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Regional variations in radial head bone volume and density: implications for fracture patterns and fixation

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Background: Fractures of the radial head are common with most partial articular fractures resulting in an anterolateral fragment. The exact mechanism of radial head fracture is unknown; however, forces transmitted and variations in local bone density are believed important. This study quantifies the regional variations in bone density and volume of the radial head to better understand the pathomechanics of fracture patterns.

Methods: Computer tomography scan data of 18 cadaver elbows were imported into imaging analysis software. The radial head was divided into quadrants based on neutral forearm rotation. Bone density and volume were calculated and compared between quadrants.

Results: The regional densities of bone expressed in Hounsfield units (HU) were posteromedial quadrant (PM) 496 ± 87 HU, anteromedial quadrant (AM) 443 ± 72 HU, anterolateral quadrant (AL) 409 ± 60 HU, and posterolateral quadrant (PL) 406 ± 57 HU. The volume of bone in descending order was PM 1138 ± 179 mm^3, PL 1013 ± 213 mm^3, AM 1010 ± 210 mm^3, and AL 938 ± 175 mm^3. The PM quadrant was significantly denser than the AM, AL, and PL quadrants, ($P = .001$) and the AM quadrant was significantly denser than the AL and PL quadrants ($P = .006$ and .009). The PM quadrant had significantly more bone volume when compared to the AM, AL, and PL ($P = .001$). The AM and PL quadrants had significantly greater bone volume compared to AL quadrant ($P = .023$ and .018, respectively).

Conclusion: Radial head bone volume and density is highest in the posteromedial quadrant and lowest in the anterolateral quadrant where fractures occur more frequently.

Level of evidence: Basic Science, Anatomy Study, Imaging.

Keywords: Radial head fracture; elbow; bone density; bone volume; open reduction and internal fixation

Fractures of the radial head most commonly include an anterolateral fracture fragment.[11] There are several hypotheses explaining why the anterolateral fragment is typically involved.[9] Some authors suggest that the subchondral bone in this area is weaker,[3] while others believe it is because of the orientation of the radial head, forearm, and wrist during load transmission at the time of impact.[1]

Limited data are available documenting regional variations in radial head bone density. Furthermore, the literature is confusing as the reference position of forearm rotation varies between studies. Some authors use a quadrant

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Institutional Review Board approval was not required for this cadaveric anatomy study.

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system referenced in the anatomic position (forearm in full supination), while others use a more clinical definition with the forearm in neutral rotation, shifting the anatomic quadrants by 90°. For clarity, in this paper, we will refer to the neutral reference orientation and convert all studies discussed to this orientation.

Bartz et al[3] observed that the highest density of bone was found on the medial/ulnar side of the radial head in the segment that articulates with the lesser sigmoid notch of the proximal radio-ulnar joint. Similarly, Koslowsky et al also reported higher bone densities on the medial side of the radial head.[4,8] Gordon et al examined regional variations in radial head cancellous bone stiffness and strength and found no significant differences in stiffness among the 4 radial head quadrants, but increased yield strength in the posteromedial and anteromedial quadrants.[6]

The purpose of this study was to determine if there are regional variations in the volume and density of bone in the radial head. This information may improve our understanding of fracture pathomechanics and assist in determining the optimal location for placement of internal fixation.

Materials and methods

Specimens

Eighteen male cadaver (mean age, 75.3 ± 7.3 years; range, 57-88) arms were scanned using a 64-slice computer tomography (CT) scanner (GE Discovery CT750 HD®, Waukesha, WI, USA). Specimens included did not have radiographic evidence of arthritis, fracture, or deformity. Approximately 1200 slices were acquired for each specimen with a 512 × 512 reconstruction matrix, tube current at 200 mA, and peak tube voltage of 120 kVp. The size of the voxels was approximately 0.621 × 0.621 × 0.625 mm.

