The median circumflex iliac artery is a branch of the femoral artery and travels through the nutrient foramen on the caudal surface of the bone into the medullary canal in most dogs. This nutrient foramen typically appears radiographically as a radiolucent line crossing the cortex through to the medullary canal. This can appear very similar to a femoral fissure, particularly those nutrient foramina that are wider or have an unusual appearance (Figure 1) (Supplementary Material S1). Femoral fissures can occur intraoperatively or postoperatively with canine total hip replacements (THRs), and these are important to recognize to prevent propagation of these fissures into fractures.

Similarly, the position of the nutrient foramina is important to consider when approaching any orthopedic surgery. Previous reports have suggested that medullary infarction following THR in dogs is thought to occur due to damage to the nutrient artery during the reaming process and that limiting the depth and reaming of the medullary canal significantly decreases the incidence of medullary infarction. Preservation of vasculature and blood supply is also integral to fracture healing and is important to consider for bone grafting. Hence, it is important to identify the position of the artery and to preserve it as much as possible during these procedures. This position of the nutrient foramens from proximal to distal can be represented numerically by

OBJECTIVE
This study aimed to document the radiographic appearance of the femoral nutrient foramina and the variation of this in dogs undergoing total hip replacement (THR). Our hypothesis was that the radiographic appearance of the foramen would be consistent with the previously described anatomy, with some variations.

ANIMALS
89 client-owned dogs.

METHODS
Preoperative radiographs were retrospectively analyzed for dogs undergoing THR at a single referral center. The signalment of all dogs was recorded. Radiographs were retrospectively examined to describe the number, direction, appearance, and foraminal index of the femoral nutrient foramen.

RESULTS
Radiographs of 89 dogs and 102 femurs were examined. In 73 cases, a single foramen was seen; in 19 cases, no foramen was visible; and in 10 cases, 2 foramina were visible. The median foraminal index was 33.1% (range, 26% to 55.3%). On the mediolateral view, 72 were of proximocaudal-to-distocranial orientation, 19 were proximocranial to distocaudal, and 1 was atypical. On the craniocaudal or ventrodorsal views, the foramen was seen as a focal round radiolucency in 65 cases, was curved or atypical in 13 cases, and was not visible in 14.

CLINICAL RELEVANCE
Radiolucent lines across the cortices that do not fit these criteria should raise suspicion of a femoral fissure, particularly within the context of THR.

Keywords: femoral, foraminal, total hip replacement (THR), nutrient foramen

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the foraminal index (Figure 2). This is a percentage that represents how far proximal to distal the foramen is, with 0% being at the most proximal aspect of the greater trochanter and 100% being at the most distal aspect of the femoral condyle. Previous studies on canine cadavers have documented that the foraminal index of the canine femur is expected to be around 35% to 40%. These studies have also demonstrated that the largest foramen is typically located on the caudal aspect of the femur, and the predominant direction seen is proximocaudal to distocranial (PrCd-DstCr). Other smaller foramina have been described; Hermanson et al1,2 described a smaller foramen penetrating from the cranial cortex in the proximal femur. The authors do not elaborate on the nature of this vessel or which vessel this is a branch of; however, Cuthbertson and Gilfillan9 describe a cranial nutrient artery in the proximal femur in 1 dog branching from the “cranial femoral artery” (now referred to as the lateral circumflex femoral artery).1,2 Little information is available with respect to the radiographic appearance or the direction of these foramina in dogs; McAllister and Tobin10 describe that the foramen is often seen on the caudal surface of the femur in the mid diaphyseal region. Otherwise, no information on the direction, variation, or number of foramina as seen on radiography is available to the best of the authors’ knowledge.

In contrast, the anatomy of the femoral nutrient foramina has been extensively studied in the human literature, including their radiographic appearance and differentiation from fracture lines.11–13 The human femur typically has 1 or 2 nutrient foramina, which course proximally after entering the femur around the facies aspera (a landmark on the caudal aspect of the femur, also known as the rough surface).14,15 In a study by Yun et al,13 1 foramen was seen on plain radiographs in 53% of cases, and in 47%, no foramen was seen. When present, the foramen entered from the caudal surface with a proximocaudal–distocranial direction.

