Assessment of vascularity of the femoral head using gadolinium (Gd-DTPA)-enhanced magnetic resonance imaging

A CADAVER STUDY

In spite of extensive accounts describing the blood supply to the femoral head, the prediction of avascular necrosis is elusive. Current opinion emphasises the contributions of the superior retinacular artery but may not explain the clinical outcome in many situations, including intramedullary nailing of the femur and resurfacing of the hip. We considered that significant additional contribution to the vascularity of the femoral head may exist. A total of 14 fresh-frozen hips were dissected and the medial circumflex femoral artery was cannulated in the femoral triangle. On the test side, this vessel was ligated, with the femoral head receiving its blood supply from the inferior vincular artery alone. Gadolinium contrast-enhanced MRI was then performed simultaneously on both control and test specimens. Polyurethane was injected, and gross dissection of the specimens was performed to confirm the extraosseous anatomy and the injection of contrast. The inferior vincular artery was found in every specimen and had a significant contribution to the vascularity of the femoral head. The head was divided into four quadrants: medial (0), superior (1), lateral (2) and inferior (3). In our study specimens the inferior vincular artery contributed a mean of 56% (25% to 90%) of blood flow in quadrant 0, 34% (14% to 80%) of quadrant 1, 37% (18% to 48%) of quadrant 2 and 68% (20% to 98%) in quadrant 3. Extensive intra-osseous anastomoses existed between the superior retinacular arteries, the inferior vincular artery and the subfoveal plexus.

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Tucker in 1949, Trueta and Harrison in 1953 and Judet et al in 1955 injected barium sulphate into the arterial tree and obtained radiographs of the slices of the femoral head in order to demonstrate the blood supply to the head of the femur. A thorough qualitative analysis of the vasculature was made. More recently, Gautier et al described the extraosseous anatomy of the medial circumflex femoral artery (MCFA) using neoprene-latex arterial injection. Despite extensive research, in-depth understanding of the vascular anatomy of the femoral head is still lacking.

The contribution of the lateral circumflex femoral artery is minimal. The contribution of the medial epiphyseal artery, the foveal artery, is limited to the perifoveolar area. The MCFA is thought to be the major contributor to the vascularity of the femoral head. Two main groups of retinacular arteries branching from retinacular arteries branching from the MCFA have been described: the posterosuperior and the inferior. We have used the term inferior vincular artery in our study as being synonymous with the inferior retinacular artery. The importance of the superior retinacular arteries alone has recently been emphasised. They are closely applied to the femoral neck before they perforate the head, and are at risk of disruption in fractures of the neck. However, the reported incidence of avascular necrosis (AVN) of the head after fracture of the neck varies from 10% to 30%. These vessels are also at risk during intramedullary nailing when using a starting point in the piriformis fossa. In a study by Dora et al describing the soft-tissue damage during nailing through this route in a cadaver model, the anterior subsynovial branches of the deep branch of MCFA were damaged in a significant number of specimens. Moein et al also describe the risk of damage to the branches of MCFA during this procedure. Despite these studies, the description of AVN developing clinically after intramedullary nailing in adult hips, is limited to a few case reports. Our current understanding of the vascular anatomy of the femoral head, emphasising the contribution of the superior retinacular arteries, does not explain the relative infrequency in the incidence of clinical AVN. There is no dispute as to the existence of the foveal artery and the two
The contributions of the retinacular groups branching from the MCFA, but their relative sizes and contributions are not clear. The contributions of the MCFA to the femoral head may not be understood in its entirety, and we have attempted to clarify them in this cadaver study using contrast-enhanced MRI.

Materials and Methods

A total of 14 fresh-frozen hips from seven pelves were obtained from the Anatomical Gifts Registry. The mean age of the specimens used was 58 years (35 to 88). The registry was checked to exclude any previous hip pathology, including operative interventions, on the specimens used. All specimens were completely thawed prior to use.