Three-dimensional model generation

The CT images were imported in DICOM (Digital Imaging and Communications in Medicine) format to Mimics 14.0® (Materialise, Leuven, Belgium) to construct 3-dimensional (3D) models. Three-dimensional model creation required segmentation of the radial head from the surrounding tissues, which was achieved using a semi-automated thresholding technique with preset values for bone of 141-2200 Hounsfield units (HU). The HU is a linear attenuation coefficient for tissue that correlates with bone mineral density and can be used to estimate regional bone strength.[10] The axial length of the model extended from the proximal articular surface of the radial head to the distal radius with the segment of interest being the radial head.

Measurements

An orthogonal coordinate system was created with the forearm in neutral rotation. Each specimen was oriented with reference to the distal radius. A coronal plane was created using an axis that was drawn to bisect the radius from the midpoint of the distal radio-ulnar joint to the apex of the radial styloid. This plane was extended proximally along the radius to the center of the articular surface of the radial head (Fig. 1).

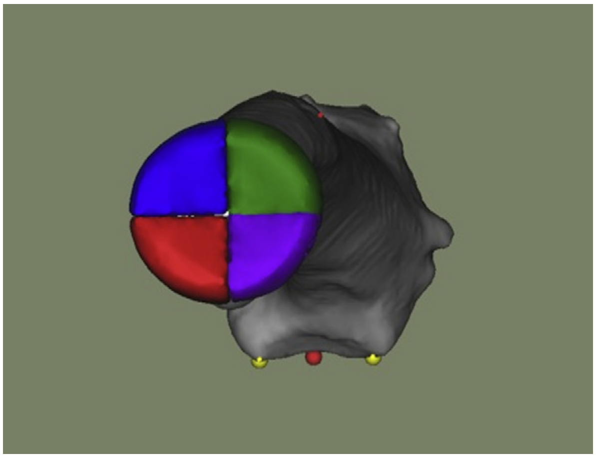

Figure 1 Landmarks to orient the quadrants of the proximal radius in a right-sided specimen oriented in neutral forearm rotation. The radial styloid (marked by the small *red* dot) and the midpoint (large *red* dot) between the volar and dorsal aspects of the lesser sigmoid notch (marked by the *yellow* dots) were used to create an anatomic plane. *Green*, anterolateral quadrant; *blue*, anteromedial quadrant; *red*, posteromedial quadrant; *purple*, posterolateral quadrant.

The radial head was divided into quadrants with the forearm in neutral rotation. Anteromedial, anterolateral, posterolateral, and posteromedial quadrants were created with an arc length of 90°, centered on the radial head. Each quadrant was analyzed separately using the Mimics 14.0® software. The volume of bone within each quadrant included both cortical and cancellous bone and was measured using preset functions for each 3D model. To determine the bone density, HU were measured for each quadrant.

Statistics

Descriptive statistics for each quadrant were computed using SPSS 18.0 (SPSS Inc., Chicago, IL). These values were analyzed for differences within subjects using general linear model analysis of variance. Significance was set at $P < .05$. Within subjects, differences were found to be significant using the Greenhouse-Geisser test for effect at $P < .05$.

Results

Qualitatively, patterns emerged when the axial images of the radial head and neck were examined (Fig. 2). Both density and volume appeared to be greatest in the areas of the radial head articulating with the proximal radio-ulnar joint. A second bone density maxima was noted at the center of the radial head articulation with the capitellum. Because of the axial division of quadrants, this central maximum was shared amongst each of the quadrants and did not factor into the quantitative differences among quadrant densities. A crescent shape of less dense bone