Although CT has been used for the assessment of THR pre- and postoperatively and would be expected to be more sensitive for the assessment of nutrient foramina/fissures, radiographs are more routinely used clinically and hence were the imaging modality prioritized in this report.16

Therefore, our aim was to document the radiographic appearance and variation of the femoral nutrient foramen by examining preoperative radiographs for dogs undergoing THR. This population was chosen due to the high volume of these cases seen and the standardized, repeatable views of the femur taken. Our hypothesis was that the previously reported gross anatomy of the femoral foramen would be consistent with radiographic appearance but with some variations from normal.

Methods

Dogs that had undergone THR at a single referral hospital were enrolled in this retrospective observational study. Medical records were retrieved from the hospital database (RxWorks, version 5.9; Coventrus) for dogs undergoing THR with preoperative radiographs or CT performed between January 1, 2021 and June 15, 2022. Data collected from cases included age, sex, weight, neuter status, and breed.

Only animals with complete and interpretable surveys were included, with required radiographic views consisting of a mediolateral (ML) femoral view, and a ventrodorsal (VD) pelvic or craniocaudal (CrCd) femoral view of the femur. Limbs were excluded if either a VD/CrCd or ML radiograph were unavailable for the femur or if radiographic technique/positioning was such that it would substantively impact the interpretation of the images. Cases were also excluded if any previous femoral surgery had been undertaken on the limb, including previous THR. Radiographs were obtained using an Arcoma Intuition x-ray machine (Xograph Healthcare Ltd). The settings used were 65 kV and 12.5 to 40 mAs for the VD pelvic views and 55 to 60 kV and 8 to 16 mAs for the ML and CrCd femoral views.
Images were retrieved from the institution's picture archiving and communication system (Fujifilm Synapse, version 5.7.212) and assessed on an appropriate reading screen (Dell UZ2315H monitor). Images were reviewed by a European College of Veterinary Diagnostic Imaging–certified veterinary diagnostic imaging specialist and separately by a rotating intern at the hospital. The 2 reviewers assessed all images independently to identify the nutrient foramen of both femurs and described the number, direction, and appearance of these. These results were then compared, and a consensus was reached on any differing results.

Foraminal indices were calculated as described by Kara et al\textsuperscript{7} by measuring from the proximal end of the greater trochanter to the distal end of the femoral condyle on the VD or CrCd view. To calculate the foraminal index, the distance measured from the proximal end of the greater trochanter to the center of the foramen was divided by the total length as shown in Figure 2.

The direction of the nutrient foramen seen on the ML view was described either as PrCd-DstCr, proximocranial to distocaudal (PrCr-DstCd), or atypical. Atypical foramina were described in further detail. As well as this, the length of the foramen as it crossed the cortex was measured, along with the width of the cortex at this point. The length of the foramen was then divided by the width of the cortex, and those with a value greater than 2 were classed as long oblique, and those less than 2 were classed as short oblique. This value was chosen based upon the classification of long oblique fractures as being as long oblique, and those less than 2 were classed as short oblique. This value was chosen based upon the classification of long oblique fractures as being twice the diameter of the bone in order to give a representation of the foramen.\textsuperscript{17} The appearance of the foramen on the CrCd femoral or VD pelvic views was also described either as an end-on lucency, curved, or atypical.

Ages, weights, and foraminal indices were tested for normality with the use of the Shapiro-Wilk and Kolmogorov-Smirnov tests; \( P < .05 \) was used as a cutoff. Normally distributed data were reported as mean values along with standard deviation; if not normally distributed, data were reported as median values and ranges. Statistical tests were performed using SPSS, version 28 (IBM Corp).

This study was conducted after being reviewed by the University of Bristol Animal Welfare and Ethical Review Body (VIN-22-047) and the Home Office Liaison Team.

