Determination of the Optimal Location for Bone Graft Harvest in the Distal Radius

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Abstract

Background: The distal radius is commonly used as a bone graft donor site for surgery in the hand and wrist. The aim of this study was to evaluate the volume and relative density of cancellous bone in the distal radius. **Methods:** Thirty-four consecutive computed tomographic scans of the wrist in 33 patients without distal radius pathology were included. For each subject, 6 spherical regions of interest (ROIs) were identified within the distal radius. In each ROI, volumetric measurements and mean Hounsfield unit (HFU) values were recorded by 2 observers using a 3-dimensional imaging reconstruction software. **Results:** Compared with proximal bone, distal bone had larger volume (0.82 vs 0.27 cm³) and greater relative density (178 vs 152 HFU) on average. Among the 6 ROIs, the distal-central region had the largest average volume (1.20 cm³) and the distal-ulnar ROI had the greatest average relative density (193 HFU). **Conclusion:** Based on these results, we recommend performing cancellous autograft harvest relatively distal and ulnar within the distal radius.

Keywords: distal radius bone graft, bone density, bone graft harvest, scaphoid nonunion, computed tomography

Introduction

The distal radius is recognized as an excellent local site for obtaining nonvascularized autogenous bone graft.¹⁻⁴ This donor site is of particular interest in the case of surgery for scaphoid nonunions or fusions of the hand and wrist, where graft harvest may be possible through the same incision as the index procedure. Multiple techniques have been described, including dorsal⁵ and volar^{6,7} approaches, as well as corticocancellous^{2,3,6} and cancellous-only^{5,6} techniques.

Despite the widespread use of the distal radius as the site of harvest for cancellous bone graft, little is known about the relative volume and density of cancellous bone among different regions within the distal radius. Subchondral bone density patterns within the distal radius are known to vary in humans and primates based on the different functional loading patterns of these species.⁸ The Wolff law states that the bone will strengthen to adapt to an increased load.⁹ This would suggest that the cancellous bone with greatest density would be in the area experiencing the greatest load.

Although the radioscaphoid joint experiences greater forces and pressures than the radiolunate joint,¹⁰⁻¹² forces across the distal radioulnar joint¹³ may affect the cancellous density patterns as well. In a recent study by Pidgeon and colleagues, quantitative computed tomographic (CT) data demonstrated highest distal radius trabecular bone density adjacent to the radiocarpal and distal radioulnar joints; however, these findings are yet to be corroborated.¹⁴

Knowledge of the relative volume and density within the distal radius may serve to guide surgeons in optimizing their graft site selection.

The purpose of this study was to use CT data to investigate the volume and relative density of cancellous bone that exists at different 3-dimensionally (3D) defined regions in the distal radius. We hypothesize that cancellous bone will be most voluminous in the distal-central region of the bone owing to the metaphyseal flare and wider cross-sectional area of the distal radius. In addition, we hypothesize that the cancellous bone of the distal-ulnar section of the distal radius will have the highest relative density due to the multidirectional forces seen in this area.

Methods

Study Group

Using the *Current Procedural Terminology* code for upper extremity CT scan (73200), 2108 consecutive upper extremity CT scans obtained at a single tertiary referral institution between January 2001 and November 2016 were identified.

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Figure 1. Representative images demonstrating the outcomes of orienting reconstructed images to define an (a) axial plane, (b) mid-sagittal plane, and (c) coronal plane. Red lines indicate axial plane; blue lines, mid-sagittal plane; and green lines, mid-coronal plane.

Medical records and imaging results were reviewed to determine which patients qualified for the study group. Only dedicated CT scans of the wrist were included. Exclusion criteria included the following: remote or recent history of fracture or surgery to the radius or ulna, polytrauma involving the ipsilateral upper extremity, congenital skeletal difference, infection, skeletal immaturity, inflammatory arthritis, or known osteoporosis. Clinical records were reviewed to determine the indication for the wrist CT and the presence of any potential exclusion criteria.

Data Collection

Wrists were imaged with a CT with a field of view of approximately 10 to 15 cm (to include the distal radius and ulna through the proximal aspects of the metacarpals). Images were acquired helically at 120 kV, 100 mA, and a voxel size of 0.625×0.625 mm. Images were reconstructed using both bone and standard kernels in the axial plane and using a bone kernel in the sagittal and coronal planes; reconstructed images were displayed at 1 and 0.625 mm. Digital CT data were uploaded onto the TeraRecon Aquar-

ius imaging software program (TeraRecon, Inc, San Mateo, California) to enable multiplane manipulation of images and definition of 3D regions of interest (ROIs).

