibial artery, opposite to the medial surgical access used for TPLO, hinders prompt and effective hemorrhage control. In this perspective, the distraction of the osteotomy was described to gain control of the bleeding vessel (Matres-Lorenzo et al., 2018). Regardless of the technique used for hemostasis, blood flow would be impaired, possibly causing ischemia, which could lead to postoperative complications such as edema, seroma, and healing disorders (Cieciora et al., 2022). Ischemia is defined as a series of cellular events resulting in the failure of tissue homeostasis and impaired cellular function consequent to inadequate tissue perfusion (Lambert, 2018). While transient ischemia is needed to initiate fracture healing, prolonged ischemia might compromise healing (Lu et al., 2007; Takahashi et al., 1999) because it leads to a reduction of cell proliferation and bone formation, increased apoptosis, and fibrous and fatty tissue formation in the fracture site, predisposing to delayed union or non-union (Lu et al., 2007).

The primary aim of the present study was to compare the radiographic bone healing in healthy dogs experiencing and not experiencing LCTA during TPLO. The secondary aim was to explore the role of signalment data, tibial conformation, osteotomy features on the occurrence of LCTA and the incidence of the perioperative complications after cranial tibial artery ligation. The underlying hypothesis was that LCTA, and consequent occlusion of the cranial tibial artery would impair bone healing.

2. Materials and methods

The electronic medical records from the Veterinary Teaching Hospital of the Department of Veterinary Medicine and Animal Sciences of the University of Milan and of the Veterinary Teaching Hospital of the Department of Veterinary Medicine of the University of Teramo were retrospectively reviewed from October 2020 to October 2023. Dogs undergoing TPLO with American Society of Anesthesiologists (ASA) status I/II were evaluated for the enrollment in this study. All surgical procedures were performed according to the best standard of veterinary practice; no changes in the clinical and operative protocols were applied for the present study. All owners signed a written informed consent for the surgery and for the use of medical data for scientific purposes.

Patients were included if the following data were available for review: signalment data, including at least age, sex, bodyweight and body condition score (BCS) (Freeman et al., 2011); mediolateral and caudocranial pre- and post-operative (immediately and at >4 weeks) radiographs of the entire stifle joint, including the whole tibia and the hock; a postoperative clinical evaluation performed together with the last radiographic follow up evaluation; surgical and anesthesiologic reports including the variables detailed in the material and methods section. Exclusion criteria were represented by concomitant corrective femoral or tibial osteotomies, TPLO performed for the management of multi-ligament injuries of the stifle, and an ASA status higher than II.

The present study was designed as a case-control study. The case-control ratio was 1:2; the statistical unit of interest was considered as each stifle joint. Dogs undergoing TPLO that experienced LCTA represented the case sample population (LCTA group). The LCTA was defined as an intraoperative extensive bleeding, synchronous with the heartbeat, that needed ligation or vascular clip application to control hemorrhage. If LCTA occurred bilaterally in the same patient, each stifle was considered as a single case. Controls were randomly selected among the remaining included patients undergoing TPLO (control group). Cases bilaterally operated in which the other hindlimb did not experience such intraoperative complication were forced in the control group. Randomization was obtained using the specific function in Excel (Excel© Microsoft for Mac, v. 16.43, Redmond, WA, USA).

For each patient included, signalment data, *i.e.*, age, sex, breed, bodyweight and BCS, were recorded. Each patient was further categorized by size (< 15 kg, > 15 kg), according to the bodyweight. The following surgical variables were recorded: involved hindlimb; TPLO saw blade radius; type of plate; occurrence of intraoperative unresponsive hypotension; the need for blood transfusion; hemostasis technique used for the management of LCTA; duration of the surgery; development of surgical site infection – inflammation (SSI) (Horan et al., 1992; Nelson, 2011); occurrence of implant failure (Johnson, 2016); time from surgery to the last re-evaluation. Intraoperative hypotension was defined as “unresponsive” if two subsequent intravenous boluses of 10 ml/kg of lactated Ringer’s solution, each infused over 15 min, were not effective to achieve normotension (mean arterial pressure higher or equal than 60 mmHg).

The following radiographic variables were recorded: proximal tibial epiphysis conformation; Z angle (Inauen et al., 2009); relative tibial tuberosity width (rTTW) (Inauen et al., 2009); preoperative, immediately postoperative, and >4 weeks follow-up evaluation of the tibial plateau angle (TPA) (Fettig et al., 2003), the mechanical medial proximal tibial angle (mMPTA) (Dismukes et al., 2007) and the mechanical medial distal tibial angle (mMDTA) (Dismukes et al., 2007); osteotomy inclination angle; apposition of the osteotomized fragments; distance of eccentricity (DOE); the ratio between the distance from the intercondylar eminence to the exit point of the radial osteotomy on the caudal tibial cortex and the radius of the used blade; time from surgery to the last radiographic evaluation. Proximal tibial epiphysis conformation was subjectively classified as “high” or “low” based on the tibial tuberosity localization (Boudrieau, 2009). Calibration was performed using a 25 mm or 10 mm radiographic reference sphere localized at the level of the proximal tibia. If the reference sphere had not been utilized, the TPLO plate was used as the calibration tool.

The intended centroid of the osteotomy (ICO) and the actual centroid of the osteotomy (ACO) were identified, and the DOE was calculated as previously described (Tan et al., 2014). Further characterization of the ACO was retrieved using a Cartesian plane having as Y axis the mechanical axis of the tibia and as X axis the perpendicular straight line to the Y axis passing through the ICO. The coordinates were considered to have a “positive” value in the proximal and caudal direction from the ICO; otherwise, the values were considered “negative” in the distal and cranial direction from the ICO. The osteotomy inclination angle was measured on the frontal plane by the means of the medial distal angle arising from the intersection of the mechanical tibial axis and the tangent to the osteotomy line (Fig. 1).

The apposition was quantified, in the sagittal plane, measuring the gap between the fragments at the wider point cranial and caudal to the TPLO plate, whereas, in the frontal plane, the magnitude of the two-fragment shifting was measured on the lateral side, without specifying if the distal fragment was translated laterally or medially.