Results

In total, 89 dogs were included, and 102 femurs were analyzed. Of those included, 45 were right femurs, and 57 were left femurs. Thirty dogs were male entire, 20 were male neutered, 16 were female entire, and 23 were female neutered. The median age at the time of radiography was 15 months (range, 3 to 168 months), and the median weight at the time of radiographs was 24.1 kg (range, 4 to 74.2 kg). Twenty-six breeds were represented, including 31 crossbreeds, 11 Labrador Retrievers, 8 Golden Retrievers, 6 Border Collies, 6 German Shepherds, 3 Cocker Spaniels, and 2 each of Miniature Poodles, Springer Spaniels, and St Bernards.

No nutrient foramen was visible in 19 femurs, a single foramen was visible in 73 cases, and 2 foramina were visible in 10 cases; therefore, a total of 93 foramina were seen.

Of these foramina, 73 of 93 (78.5%) were of a PrCd-DstCr orientation as seen (Figure 3), 19 of 93 (20.4%) were PrCr-DstCd, and 1 was classed as atypical. All foramina crossed into the medullary canal from the caudal cortex, with none crossing from the cranial cortex.

The median foraminal index was 33.1% (range, 26.0% to 55.3%). Forty-three foramina (46.2%) were classed as long oblique, and 39 (42%) were short oblique. For 10 cases (10.7%), the foramen length was unable to be measured accurately as the foramen was identifiable on these images but unable to be followed along its entire length.

Of those 10 femurs with 2 foramina, 8 of these had 1 larger foramen, which was directed PrCd-DstCr, and a second smaller foramen distally, which was directed from PrCr-DstCd, with an example of this shown (Figure 4). In the other 2 femurs, both foramina were directed PrCd-DstCr.

The foramen that was deemed atypical on the ML view is illustrated (Figure 5), with the foramen appearing as a large radiolucent depression within the medullary canal of the distal femur. At no point could this foramen be seen to cross the femoral cortices.

A radiopaque endosteal prominence on the caudal aspect of the femoral medullary canal at the point of entry of the foramen (ML view) was present in 42 of 93 (45%) cases (Supplementary Material S2). The appearance of this varied, with the size and visibility of this prominence being inconsistent between cases.

On CrCd/VD view, the foramen was seen end-on in 65 cases (69.9%), which is illustrated (Figure 6), and in 5 of these, the foramen was notable and large. It was curved in 9 cases (9.7%) and of an atypical appearance in 4 cases (4.3%). Of these 4 atypical foramina, 1 case had 2 foramina visible; 2 cases had foramina that were longer, thin, and branched into 2; and the final case is as previously illustrated in Figure 5, with the foramen being wide and just

![Figure 3](image-url)

Figure 3—An example as seen in 78.5% of the foramina analyzed on the mediolateral femoral radiographic view (white arrow), directed proximocranial to distocaudal.
medial to the medial cortex. The foramen was not visible on the CrCd/VD view in 15 cases (16.1%).

Thirteen cases had views of both left and right femurs for analysis. In 6 of these cases, both femurs had 1 foramen visible—in 5 of these, both femoral foramina were directed from PrCd to DstCr on the ML view. For the other case, both foramina were PrCr to DstCd.

In 3 of these cases, 1 femur had 2 visible foramina, and the other had a single foramen. In 3 cases, 1 femur had no foramen visible, and the other had a single foramen. In 1 case, both femurs had no foramina visible. Therefore, 7 of the 13 cases where both femurs were imaged had symmetrical appearances of their foramina on the ML view.

The appearance on CrCd femoral/VD pelvic views were more similar; 9 foramina were visible as end-on lucencies in both the left and right femurs, and in 1 of these cases, this lucency was markedly larger than expected in both limbs. In 2 cases, the foramen was not visible on either limb in this view, and in 1 case, the foramen was seen as a curved lucency on both limbs. In the final case, the left femoral foramen was visible as an end-on lucency and was not visible on the right. Therefore, for the CdCr/VD views, 12 of 13 foramina were symmetrical in appearance.