The process for manipulating the images and collecting volume and HFU data was described and overseen by a fellowship-trained musculoskeletal radiologist and performed by 2 orthopedic surgery senior residents.

Once images were uploaded into the TeraRecon software program, the axes of 3 linked viewing windows were simultaneously manipulated to provide perfect mid-coronal and mid-sagittal CT sections (Figure 1). First, an axial cut showing the fullest profile of Lister's tubercle was marked. Then, the mid-sagittal axis was confirmed when it appeared congruent with the longitudinal axis of the radius on the coronal view, bisected the distal-radial articular surface on the coronal view, and was aligned with Lister's tubercle on the axial view. Then, the mid-coronal plane was defined by the line bisecting the distal radioulnar joint on the axial view and parallel with the long axis of the radius on the sagittal view.

On the coronal view, 2 distances were measured along the mid-sagittal axis: first at a level 10.0 mm proximal to the articular surface (distal) and second at a level 20.0 mm

Figure 2. The distal and proximal levels of measurement were defined along the mid-sagittal axis as seen on the mid-coronal plane at 10.0 and 20.0 mm from the articular surface. Red lines indicate axial plane; and blue lines, mid-sagittal plane.

proximal to the articular surface (proximal) (Figure 2). Distances were chosen based on surgeon experience in conjunction with the previously described techniques.^{3,5,7}

Once these distances were defined, a perpendicular axial section was placed precisely at the 10.0-mm mark. On this axial section, three 3D spherical ROIs were defined: (1) radial; (2) ulnar; and (3) central. Radially, the sphere was drawn as large as possible and without abutting the radial, volar, and dorsal cortices. Similarly, the ulnar sphere was then drawn as large as possible without abutting the ulnar, volar, and radial cortices. The central sphere was then drawn as large as possible with its center along the previously defined mid-sagittal axis (Figure 3). Care was taken through looking at axial views, as well as corresponding sagittal and coronal views, to ensure that cortices were not included in the spherical ROI. Spherical ROIs were preset to yield volume and HFU data through the TeraRecon software, and these data were then recorded. The HFU data were interpreted as a proxy for bone density as it has previously been demonstrated that HFU data are closely correlated with dual x-ray absorptiometry (DXA) scores in the wrist,^{15,16} as well as elsewhere in the skeleton.¹⁷

Once the measurements were completely centered on the 10.0-mm level, the perpendicular axial section was then placed at the line 20.0 mm proximal to the articular surface. Three spherical ROIs were again defined in an identical manner to the description above, and data on volume and HFU were recorded. With 10.0 mm defined as the distal level and 20.0 mm defined as the proximal level, data from a total of 6 ROIs were recorded for each subject (Figure 3).

Statistical Analysis

Data were summarized using routine descriptive statistics for both continuous (averages with confidence intervals [CIs]) and categorical (counts with percentages) variables. Statistical analysis included the Student *t* test for comparisons between 2 averages. For multiple comparisons, we present least squares mean difference values adjusted using the Tukey method. A *P* value less than .05 was considered statistically significant. Ten CT scans were randomly selected for analysis by both observers to enable calculation of intraclass correlation (ICC).

Results

The final study group consisted of 34 wrist CT scans in 33 patients. Patient demographics and indications for the wrist CT appear in Table 1.

The average volume measurement in the distal regions was 0.82 cm^3 (95% CI = 0.74-0.91) compared with 0.27 cm^3 (95% CI = 0.24-0.31) in the proximal regions ($P < 0.001$). Regarding Hounsfield unit measurements, distal region measurements averaged 178 (95% CI = 163-193) compared with 152 (95% CI = 136-170) in the proximal regions ($P < .001$) (Table 2).

When regions are subdivided based on the coronal position, the subregion with the greatest volume was distal-central (1.20 cm^3 , 95% CI = 1.07-1.32) followed by distal-ulnar (0.81 cm^3 , 95% CI = 0.69-0.92) (Table 2). Both the distal-central and distal-ulnar subregion volumes were larger on average than the volumes of all other subregions when compared individually ($P < .001$). Most other individual subregion volume measurements showed statistically significant variation from each other when compared individually (Table 3).