Initial dissection. The femoral triangle was dissected in all specimens, and the femoral and profunda femoris arteries were identified. The first medial branch of the profunda femoris artery, the MCFA was carefully dissected at its origin. It was cannulated with a vascular catheter. There was 6 ml of saline injected into the artery to ensure there was no leak around the cannulation site. The specimens were then placed in the prone position. Using a computer-generated randomisation technique, either the right or the left side of the deep branch of MCFA was ligated. A posterior approach to the hip was carried out on the computer-generated randomised side. After dissecting through the gluteus maximus, the quadratus femoris was identified, incised near its insertion, and reflected medially. The conjoint tendon and obturator externus muscle were identified. Careful dissection was performed at the superior border of the obturator externus and the distal part of the deep branch of MCFA identified and ligated. The side with the ligated vessel was the test side, and the opposite side with a patent MCFA was the control side. Gadolinium-diethylenetriamine penta-acetic acid (Gd-DTPA) (Magnevist; Bayer HealthCare Pharmaceuticals Inc., Wayne, New Jersey) was introduced manually at a volume of 8 ml diluted with 3:1 saline after trials with a pilot specimen. Because venous ligation was not undertaken, no pressure fill was created. A column of contrast was maintained with no pressure in the arterial compartment at its normal calibre. The venous column is normally collapsed, leading to static imaging of the arterial tree.

Gadolinium (Gd-DTPA)-enhanced magnetic resonance imaging. All studies were acquired on a 3.0 Tesla GE MRI scanner (General Electric, Milwaukee, Wisconsin) using an eight-channel torso phased array coil. Conventional clinical MRI sequences included suppressed and unsuppressed 3D gradient echo sequences with the following acquisition parameters: 256 × 256 matrix, 18 cm field of view, 7.5/2.6 ms repetition time (TR) (unsuppressed/suppressed), 3.3 ms echo time (TE), one average 2 mm slice thickness reconstructed to 1 mm thick, and a 35° flip angle. Static fat-suppressed and unsuppressed post-contrast T1-weighted 3D GRE images were acquired immediately after injection and 20 minutes later. Three-dimensional reconstructions were also performed.

Magnetic resonance imaging data analysis. The coronal plane of the MR images was used for quantitative data analysis. On the coronal sections of the MRI, a line was drawn along the axis of the femoral neck to pass through the centre of the femoral head. A second line was drawn to bisect the first at the centre of the femoral head (Fig. 1). These divided the femoral head into four quadrants: (0) medial, (1) superior, (2) lateral and (3) inferior. The contributions of the MCFA on the control and test sides were analysed in each of the four quadrants. Automated custom software written in-house in IDL 6.4 (ITT Visual, Boulder, Colorado) was used for data analysis. Quantitative analysis of the contrast enhancement in the femoral head between the pre- and post-contrast images was performed. The signal intensity/voxel was noted in both pre- and post-contrast images. Its measurement in a small area of the surrounding muscle was used as a baseline for normalisation, and was noted for each voxel on each coronal section. The same coronal sections were used in the post-contrast images. The signal intensity/voxel on each coronal section was averaged to obtain a single reading of signal enhancement in each of the four quadrants on the test and control sides. A similar single reading of signal enhancement was also obtained in post-contrast images. Various comparisons, including the pre- and post-contrast images and the control and test sides were performed.

Statistical analysis. Signal enhancement after the gadolinium injection was calculated on the control and the test sides. The control side represented the contributions of the
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VOL. 91-B, No. 1, JANUARY 2009

patent MCFA and the test side represented those of the inferior vincular artery. A two-sided unpaired t-test was used to compare uptake of contrast among the four quadrants on the test and control sides in the post-contrast images. Paired t-tests were used to compare the signal intensities between the test and control sides on post-contrast images. When the test side was subtracted from the control side, the contribution of the superior retinacular artery alone was obtained. A paired t-test was used to compare the contributions of the superior retinacular artery and the inferior vincular artery.

Final dissection after injection of polymer into the medial femoral circumflex artery. After the MRI was performed, the specimens were injected with green or red polyurethane (PMC Smooth-on Inc, Easton, Pennsylvania). This was allowed to polymerise for 18 hours, after which gross dissection of the specimens was performed in order to confirm the MRI findings of the extra-osseous anatomy. We also confirmed whether the ligature of the deep branch of the MCFA was secure on the test side.

Results
Cannulation and injection of the MCFA was successful in all 14 hips. The vessel originated from the profunda femoris in 12 specimens, and from the common femoral artery in two. In all the seven hips the deep branch of the MCFA was ligated at the superior border of obturator externus, as confirmed by final dissection after injection of the polymer.