In terms of femoral indices, these were largely similar. The median values when comparing the left and right femurs were 36.0% and 34.5%, respectively. When individually comparing the left and right foraminal indices, there were 3 cases with foramina visible whereby these indices differ by more than 2%. For these 3 cases, the left and right were 39.3% and 26%, 26.7% and 29%, and 47.9% and 36.9%, respectively.

Discussion

Most foramina (78.5%) were of PrCd-DstCr orientation, with a smaller proportion (20.4%) from PrCr-DstCd. All foramina crossed into the medullary canal through the caudal cortex. Few cases strayed from these orientations on the ML view (1%), but there were atypical cases and more variation in appearance on the VD view.

Berard’s rule states that nutrient foramina in mammals are directed away from the stifle and toward the elbow. This is thought to reflect the difference in growth patterns, with the foramen directed away from the growing end. However, the proximal femoral nutrient foramen in dogs does not follow this rule based on previous cadaveric studies for dogs. From these studies, it is typically expected for the proximal femoral foramen to be directed PrCd-DstCr (as seen in Figure 3), which is similarly demonstrated in our data.

The mean foraminal index found in this study is in line with findings of previous studies, which have described indices of 35%, 36.4%, and 37%. Appropriate femoral stem sizing will generally lead to the tip of a prosthetic femoral stem being around a similar position in the proximal femoral diaphysis, and femoral fissures can occur at this point of the
stem due to the differences in elasticity between implant, bone, and cement if used.\textsuperscript{20,21}

One of the motivations of this study was to identify the foramen orientation to distinguish these from femoral fissures, particularly in dogs following THR. Ninety-nine percent of foramina identified in our study were of PrCd-DstCr or PrCr-DstCd orientation. Therefore, it is reasonable to conclude that radiolucent lines crossing the cortex that do not run in these orientations are more likely to represent fissures than foramina in these cases.

Often, femoral fissures will be noted intraoperatively; however, fissures can also develop in the early postoperative period.\textsuperscript{1} Identification and treatment of these fissures (either with fixation or continuation of confinement) is important to prevent propagation of these fissures into full fractures. Fissures can be identified on plain radiographs; however, this is dependent on the orientation and extent of fissuring, with careful examination of radiographs often being required.\textsuperscript{5} These fissures may not be noted on initial radiographs and may only become visible weeks later when bone healing and callus formation occur.

In human patients, compared to fracture lines, the femoral nutrient foramina were less radiolucent, smaller in diameter, had less straight pathways through the medullary cavity, showed sclerotic walls in the cortex, and had more blunted ends compared with fracture lines.\textsuperscript{12} The scope of our study did not include direct comparison of femoral fissures to foramina, and therefore detailed conclusions or agreement with these findings cannot be ascertained; however, similar findings would be expected to be the case.

A study by Sebestyen et al\textsuperscript{5} in dogs undergoing THR found that there was a significant increase in the likelihood of medullary infarction with a larger distance from the greater trochanter to the femoral nutrient foramen (ie, those with a higher foraminal index). Although the distribution of the foraminal index in our data was minimal, this is something to be noted prior to surgery as some foramina in our study were outliers with higher indices and may be at higher risk of infarction in this case, although this is not a factor that is likely to change the decision making with respect to performing surgery.

From our results, most cases (72\%) had only a single foramen visible radiographically. This contrasts with previous research on cadaveric specimens. A study by Ahn et al\textsuperscript{6} found that in a population of German Shepherds, only 6.2\% of femurs had 1 sole nutrient foramen, with all others having 2 or greater. Mohamed and Persad,\textsuperscript{8} however, found that in mixed-breed dogs in Trinidad and Tobago, a singular nutrient foramen was found in all right femurs and in 60\% of the left femurs analyzed.