The subregion with the greatest average HFU measurement was the distal-ulnar subregion (193, 95% CI = 164-222). The lowest average HFU measurement belonged to the proximal-central subregion (140, 95% CI = 109-170) (Table 2). Statistical comparisons between subregion HFU averages are shown in Table 4. The proximal-central subregion HFU measurement was significantly less on average than that of all three distal subregions when compared individually ($P < 0.01$, each). Conversely, the distal-ulnar subregion average HFU measurement was significantly greater than that of 2 of 3 proximal subregions ($P < .001$, each).

The ICC coefficient values were 0.94 and 0.99 for volume and HFU measurements, respectively. This corresponds to excellent interobserver reliability for both measurements.¹⁸

Discussion

Despite the widespread use of the distal radius as a donor site for bone graft in the upper extremity, subtle variations

Figure 3. Spherical regions of interest (ROIs) as seen on the (a) axial, (b) sagittal, and (c) coronal views. Simultaneous monitoring of the 3 views enabled assurance that ROIs did not include cortical bone. Six ROIs were included for each computed tomographic scan, consisting of 3 spheres each at both proximal and distal levels.

Table 1. Subject Information.

Category	Value
Computed tomographic scans	34
Average patient age, y	37 (range, 21-70)
Side, No. (%)	
Right	17 (50)
Left	17 (50)
Sex, No. (%)	
Male	22 (65)
Female	12 (35)
Indication, No. (%)	
Scaphoid fracture	17 (50)
Other carpal fracture	6 (18)
Distal radioulnar joint instability	4 (12)
Metacarpal fracture	2 (6)
Kienböck disease	1 (3)
Unspecified	4 (12)

in volume and density that exist within different regions of the distal radius are not well understood. To help guide

surgeons attempting to optimize graft site selection, we aimed to use CT data in 34 live patient samples to analyze cancellous bone volume and density patterns.

Our first hypothesis, that the distal-central cancellous bone is more voluminous than other regions, is supported by these data. The average spherical volume measured at the distal-central region was 1.2 cm³—a value that was significantly greater than that of any other region ($P < 0.001$). Also, the 3 distal regions when grouped had a higher average volume than did the 3 proximal regions when grouped (0.82 vs 0.27 cm³, $P < .001$). These findings are consistent with the morphology of the metaphyseal flare of the distal radius, which has greater cross-sectional areas at more distal levels. In addition, with an ovoid to trapezoidal cross-sectional shape of the distal radius, it follows that centrally based spherical regions would provide greater volume than would more peripherally centered spheres.

In a cadaveric study of 16 specimens, Bruno and colleagues measured the volume of cancellous bone graft available at 3 commonly used sites—distal radius, olecranon, and iliac

Table 2. Volume and Relative Density Averages.

Region	Subregion	Volume	95% CI		HFU	95% CI	
		Average (cm ³)	Low	High	Average	Low	High
Distal		0.82*	0.74	0.91	178*	163	193
	Radial	0.46	0.39	0.53	171	145	197
	Central	1.20	1.07	1.32	169	145	194
	Ulnar	0.81	0.69	0.92	193	164	222
Proximal		0.27*	0.24	0.31	152*	136	170
	Radial	0.19	0.16	0.22	169	137	200
	Central	0.43	0.35	0.50	140	109	170
	Ulnar	0.20	0.17	0.24	150	122	178

Volume and Hounsfield unit (HFU) averages with corresponding confidence interval (CIs) for grouped distal and proximal regions, as well as individual subregions. Individual statistics for subregion comparisons are shown elsewhere.

*The Student *t* test comparisons for grouped distal versus proximal averages resulted in values of $P < .001$.

Table 3. Individual Subregion Volume Comparisons.

Volume	Distal-radial	Distal-central	Distal-ulnar	Proximal-radial	Proximal-central	Proximal-ulnar
Distal-radial		<.001*	<.001*	<.001*	.782	<.001*
Distal-central			<.001*	<.001*	<.001*	<.001*
Distal-ulnar				<.001*	<.001*	<.001*
Proximal-radial					<.001*	.938
Proximal-central						<.001*
Proximal-ulnar						

Note. *P* values for least squares mean difference values adjusted for multiple comparisons using the Tukey method for volume. * denotes statistical significance.

crest.⁵ For the distal radius, a dorsally based technique that involves boring a 1-cm circular cortical window centered at 1.5 cm proximal to the joint line yielded an average of 2.7 cm³ of cancellous bone.⁵ This value likely exceeds ours due to the spherical shape of our region, which expectedly yields less volume than the amount of cancellous graft that is attainable using curettes through a 1-cm cortical window.