All radiographic measurements were performed by one of the authors (F.F.) with a digital software (VPOP version 2.9.2 Copyright © 2023 VetSOS Education Ltd). The radiographic healing was scored by a European boarded specialist in diagnostic imaging (ML) through two previously validated scales, the modified radiographic union scale for tibial fracture (mRUST) (Walker et al., 2022) and the visual analog scale (VAS) (Leal et al., 2023).

2.1. Statistical analysis

All data were recorded on electronic spreadsheet (Excel© Microsoft for Mac, v. 16.43, Redmond, WA, USA) and then imported into a statistical software (Prism©, GraphPad Software, Inc., v. 8.2.0, San Diego, CA, USA; IBM® SPSS® Statistics, IBM Corp., v. 26.0.0.0, Armonk, NY, USA; JMP Pro, v. 16.0, SAS Institute, Cary, NC, USA). Continuous variables were tested for normality with the Shapiro-Wilk’s W test, and data

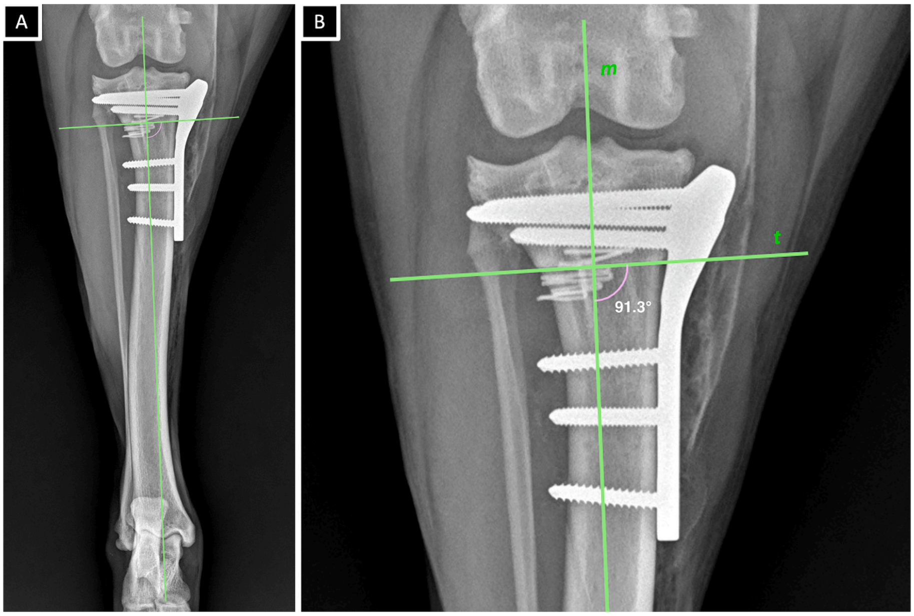

Fig. 1. Example of measurement of the osteotomy inclination angle. In A, an overview of the drawn lines to measure the osteotomy inclination angle. In B, the measured angle; *m* represents the mechanical tibial axis on the frontal plane, *t* represents the tangent to the osteotomy line.

were reported as mean ± SD or median (range), according to parametricity.

The incidence of the LCTA was calculated as the ratio of the cases over the total includable TPLO performed at the two institutions during the study period. Moreover, the incidence of LCTA was compared between the two surgeons with a Fisher's exact-test, and the corresponding odds ratio (O.R.) and 95% confidence interval (95%CI) were calculated. The homogeneity between groups was tested by comparing signalment data, the plate used, and the latest re-evaluation effective date (*i.e.*, days from the surgery). Continuous variables were compared with a pooled Student's *t*-test (days for 2-months re-check, osteotomy inclination angle, *y* coordinate) or a Welch's ANOVA, depending on Levene's test for homoscedasticity, or with the Mann-Whitney's *U* test according to data distribution. The BCS, the mRUST, and VAS scores were compared between groups with the median test. Categorical data were compared with the chi-square test.

Power analysis to explore the sample size needed to find a difference between the two groups for the mRUST and VAS scores was performed with G*Power® 3.1 software. The effect size was calculated using the mean ± SD obtained from the scores assigned in the present study. *A priori* function was used to calculate the sample size, considering non-parametric comparisons of the means between two groups with the case-to-control 1:2 allocation ratio, an effect size $d = 0.22$ for mRUST and $d = 0.14$ for VAS, $\alpha = 0.05$ and power (1-β) of 0.8 (80%).

A repeated measure ANOVA, with Geisser-Greenhouse correction and a mixed model for missing data, was applied to evaluate the influence of the group, time, and their interaction on TPA, mMPTA, and mMDTA. *Post hoc*, the Fisher's least significant difference (HSD) test was applied between and within groups.

3. Results

During the 3-year study period, a total of 154 TPLOs were selected for possible inclusion. All surgical procedures were executed by a single surgeon at each Institution (F.F. and R.T.). Eight TPLOs were excluded (4 cases due to the association of tibial tuberosity transposition and trochlear block recession sulcoplasty, 2 cases due to the association of tibial cranial closing wedge osteotomy, 1 case each for multi-ligaments injuries and femoral medial closing wedge osteotomy). Among the 146 TPLOs included, 14 cases of LCTA were identified, with a mean incidence of 9.6%, ranging between 8.7% and 10.4% in the two Institutions, without any significant differences ($P = 0.78$). In one Institution, all procedures were performed without the jig nor any caudal gauze protection (LCTA incidence 10.4%), whereas in the second Institution were performed with the use of both (LCTA incidence 8.7%). In the control group, 28 TPLOs were included. One patient undergoing bilateral staged TPLO experienced bilateral LCTA and was included twice in the LCTA group. One LCTA case underwent TPLO on the contralateral hindlimb without experiencing LCTA and, hence, it was forced in the control group.

Signalment data are summarized in Table 1. Bodyweight was significantly higher in the LCTA group compared to the controls ($P = 0.009$). Size was significantly different between groups, with all LCTA cases belonging to the >15 kg size category ($P = 0.004$) with an O.R. of 22 (95%CI 1.2–404.7). Dogs belonging to the LCTA group were significantly younger than controls ($P = 0.01$).