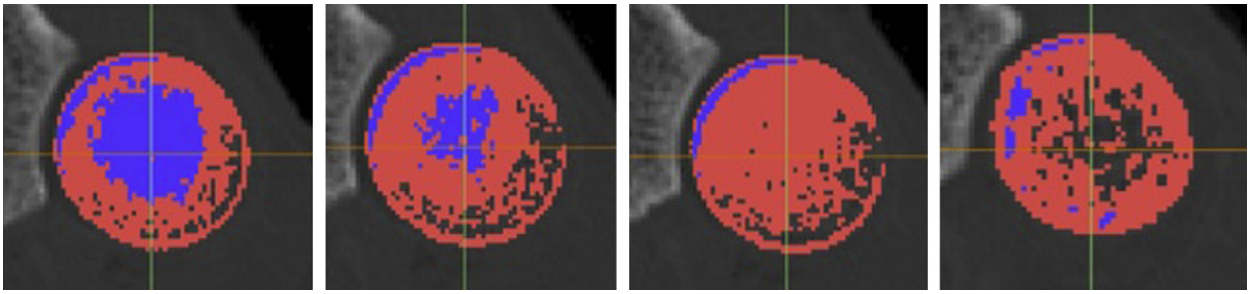

Figure 2 Axial sections through a left radial head from proximal to distal (left to right). The posteromedial quadrant is the top left quadrant and the anterolateral is the bottom right. Higher density bone is highlighted in *blue*, while less dense bone is in *red*. The *black* color within the radial head represents space between trabeculae and forms a crescent shaped pattern around the nonarticular portion of the proximal radioulnar joint. Note the increased density at the fovea of the radial head and along the articulation with the proximal radioulnar joint.

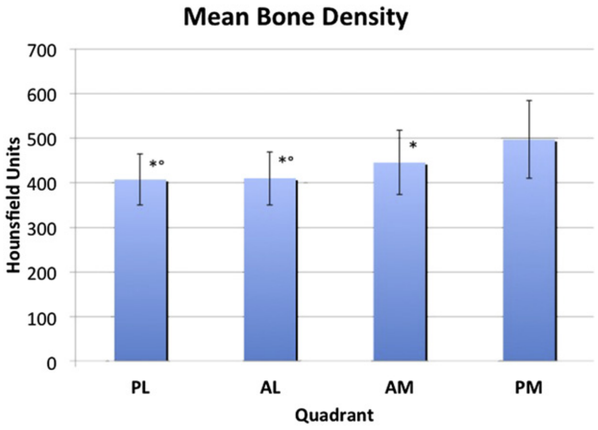

Figure 3 The mean bone density in each quadrant by Hounsfield units. The posteromedial (PM) quadrant is significantly denser than the others, and the anteromedial (AM) quadrant is significantly denser than the anterolateral (AL) and posterolateral (PL). The error bar represents one standard deviation. *, Significantly less dense than PM; °, significantly less dense than AM.

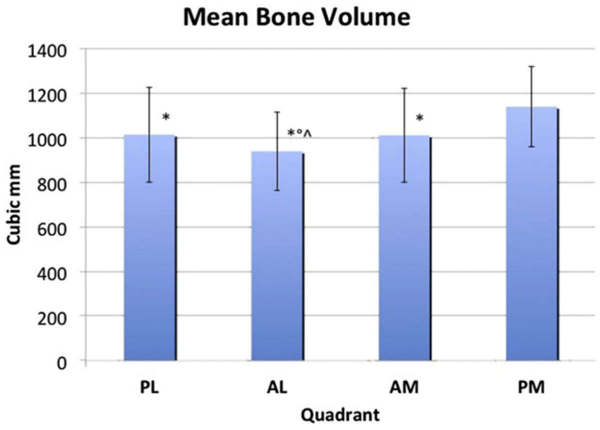

Figure 4 The mean bone volume in the radial head in cubic millimeters. The posteromedial (PM) quadrant had significantly more volume of bone compared to the other quadrants, and the anterolateral (AL) quadrant had significantly less than the other quadrants. *, Significantly less volume than PM; °, significantly less volume than AM, ^, significantly less volume than PL.

with cystic areas under the cortical shell was centered along the anterolateral quadrant and extended variably into the anteromedial and posterolateral quadrants, coinciding with our quantitative findings.