The spherical regions used in the present study are not intended to guide technique by defining the margins of a graft region, but rather to allow relative comparison of patterns in volume and density variation within the distal radius. We anticipate that cancellous graft volumes available clinically will be greater than the individual spherical volumes reported in the present study. However, it is important to note clinically that harvesting too much cancellous bone may place the patient at risk of fracture. In a cadaveric biomechanical study, Horne and colleagues demonstrated that a significant decrease in ultimate distal radius stress occurs when 25% of cancellous bone is harvested compared with 10%.¹⁹ The authors recommend harvest of less than 25% of total available metaphyseal cancellous bone.

The data of the present study also support our second hypothesis—that the distal-ulnar bone would have the high-

est relative density. Initially, in our comparison of grouped average relative cancellous density between distal and proximal regions, we see an average of 178 HFU in the distal group compared with 152 in the proximal group ($P < .001$). As the bone transitions from metaphyseal to diaphyseal more proximally in the distal radius, we see the gradual reduction of cancellous bone and transition to a medullary canal. Thus, it is reasonable to expect cancellous bone density to be greater in the more distal regions.

For the individual regions, the distal-ulnar region had the highest average relative density measurement of 193 HFU, followed by the distal-radial region at 171 HFU. These 2 regions were significantly denser on average than select proximal regions when compared individually ($P < .05$; see Table 4). The increased density seen on average in the distal-ulnar region (193 HFU) compared with the distal-central (169 HFU) and distal-radial (171 HFU) regions was not statistically significant ($P = .08$ and $.12$, respectively). However, we postulate that the combination of forces in the distal-ulnar region from the radiolunate and distal radioulnar joints renders that bone denser on average based on the principles of Wolff law.⁹

In a 2018 study, Pidgeon and colleagues used quantitative CT data to analyze trabecular bone in the distal radius and

Table 4. Individual Subregion Relative Density Comparisons.

Hounsfield units	Distal-radial	Distal-central	Distal-ulnar	Proximal-radial	Proximal-central	Proximal-ulnar
Distal-radial		1.000	.123	1.000	.005*	.155
Distal-central			.080	1.000	.009*	.223
Distal-ulnar				.065	<.001*	<.001*
Proximal-radial					.012*	.261
Proximal-central						.833
Proximal-ulnar						

Note. P values for least squares mean difference values adjusted for multiple comparisons using the Tukey method for Hounsfield units. * denotes statistical significance.

found that distal-ulnar regions had the greatest bone mineral density on average in both male and female subgroups.¹⁴ Differences between bone mineral density averages between regions were greatest (in excess of 100 mg/cm³) when distal-ulnar regions were compared with the most radial and/or proximal regions.¹⁴ Although the aim of the former study was to better understand fracture patterns and inform fixation strategies, its findings are consistent with the present study with respect to the patterns of bone mineral density variation.

Based on biomechanical data from the distal radius, it is evident that the scaphoid fossa experiences 60% to 70% more pressure than the lunate fossa.^{10,12} While this might suggest that radial cancellous bone should be denser than ulnar cancellous bone in the distal radius, the Wolff law may not pertain solely to magnitude of forces. Research on the application of the Wolff law to bone remodeling suggests that cyclic, intermittent loads are critical for the strengthening of bone.²⁰ Therefore, while the radial-sided bone experiences significant cyclic loading forces from motion at the radiocarpal joint, the ulnar-sided bone experiences both radiocarpal and radioulnar forces.

To date, most literature exploring the topic of bone density has the primary focus of assessing osteoporosis and stratifying risk for fragility fractures and uses DXA scan or advanced imaging modalities.^{21,22} More recently, HFU data ascertained from CT scans have been shown to correlate closely with DXA scores.¹⁵⁻¹⁷ Johnson and colleagues measured HFU values at the capitate in 45 women undergoing wrist CT for distal radius fracture and found that an HFU threshold of 307 was 86% sensitive and 94% specific for detecting osteoporosis as determined by standard DXA criteria.¹⁵