The BCS distribution within the LCTA group was: BCS 5 in 4 (29%) patients, BCS 6 in 5 (36%), BCS 7 in 4 (29%), and BCS 8 in 1 (7%); for the control group the BCS class distribution was: BCS 4 in 2 (7%) patients, BCS 5 in 10 (36%), BCS 6 in 7 (25%), BCS 7 in 5 (18%), BCS 8 in 2 (7%), and BCS 9 in 2 (7%). Sex distribution and represented breeds in the sample are summarized in Fig. 2.

The hindlimb involved by the LCTA was the left in 4 (29%) and the right in 10 (71%) cases; control cases had the TPLO performed on the left hindlimb in 9 (32%) and on the right one in 19 (68%). No significant differences were detected for BCS ($P = 0.48$), sex ($P = 0.54$), breed distribution ($P = 0.12$), and hindlimb involved ($P = 0.81$).

Intraoperative unresponsive hypotension was reported in 7 patients, all belonging to the LCTA group ($P = 0.0001$). Similarly, blood transfusion was performed in 1 patient from the LCTA group ($P = 0.33$). Hemostasis techniques applied in the LCTA group for the management

Table 1
Mean ± SD or number of cases of the signalment data in the two study groups.

	Bodyweight (kg)	Age (months)	Size (≤15 kg, >15 kg)
LCTA	$34.9 \pm 10.0\ ^{A}$	58 ± 34^{B}	$14 > 15\text{kg}^{A}$
Control	23.3 ± 14.1^{B}	$84 \pm 28\ ^{A}$	$12 \leq 15\text{ kg} – 16 > 15\text{kg}^{B}$

Statistic: between groups analysis within each variable A > B $P < 0.01$; LCTA: laceration of the cranial tibial artery group.

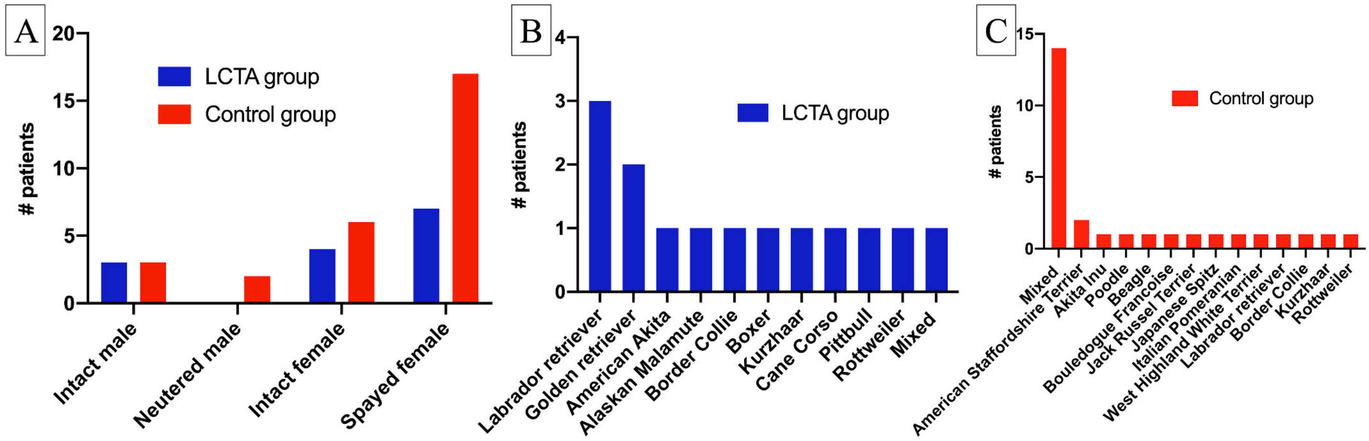

Fig. 2. Graphic representation of the number of patients by sex and breed in the two study groups. In A, number of patients by sex in the LCTA group (in blue) and in the Control group (in red). In B, number of patients by breed in the LCTA group. In C, number of patients by breed in the Control group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the hemorrhage, after the distraction of the two fragments (Matres-Lorenzo et al., 2018), were the application of vascular clip in 9 (64%) and artery ligation in 5 (36%) patients. Duration of surgery was significantly longer ($P = 0.026$) for the LCTA group (122; 88–230 min) than the control group (100; 67–198 min). Two types of TPLO locking compression plates were used in the study (TPLO clover, Intrauma S.p.A.; Rivoli, Italy; TPLO plate, DePuy Synthes, Johnson & Johnson; Oberdorf, Switzerland) and there was no significant difference between groups ($P = 0.73$); the TPLO clovers were used in 5 patients from the LCTA group and 8 patients from the control group, whereas the TPLO plates were used in 9 patients from the LCTA group and 20 patients from the control group. Development of surgical site infection - inflammation was detected in 2 patients belonging to the LCTA group and in 2 patients belonging to the control group, without any significant difference between the two groups ($P = 0.59$). No implant failure was detected in any patient.

Proximal tibial epiphysis conformation did not significantly differ between group ($P = 1.0$); the tibia was classified as ‘high’ in 7 patients from the LCTA group and 13 patients from the control group, whereas it was classified as ‘low’ in 7 patients from the LCTA group and 15 patients from the control group. The z angle and the rTTW did not significantly differ between the two groups ($P = 0.55$ and $P = 0.81$, respectively); the z angle and rTTW values in the two groups are summarized in Table 2.

The TPA resulted significantly reduced at both the post-operative ($P < 0.0001$ both groups) and >4 weeks follow-up evaluation ($P < 0.0001$ both groups) compared to the pre-operative measurements, without any significant difference between the two groups (Fig. 3). No significant differences over time within or between the two groups could be detected for the mMPTA nor the mMDTA. The TPA, mMPTA and mMDTA values are summarized in Table 3.

Osteotomy inclination angle did not significantly differ between groups ($P = 0.85$). The gap between the two fragments in the sagittal plane cranial and caudal to the TPLO plate, as well as the shift measured in the frontal plane, did not significantly differ between the two groups ($P = 0.36$, $P = 0.45$, $P = 0.47$, respectively). The ratio between the distance from the intercondylar eminence to the exit point of the osteotomy and the radius of the blade did not significantly differ between groups ($P = 0.81$). The aforementioned post-operative radiographic variables are summarized in Table 4.