Quantitative. There was an average increase of 93.3% in the signal intensity on the coronal side and of 66.2% on the test side after injection of the contrast. The signal enhancement was 99.5%, 127.4%, 67% and 97% in quadrants 0, 1, 2, and 3, respectively, on the control side, and 94%, 39%, 31% and 99% in quadrants 0, 1, 2 and 3, respectively, on the test side. The inferior vincular artery contributed 56% (25% to 90%) of blood flow in quadrant 0, 34% (14% to 80%) in quadrant 1, 37% (18% to 48%) in quadrant 2, and 68% (20% to 98%) in quadrant 3 (Fig. 2; Table I). Signal enhancement was noticed in all quadrants due to the contribution of the inferior vincular artery alone, but it was higher in quadrants 0 and 3. There was no statistically significant difference in the uptake between the test and the control sides in quadrants 0, 1, 2 and 3 on the post-contrast images. The p-values were 0.46, 0.19, 0.27 and 0.21 in quadrants 0, 1, 2 and 3, respectively. Comparison between the control minus the test side and the test side revealed no statistically significant difference in uptake in quadrants 0, 1, 2, and 3. The p-values were 0.92, 0.47, 0.36 and 0.6 for quadrants 0, 1, 2 and 3, respectively.

Qualitative. The onward course of the deep branch of the MCFA from the inferior border of the quadratus femoris was studied. A consistent branch, the inferior vincular artery, was found in all 14 specimens. This nomenclature has been used in our study in accordance with the morphology of the artery. It is typically a single branch, originating 3 cm to 4 cm proximal to the inferior border of quadratus femoris. This was identifiable only after reflecting the quadratus medially and tracing the deep branch of MCFA proximally. The
inferior vincular artery traversed superiorly to pierce the capsule and perforated the inferior aspect of the femoral head-neck junction. In most cases one or two branches entered near the inferior aspect of the head-neck junction, within 1 cm of the cartilage rim of the femoral head (Fig. 3). The artery was not closely applied to the femoral neck. Another consistent branch was noted adjacent to the proximal border of the quadratus femoris, which crossed the trochanteric crest towards the greater trochanter, the trochanteric branch. The MCFA passed 1 cm to 1.5 cm medial to the trochanteric crest. It crossed anterior to the conjoint tendon of the obturator internus and the gemelli, and posterior to the obturator externus before perforating the capsule superior to the insertion of the superior gemellus.

While studying the intra-osseous vascular anatomy of the femoral head we found an extensive intra-osseous anastomosis between the superior retinacular and inferior vincular arteries (Fig. 4). A subfoveal plexus was also found in ten of the 14 specimens (Fig. 5). This plexus had connections with the lateral epiphyseal artery, the inferior vincular artery and the foveal artery. In ten specimens contrast was present in the artery for the ligament of the head of the ligamentum teres. In ten specimens we found an anastomosis between the MCFA and the inferior gluteal artery (Fig. 6). Of those ten specimens demonstrating the anastomosis between these vessels, four were found on the test side and six on the control side (Tables II and III).

**Discussion**

The clinical implications of an avascular femoral head can be profound. A thorough understanding of the intra- and extra-osseous anatomy of the blood vessels supplying the femoral head is critical in determining surgical approaches. Tucker, in 1949, described two groups of arteries, the superior and the inferior retinacular arteries branching from the MCFA. The relatively minimal contribution of the foveal artery and a striking alteration in the size and arrangement of foveal vessels was noted. Trueta and Harrison in 1953 and Judet et al in 1956 also described the superior and inferior retinacular arteries, but noted that the inferior vincular artery was a smaller branch. More recently, the focus has shifted to the

![Fig. 3a](image1) ![Fig. 3b](image2) ![Fig. 3c](image3)  
Posterior photograph of the hip showing the a) inferior vincular artery (GT, greater trochanter; LT, lesser trochanter; C, capsule being reflected; IVA, inferior vincular artery; ER, short external rotators) and b) after the femoral head (FH) has been dislocated posteriorly; demonstration of discontinuity of polyurethane at the ligature site of distal medial circumflex femoral artery (MCFA); M, main trunk of the MCFA; IVA, inferior vincular artery; TB, trochanteric branch. c) Demonstration of discontinuity of polyurethane at the ligature site of distal MCFA.