The difference between these findings and our own could be for several reasons. Firstly, it may be that other smaller foramina are positioned such that they are not visible with standard radiographic positioning or that other structures are typically superimposed. Another possible explanation would be that these other foramina are not large enough to be visible. These studies are also investigating different populations, and it may be that there are differences between breeds and populations of dogs in terms of the number or size of foramina. Similarly, small changes and differences in positioning can affect the appearance and ability to accurately identify these foramina, particularly if the foramen is oblique to the x-ray beam.\textsuperscript{11}

Of those femurs that were identified with 2 visible foramina, 8 of 10 had a more proximal foramen directed from PrCd-DstCr and a more distal foramen directed PrCr-DstCd as seen in Figure 4. Similarly, a study by Ahn\textsuperscript{6} found that of the foramina identified in the mid and distal thirds of the femur, almost all were directed away from the stifle joint (ie, PrCr-DstCd) and had a concurrent proximal foramen directed toward the stifle joint (PrCd to DstCr) in most cases. As well as this, Kara et al\textsuperscript{10} described a secondary foramen at various points on the facies aspera. This could represent the second distal foramen as identified in these cases. The radiographic presence or absence of this foramen could be due to variation in the individual blood supply, the size of this foramen, the size of the femur, or positioning. Anatomically, nutrient foramina have also been identified more proximally in the femur. A study by Frame et al\textsuperscript{22} assessing the radiographic appearance of the canine trochanteric fossa found that in 10\% of cases, a defined nutrient foramen was seen in the trochanteric fossa. Similarly, Hermanson et al\textsuperscript{1,2} reported a smaller proximal foramen that could represent this, although its exact location is not described. Interestingly, no such foramina were identified within our radiographic population; however, this was noted in the case where CT was available. This difference could be accounted for by differences in positioning, radiographic settings, or equipment; by variation in the populations studied; or due to the presence of periarticular new bone formation.

Although this study was focused on radiography of the femur, CT would be expected to be more sensitive for the detection of fissures/foramina and may detect those that are too small to be detected with standard radiographic views. Further research would be needed to determine whether this is the case.

Although the indication for THR was not recorded in this study, most dogs were undergoing THR for hip dysplasia, with a few cases due to avascular necrosis of the femoral head or proximal femoral fractures. The severity of disease varied, and some coxofemoral joints were dysplastic, with radiographic signs of secondary degenerative joint disease present. This may have influenced measurement of the foraminal index as the proximal femoral anatomy was abnormal. However, given the agreement of our calculated foraminal index with other reports, any variation of the calculated index due to changes in trochanteric contour is likely to be small. Also, it has been previously noted that in those dogs with a greater degree of degenerative disease present, the trochanteric foramina observed were larger and more branching.\textsuperscript{22} This was thought to reflect the inflammatory nature of hip dysplasia as this would cause a reduction in venous drainage, leading to increased size of

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the venules, which is thought to be responsible for the increased size of the foramen. Therefore, it is possible that our population may have had foramina of increased size and hence potentially increased visibility due to hip dysplasia, meaning that our results cannot necessarily be extrapolated to healthy dogs.

It was noted in several cases that the os penis was superimposed over the proximal femur. This occasionally made accurate identification of the foramen more challenging and is something to note when positioning male dogs for ML radiographs of the femur.

Thirteen dogs had radiographs of both femurs, with 7 of these having the same number and direction of foramina on both and 6 being asymmetrical. This suggests that radiographic appearance cannot necessarily be extrapolated from one side to the other, at least in terms of the number of foramina present. However, the small number of available cases limits any conclusions that can be made in terms of differences between limbs within the same animal—more research would be needed to investigate this finding further.

From these results, it can be concluded that the nutrient foramen of the femur is typically of proximocaudal-to-distocranial orientation in 78.5% of cases, with 20.4% being of PrCr-DstCd orientation. All foramina were located on the caudal surface of the femur, and the foraminal index was 33%. One case was atypical and did not fit these orientations. Radiolucent lines across the cortices that do not fit these appearances should raise suspicion of a femoral fissure.

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Supplementary Materials

Supplementary materials are posted online at the journal website: avmajournals.avma.org.