Table 2
Mean ± SD or median (range) of the Z angle and relative tibial tuberosity width in the two study groups.

	Z angle (°)	rTTW
LCTA	63.9 ± 4.7	0.55 (0.36–1.04)
Control	64.0 (57.1–84.4)	0.54 ± 0.07

rTTW: relative tibial tuberosity width; LCTA: laceration of the cranial tibial artery group.

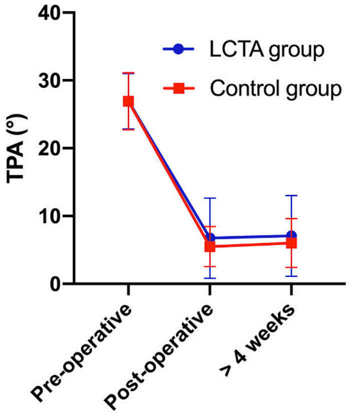

Fig. 3. Graphic representation of the mean ± SD of the tibial plateau angle (TPA, °) in the two groups at the three time points.

Table 3
Mean ± SD of the tibial plateau angle and mechanical tibial angles in the two study groups at the three time points.

Time Point	Pre-operative	Post-operative	> 4 weeks
TPA (°)			
LCTA	26.9 ± 4.1 ^{A}	6.7 ± 5.9^{B}	7.1 ± 5.9^{B}
Control	26.9 ± 4.2 ^{A}	5.5 ± 2.9^{B}	6.0 ± 3.6^{B}
mMPTA (°)			
LCTA	93.0 ± 1.7	91.6 ± 1.8	92.1 ± 1.7
Control	93.9 ± 3.3	91.3 ± 3.6	91.7 ± 3.8
mMDTA (°)			
LCTA	95.9 ± 2.5	95.6 ± 3.5	95.6 ± 2.9
Control	96.1 ± 2.8	95.6 ± 2.4	96.0 ± 2.7

Statistic: within and between groups analysis over time A > B $P < 0.01$; TPA: tibial plateau angle; mMPTA: mechanical medial proximal tibial angle; mMDTA: mechanical medial distal tibial angle; LCTA: laceration of the cranial tibial artery group.

In the evaluation of the ACO, no significant differences for the X and Y coordinates could be detected between the two groups ($P = 0.10$, $P =$

Table 4

Mean ± SD or median (range) of the post-operative radiographical variables.

	LCTA	Control
OIA (°)	90.8 ± 2.6	91.0 ± 3.2
Cranial gap (mm)	0.0 (0.0–3.5)	0.0 (0.0–1.9)
Caudal gap (mm)	0.0 (0.0–0.8)	0.0 (0.0–1.8)
Shift (mm)	0.0 (0.0–3.1)	1.1 (0.0–4.2)
Ratio	1.0 (0.9–1.5)	1.1 ± 0.1

OIA: osteotomy inclination angle; Cranial gap: the gap between the fragment in the sagittal plane at the wider point cranial to the TPLO plate; Caudal gap: the gap between the fragment in the sagittal plane at the wider point caudal to the TPLO plate; Shift: magnitude of the two-fragment shifting measured in the frontal plane; Ratio: the ratio between the distance from the intercondylar eminence to the exit point of the osteotomy and the radius of the blade; LCTA: laceration of the cranial tibial artery group.

0.11, respectively), nor for the DOE (P = 0.55). The power calculation for the X coordinate resulted in 23% with a sample size of 207 (69 cases and 138 controls), and for the Y coordinate the power was in 42% with a sample size of 105 (35 cases and 79 controls). The distribution of the ACO in the two groups is reported in Fig. 4.

Time from surgery to the last radiographic follow-up evaluation did not significantly differ between groups ($P = 0.42$). No significant differences between the two groups could be detected for both mRUST and VAS ($P = 0.41$ and $P = 0.36$, respectively). The sample size needed for mRUST was 772 (257 cases and 515 controls), and for the VAS was 1898 (633 cases and 1265 controls). The time from surgery to the last clinical and radiographical evaluation, mRUST and VAS scores are summarized in Table 5.

Table 5

Mean ± SD time from surgery to the last radiographic follow-up evaluation, and median (range) of the mRUST and VAS scores in the two study groups.

	Time (day)	mRUST	VAS
LCTA	67 ± 19	9 (4–12)	8.0 (3.5–9.5)
Control	62 ± 10	8 (6–12)	7.5 (5.0–10.0)

Time: Time from surgery to the last clinical and radiographic evaluation; mRUST: modified radiographic union scale for tibial fracture; VAS: visual analog scale; LCTA: laceration of the cranial tibial artery group.

4. Discussion

The primary aim of the present study was to compare the radiographic bone healing between dogs experiencing and not experiencing LCTA during TPLO surgery. The underlying hypothesis, that LCTA and the subsequent cranial tibial artery occlusion could impair bone healing, was rejected. Indeed, the results of the present study showed no difference in bone healing between the LCTA group and the control group. This finding appears in contrast with both clinical human studies and experimental rat models, in which a correlation between ischemia and fracture delayed healing or non-union was detected (Brinker and Bailey Jr., 1997; Deitz et al., 1989; Dickson et al., 1994; Lu et al., 2007; Menger et al., 2022). Indeed, during hypoxia, inflammatory cells, oxygen, and nutrients delivery is impaired, as well as cells survival and differentiation (Lu et al., 2007; Miclau et al., 2017). The cranial tibial artery continues the popliteal artery after the caudal tibial artery arises at the interosseus space (Bezuidenhout, 2013). It passes caudal to the stifle joint between the tibial condyles, in a lateral and distal direction (Bezuidenhout, 2013; Moles and Glyde, 2009). It is important to emphasize that the caudal tibial artery supplies the nutrient artery of the

