Quantitative Assessment of the Vascularity of the Proximal Part of the Humerus

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Background: The current consensus in the literature is that the anterolateral branch of the anterior humeral circumflex artery provides the main blood supply to the humeral head. While the artery is disrupted in association with 80% of proximal humeral fractures, resultant osteonecrosis is infrequent. This inconsistency suggests a greater role for the posterior humeral circumflex artery than has been previously described. We hypothesized that the posterior humeral circumflex artery provides a greater percentage of perfusion to the humeral head than the anterior humeral circumflex artery does.

Methods: In twenty-four fresh-frozen cadaver shoulders (twelve matched pairs), we cannulated the axillary artery proximal to the thoracoacromial branch and ligated the brachial artery in the forearm. In each pair, one shoulder served as a control with intact vasculature and, in the contralateral shoulder, either the anterior humeral circumflex artery or the posterior humeral circumflex artery was ligated. Gadolinium was injected through the cannulated axillary arteries, and magnetic resonance imaging was performed. After imaging, a urethane polymer was injected, and specimens were dissected. For volumetric analysis, the gadolinium uptake on the magnetic resonance imaging was quantified in each quadrant of the humeral head with use of a custom automated program. The gadolinium uptake was compared between the control and ligated sides and between the ligated anterior humeral circumflex artery and ligated posterior humeral circumflex artery groups.

Results: The posterior humeral circumflex artery provided 64% of the blood supply to the humeral head overall, whereas the anterior humeral circumflex artery supplied 36%. The posterior humeral circumflex artery also provided significantly more of the blood supply in three of the four quadrants of the humeral head.

Conclusions: The finding that the posterior humeral circumflex artery provides 64% of the blood supply to the humeral head provides a possible explanation for the relatively low rates of osteonecrosis seen in association with displaced fractures of the proximal part of the humerus. In addition, protecting the posterior humeral circumflex artery during the surgical approach and fracture fixation may minimize loss of the blood supply to the humeral head.

Clinical Relevance: Understanding the contributions to the blood flow to the humeral head can better aid in surgical planning and fracture fixation.

The reported rates of osteonecrosis associated with three and four-part proximal humeral fractures have ranged from 0% to 34%; however, many patients with osteonecrosis are not clinically symptomatic. Osteonecrosis can result from the injury or from the surgical approach and exposure during fracture fixation. These relatively low rates of osteonecrosis are not explained by the existing literature.

The current consensus in the literature is that the anterolateral branch of the anterior humeral circumflex artery provides the main blood supply to the humeral head. Gerber et al. concluded that this branch provided the main blood supply to the humeral head, with the arcuate artery supplying almost the entire epiphysis and with the posterior humeral circumflex artery supplying only the posterior aspect of the greater tuberosity and a small posteroinferior part of the articular segment.

Other articles have indicated that the posterior humeral circumflex artery may play a more important role. In a

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study by Brooks et al. in which the anterolateral branch of the anterior humeral circumflex artery was ligated, the arcuate artery filled through its anastomoses with the posterior humeral circumflex artery, with good filling of the arterial arcades of the entire head. In another study, arteriography was performed in twenty patients after proximal humeral fracture, and the anterior humeral circumflex artery was found to be disrupted in 80% of the cases whereas the posterior humeral circumflex artery was normal in 85% of the cases. These findings were not consistent with the previous conclusion that the anterior humeral circumflex artery provides the major blood supply to the humeral head, as osteonecrosis is infrequent and would occur much more frequently if the anterior humeral circumflex artery were indeed the primary blood supply to the humeral head.

Understanding the contribution of the vessels to the blood flow of the humeral head is fundamental for the development of treatment algorithms for proximal humeral fractures, including the surgical approaches that are used during fracture fixation. As a result of the discrepancy in the literature with regard to the primary blood supply of the humeral head and the actual observed rate of occurrence of osteonecrosis, we hypothesized that the posterior circumflex artery provides more perfusion to the humeral head than the anterior circumflex artery does. To study this hypothesis, we developed a novel technique to determine the relative intraosseous contributions of these two vessels to each quadrant of the humeral head with use of gadolinium-enhanced magnetic resonance imaging.

Materials and Methods

Initial Dissection and Cannulation

Twenty-four fresh-frozen cadaver shoulders (twelve matched pairs) from donors with an average age of 64.1 years (range, fifty-two to seventy-two years) at the time of death were obtained from the anatomic gift registry. Previous shoulder pathology was excluded by reviewing medical histories, the absence of surgical incisions, and visual inspection of the osseous surfaces. In each specimen, we inserted a 14-gauge vascular catheter into the axillary artery, just proximal to the thoracoacromial branch. The brachial artery was ligated at the level of the midpoint of the humerus. For each pair of shoulders, one served as a control with intact vasculature and on the contralateral side either the anterior circumflex artery or the posterior circumflex artery was ligated as it branched off the axillary artery. We did not ligate any other vessels because other studies have demonstrated that other vessels have little or no contribution to the blood supply of the humeral head.