Quantitatively, the mean [± standard deviation (SD)] bone density within each quadrant measured in HU in descending order was posteromedial quadrant 496 ± 87 HU, anteromedial quadrant 443 ± 72 HU, anterolateral quadrant 409 ± 60 HU, and posterolateral quadrant 406 ± 57 HU (Fig. 3). The density of bone in the posteromedial quadrant was significantly greater than in the anteromedial, anterolateral, or posterolateral quadrants ($P < .001$). The density of bone in the anteromedial quadrant was significantly greater than the density in the anterolateral and posterolateral quadrants ($P = .006$ and.009). There was no significant difference in the density of bone in the posterolateral or anterolateral quadrants ($P > .05$). The highest bone density was noted to be in the posteromedial quadrant in 16/18 specimens. The lowest density quadrant was most frequently the anterolateral quadrant (8/18), followed by the posterolateral quadrant (7/18).

The mean volume of bone within each quadrant in descending order was posteromedial 1138 ± 179 mm^3, posterolateral 1013 ± 213 mm^3, anteromedial 1010 ± 210 mm^3, and anterolateral 938 ± 175 mm^3 (Fig. 4). The posteromedial quadrant was found to have significantly greater bone volume than the anteromedial, anterolateral, and posterolateral quadrants ($P < .001$). The anteromedial and posterolateral quadrants were found to have significantly greater bone volume than the anterolateral quadrant ($P = .023$ and .018, respectively). There was no significant difference in the bone volume between the anteromedial and posterolateral quadrants ($P > .05$). The highest volume of bone was noted to be in the posteromedial quadrant in 15/18 and the lowest volume was in the anterolateral quadrant in 11/18 specimens.

Discussion

Skeletal mass, geometric properties, and material quality are 3 determinants of structural bone strength.[5] Bone mineral density serves as a surrogate measure for the mechanical competence of bones and is used as a direct measure of an individual's fracture risk.[2]

Gordon et al suggested that one common mechanism of radial head fractures may be a combined axial, valgus, and external rotatory loading mechanism, causing shearing of the anterolateral segment of the radial head as it subluxates posterior to the capitellum.[6,11,12] While there is evidence that specific axial and rotational loads applied to the forearm can result in radial head fractures, it is uncertain whether bone architecture plays a substantial role in fracture patterns.[1]

Our results indicate the posteromedial quadrant has significantly greater bone density and volume. We hypothesize that this may be because of the increased joint reactive forces experienced by the radial head in this location, as it articulates with the lesser sigmoid notch of the ulna. This is in keeping with Wolff's law[13] as well as previous studies that have estimated the joint reactive forces to be substantial at the proximal radio-ulnar joint.[3] The increased density and bone volume may act as a protective factor in reducing the incidence of fracture propagation through this posteromedial quadrant.

The anteromedial, anterolateral, and posterolateral quadrants have qualitatively and quantitatively reduced density and larger spaces between the bony trabeculae. The combination of lower density and decreased volume of bone may decrease the yield strength of these regions and predispose them to fracture. The observation that many radial head fractures include a fragment from the anterolateral aspect[12] may be a consequence of this decreased density and volume.

Several studies have examined the mechanical properties of the radial head and kinetics of the injury to explain why radial head fractures occur in a characteristic manner.[1,4,6,7] A direct comparison of methods and results is difficult and must be undertaken with caution because the orientation of the forearm is not clearly defined in the majority of the articles. For clarity in the present paper, we converted all studies to the neutral reference position.