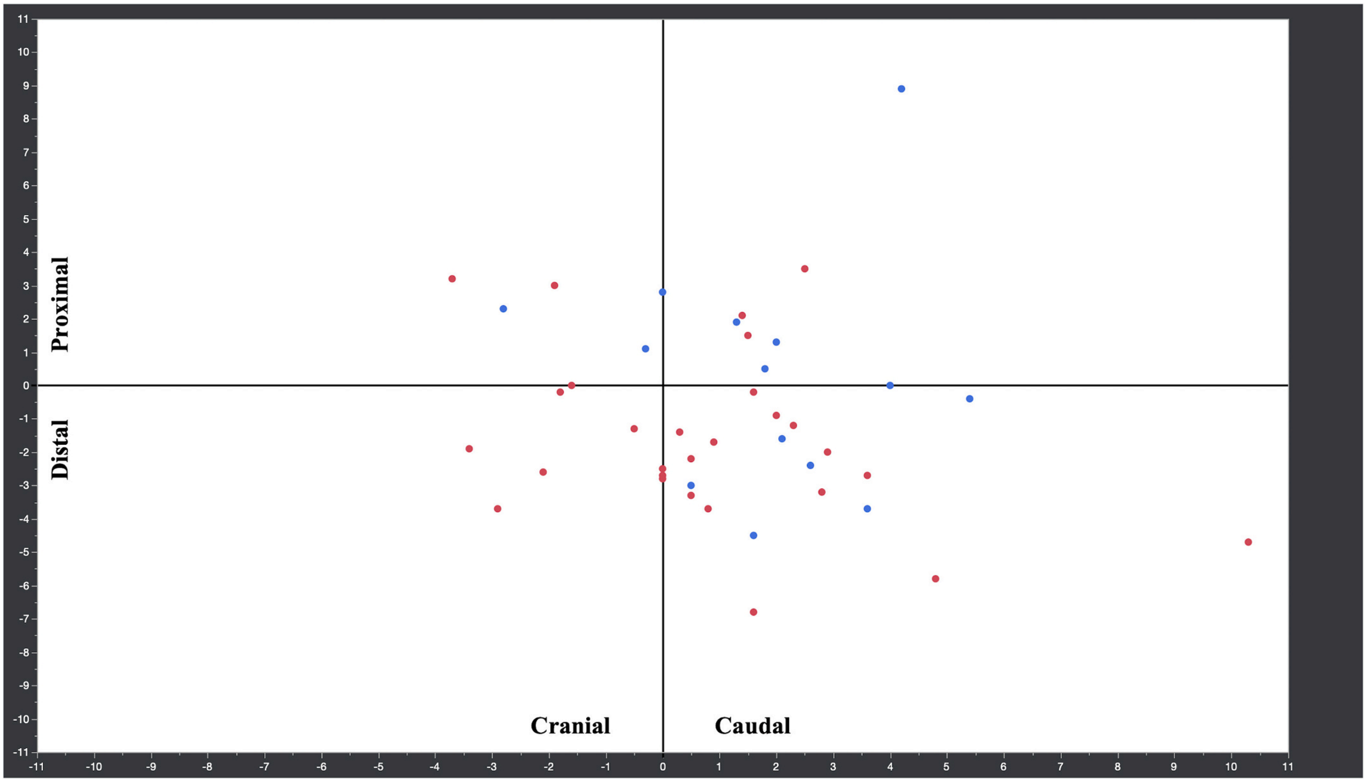

Fig. 4. Graphic representation of the actual centroid of the osteotomy (ACO). Blue dots represent the ACO in the LCTA group, and red dots the ACO in the control group. The Cartesian plane has the mechanical axis of the tibia as the Y axis and the perpendicular straight line to the Y axis passing through the intended centroid of the osteotomy (ICO) as the X axis. The coordinates have "positive" values in the proximal and caudal direction from the ICO; otherwise, the coordinates have "negative" values in the distal and cranial direction from the ICO. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tibia, which enters the nutrient foramen on the lateral or caudal surface at the junction of the proximal and middle third of the tibia (Ahn, 2013). The LCTA may result in hypoperfusion, and consequent ischemia of the region supplied by the cranial tibial artery. It might be hypothesized that the intact caudal tibial artery and the consequent maintained diaphyseal blood supply, and the presence of anastomosis between the cranial tibial artery and the saphenous artery (Bezuidenhout, 2013), could explain the lack of difference in bone healing between dogs experiencing and not experiencing LCTA. Indeed, the ligation of any arteries or veins of the canine hindlimb has been demonstrated to result in a negligible circulatory interference due to well-developed collateral circulations (Coolbaugh, 1952; Degner et al., 2005). Another possible explanation for the lack of differences in bone healing after LCTA could be represented by the anatomical location of the TPLO. The osteotomy is performed at the level of the metaphyseal region. This region is richer in spongy bone, more metabolically active compared with compact bone (Haffner-Luntzer and Ignatius, 2020). In addition, the periosteum surrounding the metaphysis is rich in periosteal cells and it is well vascularized (Fan et al., 2008). Hence, metaphyseal bone seems to have a greater healing potential due to its intrinsic characteristics (Aronson and Shen, 1994). Thus, the "metaphyseal healing environment", associated with the preserved tibial diaphyseal vascular supply, could overwhelm the "ischemic environment" possibly induced by the LCTA, which could explain the absence of difference in bone healing highlighted between the two groups.