![Fig. 4](image4)  
Reconstructions showing extensive intra-osseous anastomoses in the femoral head.
superior retinacular arteries as the major source of the blood supply. Gautier et al. 4 emphasised this and noted inferior retinacular arteries in four of 20 specimens.

In a study analysing the predictors of nonunion and AVN in intracapsular fractures of the neck of the femur, no association was found between the development of AVN and the displacement of the fracture. 19 A 12% incidence of AVN was noted in a series which described the outcome of 48 intracapsular fractures treated with a dynamic hip screw. 18 In a recent study on the outcome of delayed internal fixation in displaced fractures of the femoral neck the authors noted a rate of AVN of 10% at a mean follow-up of 44 months. 18 The superior retinacular artery is closely applied along the superior aspect of the neck. In displaced fractures the bony fragments place the superior retinacular branches at significant risk of injury, although this artery alone may not explain the rate of AVN noted in the literature. These fractures heal by revascularisation and creeping substitution, as described by Catto 26 and by Phemister 27 may be an explanation. The inferior vascularity artery, with its redundant course and by the virtue of its non-proximity to the femoral neck, may be a potential source of blood supply in fractures of the neck. In clinical situations where revascularisation of the head is vital in maintaining structural integrity, contributions from all the branches become important.

Careful analysis of the results reveals the greatest signal uptake in quadrants 0 and 3 on both the control and the test sides. The reasons for the greater uptake in the inferior and medial quadrants can be explained by the architecture of the intra-osseous vasculature and the point of entry of the inferior vascularity artery. The subfoveal plexus was found in all the specimens and was fed by superior retinacular and the inferior vascularity arteries. The plexus had connections with the foveal artery, but the study design and the injection pattern of the gadolinium precluded direct antegrade flow into the artery. The location of the plexus was directly beneath the fovea. Quadrant 3 received most of the supply from the inferior vascularity artery. Signal enhancement in quadrants 1 and 2 was 39% and 31% on the test side, compared to 127.4% and 67%, respectively on the control side. This shows that there was a relatively higher uptake in the weight-bearing portion of the femoral head when the superior retinacular branches were patent; however, these results were statistically insignificant. When the control minus test and the test were compared, a direct comparison of the contributions of the superior retinacular and inferior vascularity arteries was made. This revealed a statistically significant difference in all the quadrants.

Various extra-osseous anastomotic patterns have been described around the femoral neck, including those encircling the neck of femur. 1, 28-33 However, no such pattern was noted in our study. We observed a constant anastomosis between the inferior gluteal artery and the MCFA in ten specimens. In our previous study this anastomosis was specifically described. 34 In the same ten specimens we noted filling in the foveal artery. As the internal iliac artery was not injected, we explained this by the anastomosis between the MCFA and the inferior gluteal artery. Figure 6 demonstrates the anastomotic pattern through retrograde flow from the inferior gluteal artery into the internal iliac artery, then to the foveal artery via the obturator artery. A complete description of this anastomotic pattern was not undertaken, but the pattern noted in our study is the same as that described by Gautier et al. 4
There are some limitations to this study. In all cases we injected 8 ml of Gd-DTPA into the MCFA. There was a chance that the contrast might have spilled into the venous sinuses. Although such spillage cannot be ruled out entirely, given that the veins are collapsed in an open non-pressurised system, the presence of contrast in the venous compartment is unlikely. Careful analysis of the MR imaging revealed no fill in any extra-osseous veins in all specimens. The purpose of our study was to carry out a precise volumetric analysis on the contribution of the different branches. We did not intend to study the intra-osseous vascular architecture. Therefore, signal enhancement in any given area was due to a contribution from the arterial branch.

The inferior vincular artery is a constant branch from the MCFA. It arises 3 cm to 4 cm proximal to the inferior border of quadratus femoris. This branch has a significant contribution to the vascularity of the femoral head. Extensive intra-osseous anastomoses exist between the superior retinacular arteries, the inferior vincular artery and the subfoveal plexus. This branch has the potential to feed the intra-osseous anastomoses and may revascularise the avascular femoral head.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References