Gordon et al examined the mechanical properties of the subchondral cancellous bone of the radial head using a flat indentor.[6] Local yield strength was significantly higher in the posteromedial quadrant than in the anterolateral and posterolateral quadrants, and in the anteromedial quadrant compared with the anterolateral quadrant. In their study, the authors tested exclusively the subchondral cancellous bone, while in our study we analyzed both cortical and cancellous bone in all regions of the radial head. Their study does support the results of our study, in that increased bone density in the posteromedial quadrant is consistent with increased yield strength compared to other quadrants, and that the anteromedial quadrant has significantly higher yield strength compared to the anterolateral and the posterolateral quadrants.

In another study, Eckstein et al used CT osteo-absorptiometry to assess subchondral mineralization of the elbow.[4] They found a central bone density maximum in the center of the radial head, with mineralization falling off concentrically toward the margins of the radial head. This study also used HU to quantify bone density but interpreted the results qualitatively by the location of increased density. This agrees with our qualitative imaging that details a consistent area of maximal density in the subchondral surface at the center of the radial head. They attribute the central density maximum in the radial head to central pressure transmission in the radio-capitellar joint. Focusing on the subchondral bone, they did not evaluate the adjacent cancellous bone and did not examine the proximal radio-ulnar joint as in our study.

Koslowsky et al developed a 2-dimensional density distribution pattern of the subchondral cortical bone of the radial head using subtraction densiometry.[8] They noted high density in the posteromedial quadrant ''ulnar-dorsal'' in 21 of 37 specimens, anteromedial quadrant ''ulnar-ventral'' in 5 of 37 specimens, and central density maximums in 6 of 37 specimens. These results generally agree with our assessment of increased density in the posteromedial quadrant with a secondary area of increased density in the subchondal bone at the center of the radial head.

During open reduction and internal fixation of radial head fractures, screw purchase into bone is important for secure fixation. Based on the results of this study, screws directed across marginal fragment fractures will find better bony purchase if directed towards the subchondral bone of the posteromedial quadrant. The authors' clinical experience has been that screw heads are commonly predisposed to subsidence in the lateral sided quadrants, where a thin cortical rim covers the relatively osteopenic underlying cancellous bone (Fig. 2). Our results help explain this clinical entity, as the crescent of less dense bone and a paucity of cortical bone were found in the nonarticulating portion of the radial head. Smith and Hotchkiss called this area of the radial head ''the safe-zone,'' where hardware can be placed without impingement with the ulna during forearm rotation; however, it is also the area where fixation is the most compromised.[10]

Any study of the radius is limited by the variability in the anatomy of the radial head and rotational relationships with the landmarks, including the distal radius and proximal radio-ulnar joint. Dividing the radial head into a quadrant system, though previously described, is an artificial distinction, as fractures rarely affect one quadrant in isolation. Error is also introduced as the radial head is not circular but rather elliptical; it is therefore difficult to divide into exact quarters. Our study was limited in that cadaver specimens were all male and generally older. Female specimens should be included in future studies. As bone mineral density in the radial head is known to decrease with age, the results of this study may not be applicable to younger patients with increased density.[5]

The strengths of this study include the fact that the entire radial head was examined via an anatomic 3D model, as compared to previous studies that examined only specific areas of the radial head. The analysis of the radial head was also extended to the head-neck junction where fractures typically exit, so that all of the cortical and cancellous bone involved in fractures could be assessed.

Conclusion

This study hypothesized that regional variations in radial head bone density and volume may be a substantial factor in fracture of the anterolateral aspect of the radial head. The posteromedial quadrant was found to have a significantly greater density and volume of bone than the anteromedial, anterolateral, and posterolateral quadrants. Clinically, fractures of the posteromedial quadrant are less common, and the increased bone density and volume may prevent propagation of fractures in this area. Lower bone density in the remaining quadrants may pre-dispose them to fracture and comminution. A convention noting orientation of the forearm should be adopted for studies involving the radial head to improve clarity when communicating results. We suggest using the forearm in neutral rotation, as this is how fractures are typically described intra-operatively; it is also the position that places the safe zone of the radial head directly lateral.

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Disclaimer

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