According to the secondary aim of the present study, complications possibly linked to cranial tibial artery ligation and potential resulting ischemia were evaluated. Beyond the delayed- and non-union during bone healing, other postoperative disorders should be considered when local blood circulation is compromised. Arterial occlusion seems to be correlated to a higher rate of osteomyelitis in open tibial fractures in humans, even if a compensating collateral supply develops (Dickson et al., 1994). Other than ischemia *per se*, different factors could predispose to SSI such hypoxia (Nelson, 2011), hypotension (Turk et al., 2015), and length of surgery (Coletti et al., 2014; Eugster et al., 2004; Lopez et al., 2018; Yap et al., 2015). Even though hypotension, probably due to the severe yet controlled hemorrhage (Van Leeuwen et al., 1989), and length of the surgery were significantly higher in the LCTA group, no differences were found in SSI and implant failure between the two groups. According to previous anatomical and *ex vivo* studies, the osteotomy position could predispose to LCTA (Cieciora et al., 2022; Moles and Glyde, 2009). This theory was not confirmed by the present case-control study. The TPLO radial osteotomy should be centered over intercondylar eminences (Kowaleski et al., 2005). Different clinical factors could influence the ACO, such as the proximal jig pin, the size of the tibial tuberosity, the radius of the saw blade, and the size and type of the plate (Moles and Glyde, 2009). A more distal and caudal ACO leads to a larger tibial tuberosity and a longer proximal fragment, more accessible for plate fixation. At the same time, the osteotomy performed as described appears in a safer position. On the other hand, with a proximal osteotomy, the exit-point of the blade ends in the region where the cranial tibial artery runs within the concave caudal tibial surface (Cieciora et al., 2022). Hence, the ACO position might increase the risk of LCTA, even if the results of the present study could not corroborate this hypothesis, probably due to the low statistical power.

The overall incidence of LCTA was 9.6% (14\146). This result appears in contrast with previous studies (Pacchiana et al., 2003; Priddy 2nd et al., 2003; Stauffer et al., 2006), but more similar to the incidence reported in two recent manuscripts (Montano et al., 2023; Pages et al., 2022). Even though LCTA is an infrequent intraoperative complication during TPLO, it is reasonable to consider it underreported (Mullins et al., 2020). Interestingly, in the LCTA group, dogs with a body weight of >15 kg were significantly overrepresented showing 22 times more chance of experiencing LCTA. Moreover, no patient weighing <15 kg experienced LCTA. A significant association between large-breed dogs and LCTA has never been reported previously. Other studies reporting LCTA included only dogs with a body weight higher than 15 kg (Matres-Lorenzo et al., 2018; Pages et al., 2022; Roses et al., 2022), and LCTA has never been described as an intraoperative complication in small-breed dogs undergoing TPLO (Cosenza et al., 2015; Knight and Danielski, 2018; Witte and Scott, 2014). One possible explanation is that LCTA in small-breed dogs results in a less severe hemorrhage due to the smaller size of the cranial tibial artery. Therefore, in this class of patients, LCTA might have not been recognized, and the resulting bleeding misinterpreted as arising from the osteotomized bone. Anatomical differences between small- and large-breed dogs might be another possible explanation. According to previous studies, the TPA, the Z angle (Aertsens et al., 2015), and the rTTW (Vedrine et al., 2013) were found greater in small-breed dogs compared to large-breed, and a peculiar caudal bowing resulting in a caudal proximal tibial deformity has been described in small-breed dogs (Macias et al., 2002). In a recent study, it was supposed that different tibial conformations could lead to variation in the cranial tibial artery and tibia relationship, which may be associated with a different risk of LCTA (Cieciora et al., 2022). The "high" tibial conformation seems to display, proximally, a concavely shaped lateral and caudal cortex, which embeds the vasculature. Conversely, the "low" tibial conformation has a less concave cortex with a clear prominent medial cortex. In this latter conformation, the cranial tibial artery runs at a distance from the cortex (Cieciora et al., 2022). In the present study, both subjective and objective evaluations of the proximal tibial conformation were applied, and no differences could be detected for the tibial conformation between the two groups. It would be interesting to evaluate and compare the different tibial conformations and vascularization patterns of the proximal tibia in small- and large-breed dogs.

The present study inherits different limitations. The first limitation is the impossibility of precisely identifying which vessel was causing the hemorrhage. Considering the severity of the hemorrhage, the need to use ligation or vascular clips, and the anatomic location, the bleeding vessel was considered consistent with the cranial tibial artery or one of its five branches (Moles and Glyde, 2009). Probably, the closure of the cranial tibial artery itself proximal to the rising of its branches might have more severe consequences on bone healing compared to the laceration and occlusion of one of the branches themselves. Unfortunately, intraoperatively, defining what is the damaged artery would be challenging due to the ongoing hemorrhage. To overcome this problem and collect precise information about vascularization, a selective intraoperative angiography, or a selective postoperative vascular computed tomography of the hindlimb could be performed. Unfortunately, both these techniques are difficult to apply in a clinical setting. Nevertheless, such information would be of paramount importance to categorize the vascular damage and the resulting ischemia, potentially making the LCTA and closure of the cranial tibial artery during TPLO a spontaneous clinical model for metaphyseal bone healing with concurrent ischemia (Haffner-Luntzer and Ignatius, 2020). A second limitation might be the use of radiographic scales for the evaluation of bone healing. Nonetheless, the mRUST and VAS scales have been previously used and validated for evaluating TPLO bone union (Leal et al., 2023; Walker et al., 2022). Furthermore, even in human medicine, there is no consensus on radiographic criteria nor on a gold standard for bone healing estimation (Fisher et al., 2019). Another source of error could be the non-blinded radiographic assessment since the presence of vascular clip for arterial occlusion in most of the cases proved their belonging to the LCTA case group. Although no significant difference was found between the two study groups, the time from surgery to the last radiographic follow-up evaluation was not standardized due to the retrospective nature of the study. Nonetheless, even if considering the small sample included in this study, the absence of a difference between the two study groups might be a real lack of difference in bone healing between dogs experiencing and not experiencing LCTA.

In conclusion, according to the present study, ischemia resulting from LCTA and the closure of the cranial tibial artery did not delay bone healing, nor affected the incidence of SSI and implant failure. On the other hand, the LCTA resulted in prolonged surgical time and predisposed patients to intraoperative hypotension. Finally, the LCTA during TPLO seem to be an exclusive complication of large-breed dogs.

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CRediT authorship contribution statement

Francesco Ferrari: Writing – original draft, Resources, Methodology, Investigation, Data curation, Conceptualization. **Roberto Tamburro:** Writing – review & editing, Resources, Investigation. **Maurizio Longo:** Writing – review & editing, Investigation. **Federica Alessandra Brioschi:** Writing – review & editing, Resources, Investigation. **Luigi Auletta:** Writing – original draft, Formal analysis, Data curation. **Damiano Stefanello:** Writing – original draft, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are available from the corresponding author upon reasonable request.