Magnetic Resonance Imaging Acquisition Methods

All imaging studies were acquired on a 3.0-T magnetic resonance imaging scanner (GE Healthcare, Waukesha, Wisconsin) with use of a quadrature head coil. Conventional clinical magnetic resonance imaging sequences included suppressed and unsuppressed three-dimensional gradient-echo sequences; the acquisition parameters were a 352 × 256 matrix (reconstructed to 512 × 512), a 26-cm field of view, a repetition time of 8.1/13.8 ms (unsuppressed/suppressed), 3.9 ms echo time, one average, a 2-mm slice thickness (reconstructed to 1 mm), and a 35° flip angle. Gadolinium-diethylenetriamine pentaacetic acid (Gd-DTPA) (Magnevist; Bayer HealthCare Pharmaceuticals, Wayne, New Jersey) was manually administered at a volume of 10 mL, diluted with saline at a ratio of 3:1 over ten seconds. Static fat-suppressed and unsuppressed post-contrast T1-weighted three-dimensional gradient echo images were then acquired immediately and at twenty minutes after injection.

Injection of Latex with Gross Dissection

After completion of the magnetic resonance imaging, a urethane polymer (PMC-780; Smooth-On, Easton, PA) was injected into the specimens, and the specimens were left overnight for at least eighteen hours for the urethane to polymerize. After polymerization, the specimens were grossly dissected to visualize the extraosseous vessels and to confirm successful ligation. Characteristics of the vascular anatomy were recorded, and photographs were made.

Analysis

For volumetric analysis, the gadolinium uptake was quantified in each quadrant on the coronal images with use of a custom automated program. Software was written to analyze the enhancement characteristics of the humeral head. The anterior and posterior limits of the head were defined in order to place the locus of the major axis of an ellipse in three dimensions.
The minor axis of the ellipse was then defined within a region centered on the humeral head. The quadrants were determined by drawing (1) a line from the medial border of the greater tuberosity to the inferior margin of the humeral head and (2) a second line that bisected the midpoint of the head perpendicular to the first line. These lines divided the head in the coronal plane into (1) medial, (2) superior, (3) lateral, and (4) inferior quadrants (Fig. 1). Voxels were grouped by slice and quadrant in the control and test specimens to produce weighted average signal intensities as well as histograms. Signal intensities were normalized to non-enhancing regions of muscle to compare data before and after the administration of Gd-DTPA. Histograms were normalized to the total number of voxels contained within each quadrant to allow for comparison between specimens. The definition of the humeral head on the precontrast images was then directly read into the postcontrast image set, requiring only identification of regions of non-enhancing muscle to complete the analysis. A weighted average of the signal intensity within each quadrant was then calculated before and after the administration of Gd-DTPA. This allowed for a measure of change in normalized signal intensity to muscle to be compared between specimens and among quadrants. Paired t tests were used to compare the gadolinium uptake in the control specimens and the contralateral, ligated specimens. Unpaired t tests were used to compare the uptake in the specimens in which the posterior circumflex artery was ligated with the specimens in which the anterior circumflex artery was ligated. This was done for the entire humeral head as well for individual quadrants. The quadrants can be seen in Figure 1.

**Source of Funding**

This study was funded by an unrestricted educational grant from Synthes (Paoli, Pennsylvania). The funds were used to pay for cadavers, supplies, and the use of magnetic resonance imaging.

**Results**

**Gross Dissection**

Ligation of the vessel was confirmed in all specimens. The posterior humeral circumflex artery and the anterior humeral circumflex artery branched from the axillary artery in all

**TABLE I Contribution of the Posterior and Anterior Circumflex Arteries to the Individual Quadrants and the Total Humeral Head**

<table>
<thead>
<tr>
<th></th>
<th>Quadrant 1</th>
<th>Quadrant 2</th>
<th>Quadrant 3</th>
<th>Quadrant 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posterior</td>
<td>48.7%</td>
<td>63.3%</td>
<td>70.0%</td>
<td>75.1%</td>
<td>64.3%</td>
</tr>
<tr>
<td>circumflex</td>
<td>artery</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>51.3%</td>
<td>36.7%</td>
<td>30.0%</td>
<td>24.9%</td>
<td>35.7%</td>
</tr>
<tr>
<td>circumflex</td>
<td>artery</td>
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**Fig. 2** The posterior humeral circumflex artery (PCA) as it travels around the humeral head. Note that it is not adherent to the head and has several perforating branches. **Fig. 3** The anterior humeral circumflex artery, which is intimately adherent to the humeral head. AL Branch = anterolateral branch of the anterior humeral circumflex artery.
specimens; however, they branched from the axillary artery as a single trunk in seven of the twenty-four specimens. The ascending anterolateral branch of the anterior humeral circumflex artery was present in all specimens. Photographs of dissected specimens are seen in Figures 2 and 3.

**Magnetic Resonance Imaging**

The average increase in signal intensity per voxel was 0.70, 0.32, 0.60, and 1.18 in quadrants 1, 2, 3, and 4, respectively, with the anterior humeral circumflex artery ligated (and the posterior humeral circumflex artery patent), and 0.60, 0.16, 0.38, and 0.61 in quadrants 1, 2, 3, and 4, respectively, with the posterior humeral circumflex artery ligated (and the anterior humeral circumflex artery patent). The posterior humeral circumflex artery provided 64% of the blood supply to the humeral head overall, with the anterior humeral circumflex artery supplying 36%. The posterior humeral circumflex artery also provided significantly more of the blood supply in quadrants 2, 3, and 4 (p < 0.05), with the anterior circumflex artery supplying slightly more blood to quadrant 1 (Table I and Figs. 4-A through 5-C).

There was also a significant difference between the control specimens and the ligated specimens, with the controls having 46% more gadolinium uptake (p < 0.05). The control specimens had 32% more uptake than the specimens with the anterior humeral circumflex artery ligated and 60% more than the specimens with the posterior circumflex artery ligated.
Discussion

To our knowledge, this is the first study to quantify blood supply to the humeral head with use of magnetic resonance imaging technology. Other studies have been performed in an attempt to examine the contribution of the vessels qualitatively but may have underestimated the importance of the posterior humeral circumflex artery. The present investigation demonstrated that the posterior humeral circumflex artery perfuses more of the humeral head than the anterior humeral circumflex artery does, especially in the superior, lateral, and inferior quadrants, and provides a more biologically plausible explanation for patterns of osteonecrosis seen after fracture.

Gadolinium-enhanced magnetic resonance imaging allowed us to objectively quantify the relative contributions to humeral head blood flow of each of the arteries when the other artery was ligated. This has not been possible in previous studies. Gadolinium-enhanced magnetic resonance imaging is not a new technique as it has been used to quantitate organ perfusion in cases of stroke, myocardial infarction, cancer, and liver disease, for which it is used to demarcate areas of disease. In the musculoskeletal system, it has been used to examine bone tumors, bone marrow perfusion, Legg-Calvé-Perthes disease, scaphoid fractures, vascularized bone grafts, fracture patterns, and osteonecrosis. It also has been used to evaluate perfusion in animal models of fracture and ischemia. We recently described the vascular anatomy of the hip with use of this technology.

The assessment of static contrast-enhanced magnetic resonance images is a fundamental tool in clinical radiology. This method is used throughout oncology to assess contrast enhancement by means of image subtraction. The present study went beyond a qualitative visual grading of contrast enhancement in the humeral head and used a percentage enhancement ratio normalized to a reference tissue for comparison of precontrast and postcontrast enhanced images. The absolute signal intensity obtained in a magnetic resonance imaging scan is a complex combination of effects due to relaxation times, spin densities, receiver gains, coil loading, flip angle accuracy, field homogeneities, and other factors. However, a ratio of magnetic resonance imaging signal intensities is insensitive to variances in receiver nonuniformity and provides a unitless number that normalizes these factors and allows for comparison between precontrast and postcontrast acquisitions.

Recently, there has been a trend toward plate osteosynthesis of three and four-part proximal humeral fractures. Recognition of posterior humeral circumflex artery predominance not only is important for the prediction of osteonecrosis on the basis of injury pattern but also should be considered in terms of surgical technique. Dissection posteromedially should be avoided, and manipulation of fracture fragments should be performed with care with regard to the posterior humeral circumflex artery.

The differences between the current study and previous studies that have indicated that the anterior humeral circumflex artery provides the main blood supply to the humeral head are likely due to the differences in methodology. The previous studies all involved the use of two-dimensional, not three-dimensional, imaging or sectioning. The previous studies were also all qualitative descriptions. In studies that involved the use of latex for vascular injections, perfusion of the smaller-diameter intraosseous vessels may not have occurred because latex is much more viscous than blood. In the paper by Gerber et al., radiographs were made in perpendicular planes for all twenty-seven whole specimens, but microradiography was possible for only sixteen of the twenty-seven specimens because of incomplete vascular filling. Only three of the eight specimens in which the posterior humeral circumflex artery was injected were deemed satisfactory, compared with eight of the ten specimens in which the anterior humeral circumflex artery was injected. Failure of filling of the small vessels in 41% of the specimens calls into question the ability to draw any clear conclusions from the study.

Other cadaveric and human fracture studies have indicated that the posterior humeral circumflex artery plays a more considerable role in perfusing the humeral head. The studies of humeral head fractures demonstrated that the posterior humeral circumflex artery is less likely to be disrupted and that the length of the posterosmedial metaphyseal extension and disruption of the medial hinge (which determines if the posterior humeral circumflex artery is intact) are the most important factors for predicting perfusion of the head, consistent with our findings.

To our knowledge, this is the first study in which the posterior humeral circumflex artery has been demonstrated to contribute a greater percentage of the blood supply to the humeral head than the anterior humeral circumflex artery does. As the trend toward reconstruction of complex proximal humeral fractures continues, detailed understanding of the relevant vascular anatomy will be crucial for success. Protection of the posterior blood supply may be very important during fracture dissection, reduction, and fixation. Long-term studies are needed to confirm the prediction of osteonecrosis on the basis of this new understanding of the vascular anatomy.