References

Aertsens, A., Rincon Alvarez, J., Poncet, C.M., Beaufrere, H., Ragetly, G.R., 2015. Comparison of the tibia plateau angle between small and large dogs with cranial cruciate ligament disease. Vet. Comp. Orthop. Traumatol. 28, 385–390.

Ahn, D., 2013. Anatomical study on the diaphyseal nutrient foramen of the femur and tibia of the German shepherd dog. J. Vet. Med. Sci. 75, 803–808.

Aronson, J., Shen, X., 1994. Experimental healing of distraction osteogenesis comparing metaphyseal with diaphyseal sites. Clin. Orthop. Relat. Res. 25–30.

Bezuidenhout, A., 2013. Miller's anatomy of the dog. In: Evans, H.E., DeLahunta, A. (Eds.), The Heart and Arteries, 4th edition ed. Elsevier Saunders, St. Louis, Miss, pp. 428–504.

Boudrieau, R.J., 2009. Tibial plateau leveling osteotomy or tibial tuberosity advancement? Vet. Surg. 38, 1–22.

Brinker, M.R., Bailey Jr., D.E., 1997. Fracture healing in tibia fractures with an associated vascular injury. J. Trauma 42, 11–19.

Cieciora, L.C., Harms, O., Freise, F., Seifert, H., Fehr, M., 2022. Ex vivo evaluation of the cranial Tibial artery and its compression through fragment rotation during tibia plateau levelling osteotomy: an angiographic three-dimensional reconstruction. Vet. Comp. Orthop. Traumatol. 35, 220–229.

Coletti, T.J., Anderson, M., Gorse, M.J., Madsen, R., 2014. Complications associated with tibial plateau leveling osteotomy: a retrospective of 1519 procedures. Can. Vet. J. 55, 249–254.

Coolbaugh, C.C., 1952. Effects of reduced blood supply on bone. Am. J. Phys. 169, 26–33.

Cosenza, G., Reif, U., Martini, F.M., 2015. Tibial plateau levelling osteotomy in 69 small breed dogs using conically coupled 1.9/2.5 mm locking plates. A clinical and radiographic retrospective assessment. Vet. Comp. Orthop. Traumatol. 28, 347–354.

Degner, D.A., Walshaw, R., Fowler, J.D., Lanz, O.I., Ocello, P., Maier, J., Blaezer, L., Smith, R.J., 2005. Surgical approaches to recipient vessels of the fore- and hindlimbs for microvascular free tissue transfer in dogs. Vet. Surg. 34, 297–309.

Deitz, D.M., Taylor Jr., L.M., Beals, R.K., Porter, J.M., 1989. Role of revascularization to treat chronic nonhealing fractures in ischemic limbs. J. Vasc. Surg. 10, 535–540 (discussion 541).

Dickson, K., Katzman, S., Delgado, E., Contreras, D., 1994. Delayed unions and nonunions of open tibial fractures. Correlation with arteriography results. Clin. Orthop. Relat. Res, 189–193.

Dismukes, D.I., Tomlinson, J.L., Fox, D.B., Cook, J.L., Song, K.J., 2007. Radiographic measurement of the proximal and distal mechanical joint angles in the canine tibia. Vet. Surg. 36, 699–704.

Eugster, S., Schawalder, P., Gaschen, F., Boerlin, P., 2004. A prospective study of postoperative surgical site infections in dogs and cats. Vet. Surg. 33, 542–550.

Fan, W., Crawford, R., Xiao, Y., 2008. Structural and cellular differences between metaphyseal and diaphyseal periosteum in different aged rats. Bone 42, 81–89.

Fettig, A.A., Rand, W.M., Sato, A.F., Solano, M., McCarthy, R.J., Boudrieau, R.J., 2003. Observer variability of tibial plateau slope measurement in 40 dogs with cranial cruciate ligament-deficient stifle joints. Vet. Surg. 32, 471–478.

Fisher, J.S., Kazam, J.J., Fufa, D., Bartolotta, R.J., 2019. Radiologic evaluation of fracture healing. Skeletal Radiol. 48, 349–361.

Freeman, L., Becvarova, I., Cave, N., MacKay, C., Nguyen, P., Rama, B., Takashima, G., Tiffin, R., Tsjimoto, H., van Beukelen, P., 2011. WSAVA Nutritional Assessment Guidelines. J. Small Anim. Pract. 52, 385–396.

Haffner-Luntzer, M., Ignatius, A., 2020. Animal models for studying metaphyseal bone fracture healing. Eur. Cell. Mater. 40, 172–188.

Horan, T.C., Gaynes, R.P., Martone, W.J., Jarvis, W.R., Emori, T.G., 1992. CDC definitions of nosocomial surgical site infections, 1992: a modification of CDC definitions of surgical wound infections. Infect. Control Hosp. Epidemiol. 13, 606–608.

Inauen, R., Koch, D., Bass, M., Haessig, M., 2009. Tibial tuberosity conformation as a risk factor for cranial cruciate ligament rupture in the dog. Vet. Comp. Orthop. Traumatol. 22, 16–20.

Johnson, A., 2016. Implant Failure. In: Griffon, D., Hamaide, A. (Eds.), Complications in Small Animal Surgery. John Wiley & Sons, Ltd, Chichester, West Sussex ; Hoboken, pp. 641–648.

Knight, R., Danielski, A., 2018. Long-term complications following tibial plateau levelling osteotomy in small dogs with tibial plateau angles > 30 degrees. Vet. Rec. 182, 461.

Kowaleski, M.P., Apelt, D., Mattoon, J.S., Litsky, A.S., 2005. The effect of tibial plateau leveling osteotomy position on cranial tibial subluxation: an in vitro study. Vet. Surg. 34, 332–336.

Lambert, S.M., 2018. Ischaemia, healing and outcomes in proximal humeral fractures. EFFORT. Open. Rev. 3, 304–315.

Leal, R.A., Lambrechts, N.E., Crowley, J.D., Griffin, J.F.T., Karnia, J.J., Torres, B.T., Maritato, K.C., Kieves, N.R., Duerr, F.M., 2023. Comparison of radiographic scoring systems for assessment of bone healing after tibial plateau leveling osteotomy in dogs. Front. Vet. Sci. 10, 1147386.

Lopez, D.J., VanDeventer, G.M., Krotscheck, U., Aryazand, Y., McConkey, M.J., Hayashi, K., Todhunter, R.J., Hayes, G.M., 2018. Retrospective study of factors associated with surgical site infection in dogs following tibial plateau leveling osteotomy. J. Am. Vet. Med. Assoc. 253, 315–321.

Lu, C., Miclau, T., Hu, D., Marcucio, R.S., 2007. Ischemia leads to delayed union during fracture healing: a mouse model. J. Orthop. Res. 25, 51–61.

Macias, C., McKee, W.M., May, C., 2002. Caudal proximal tibial deformity and cranial cruciate ligament rupture in small-breed dogs. J. Small Anim. Pract. 43, 433–438.

Matres-Lorenzo, L., McAlinden, A., Bernarde, A., Bernard, F., 2018. Control of hemorrhage through the osteotomy gap during tibial plateau leveling osteotomy: 9 cases. Vet. Surg. 47, 60–65.

Menger, M.M., Stutz, J., Ehnert, S., Nussler, A.K., Rollmann, M.F., Herath, S.C., Braun, B. J., Pohlemann, T., Menger, M.D., Histing, T., 2022. Development of an ischemic fracture healing model in mice. Acta Orthop. 93, 466–471.

Miclau, K.R., Brazina, S.A., Bahney, C.S., Hankenson, K.D., Hunt, T.K., Marcucio, R.S., Miclau, T., 2017. Stimulating fracture healing in ischemic environments: does oxygen direct stem cell fate during fracture healing? Front. Cell Dev. Biol. 5, 45.

Moles, A., Glyde, M., 2009. Anatomical investigation of the canine cranial tibial artery. Vet. Comp. Orthop. Traumatol. 22, 351–355.

Montano, H.G., Moores, A.P., Grierson, J., 2023. Outcome and owner assessment after single-session bilateral tibial plateau leveling osteotomy in 127 dogs. Can. Vet. J. 64, 153–158.

Mullins, R.A., Escribano Carrera, A., Espinel Ruperez, J., Bresciani, L., Arthurs, G.I., Hoey, S., 2020. Effect of stifle flexion on the position of the cranial tibial artery relative to the proximal tibia in dogs. Vet. Surg. 49, 1527–1535.

Nelson, L.L., 2011. Surgical site infections in small animal surgery. Vet. Clin. North Am. Small Anim. Pract. 41, 1041–1056 viii.

Pacchiana, P.D., Morris, E., Gillings, S.L., Jessen, C.R., Lipowitz, A.J., 2003. Surgical and postoperative complications associated with tibial plateau leveling osteotomy in dogs with cranial cruciate ligament rupture: 397 cases (1998-2001). J. Am. Vet. Med. Assoc. 222, 184–193.

Pages, G., Hammer, M., Grand, J.G., Irubetagoyena, I., 2022. Long-term outcome of tibial plateau leveling osteotomy using an antimicrobial silver-based coated plate in dogs. PLoS One 17, e0272555.

Priddy 2nd, N.H., Tomlinson, J.L., Dodam, J.R., Hornbostel, J.E., 2003. Complications with and owner assessment of the outcome of tibial plateau leveling osteotomy for treatment of cranial cruciate ligament rupture in dogs: 193 cases (1997-2001). J. Am. Vet. Med. Assoc. 222, 1726–1732.

Roses, L., Lopez de la Oliva, P., Arnott, D., 2022. Rotation of the Tibial plateau segment to control arterial Haemorrhage during Tibial plateau levelling osteotomy: a cadaveric experimental study and nine clinical cases. Vet. Comp. Orthop. Traumatol. 35, 331–338.

Stauffer, K.D., Tuttle, T.A., Elkins, A.D., Wehrenberg, A.P., Character, B.J., 2006. Complications associated with 696 tibial plateau leveling osteotomies (2001−2003). J. Am. Anim. Hosp. Assoc. 42, 44–50.

Takahashi, T., Kalka, C., Masuda, H., Chen, D., Silver, M., Kearney, M., Magner, M., Isner, J.M., Asahara, T., 1999. Ischemia- and cytokine-induced mobilization of bone marrow-derived endothelial progenitor cells for neovascularization. Nat. Med. 5, 434–438.

Tan, C.J., Bergh, M.S., Schembri, M.A., Johnson, K.A., 2014. Accuracy of tibial osteotomy placement using 2 different tibial plateau leveling osteotomy jigs. Vet. Surg. 43, 525–533.

Turk, R., Singh, A., Weese, J.S., 2015. Prospective surgical site infection surveillance in dogs. Vet. Surg. 44, 2–8.

Van Leeuwen, A.F., Evans, R.G., Ludbrook, J., 1989. Haemodynamic responses to acute blood loss: new roles for the heart, brain and endogenous opioids. Anaesth. Intensive Care 17, 312–319.

Vedrine, B., Guillemot, A., Fontaine, D., Ragetly, G.R., Etchepareborde, S., 2013. Comparative anatomy of the proximal tibia in healthy Labrador retrievers and Yorkshire terriers. Vet. Comp. Orthop. Traumatol. 26, 266–270.

Walker, K.J., Litterine-Kaufman, J., Barnes, R.F., French, J.M., Tsai, S.L., Keys, D.A., 2022. Evaluation of a modified radiographic union scale for tibial fractures scoring system in staged bilateral tibial plateau leveling osteotomy procedures and comparison of first and second side radiographic bone healing. Vet. Surg. 51, 1231–1239.

Witte, P.G., Scott, H.W., 2014. Tibial plateau leveling osteotomy in small breed dogs with high tibial plateau angles using a 4-hole 1.9/2.5 mm locking T-plate. Vet. Surg. 43, 549–557.

Yap, F.W., Calvo, I., Smith, K.D., Parkin, T., 2015. Perioperative risk factors for surgical site infection in tibial tuberosity advancement: 224 stifles. Vet. Comp. Orthop. Traumatol. 28, 199–206.