It remains to be determined how much radiographic bone density translates clinically to bone graft substrate utility. In our clinical experience, patients with poor bone quality (ie, low cancellous bone density) often have softer, weaker cancellous bone that requires more harvest volume to fill a void of particular size. Thus, it would follow that harvesting bone graft from an area of stronger, denser bone would provide more optimal structural support at the recipient site and would decrease donor site morbidity through

maximizing yield from a harvest. This principle should be applied thoughtfully, however, given the suggestion that higher bone graft porosity may allow for better compaction, more accurate filling of defects, and easier hematogenous nourishment.²³

The study has several limitations. First, its retrospective nature renders it susceptible to bias by the observers inherent to a study of this design. Second, this study included no assessment of cortical bone quality or size, which may have added value given that distal radius bone grafting techniques often include corticocancellous harvest. We chose to evaluate cancellous bone only to be applicable to both techniques—cancellous only and corticocancellous. In addition, methodological limitations and disparity between cortical and cancellous density would likely render the output values highly variant based on how much cortical bone was included in the ROI. Third, because this study was retrospective there is no calibration at the time of the study to enable a conversion of HFU to real units of density (mass/volume). Despite this, HFUs provide a reliable proxy to density given that each CT scan was performed with the same protocol, and measurements from each scan were performed in a uniform fashion. Finally, the use of spherical ROIs likely does not perfectly represent the clinical shape of a region of graft harvest, although, as stated previously, the spherical ROIs are intended to create a representative snapshot that enables relative comparisons of volume and density to guide surgeons toward the region of the bone most appropriate for graft harvest.

Conclusion

In conclusion, cancellous bone radiographic density and volume are greatest in the distal portions of the distal radius compared with its more proximal portions. There is a trend toward greater density in the distal-ulnar region compared with the other 5 regions assessed. Based on these results, we recommend performing distal radius cancellous bone graft approximately 10 mm proximal to the articular surface, with an ulnar bias relative to the coronal midline of the bone.

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Ethical Approval

This study was approved by the Duke Medicine Institutional Review Board (#Pro00080164).

Statement of Human and Animal Rights

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and the Helsinki Declaration of 1975, as revised in 2008.

Statement of Informed Consent

Informed consent was not required.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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References

- McGrath MH, Watson HK. Late results with local bone graft donor sites in hand surgery. *J Hand Surg Am.* 1981;6(3):234-237.
- Tambe AD, Cutler L, Murali SR, et al. In scaphoid non-union, does the source of graft affect outcome? iliac crest versus distal end of radius bone graft. *J Hand Surg Am.* 2006;31(1):47-51.
- Jarrett P, Kinzel V, Stoffel K. A biomechanical comparison of scaphoid fixation with bone grafting using iliac bone or distal radius bone. *J Hand Surg Am.* 2007;32(9):1367-1373.
- Myeroff C, Archdeacon M. Autogenous bone graft: donor sites and techniques. *J Bone Joint Surg Am.* 2011;93(23):2227-2236.
- Bruno RJ, Cohen MS, Berzins A, et al. Bone graft harvesting from the distal radius, olecranon, and iliac crest: a quantitative analysis. *J Hand Surg Am.* 2001;26(1):135-141.
- Mirly HL, Manske PR, Szerzinski JM. Distal anterior radius bone graft in surgery of the hand and wrist. *J Hand Surg Am.* 1995;20(4):623-627.
- Lee SK, Byun DJ, Roman-Deynes JL, et al. Hybrid russe procedure for scaphoid waist fracture nonunion with deformity. *J Hand Surg Am.* 2015;40(11):2198-2205.
- Patel BA, Carlson KJ. Bone density spatial patterns in the distal radius reflect habitual hand postures adopted by quadrupedal primates. *J Hum Evol.* 2007;52(2):130-141.
- Wolff J. Ueber die innere Architektur der Knochen und ihre Bedeutung für die Frage vom Knochenwachstum. *Virchows Archiv.* 1870;50(3):389-450.
- Hara T, Horii E, An KN, et al. Force distribution across wrist joint: application of pressure-sensitive conductive rubber. *J Hand Surg Am.* 1992;17(2):339-347.
- Schuind F, Cooney WP, Linscheid RL, et al. Force and pressure transmission through the normal wrist. A theoretical two-dimensional study in the posteroanterior plane. *J Biomech.* 1995;28(5):587-601.
- Christen P, Ito K, Knippels I, et al. Subject-specific bone loading estimation in the human distal radius. *J Biomech.* 2013;46(4):759-766.
- Ishii S, Palmer AK, Werner FW, et al. Pressure distribution in the distal radioulnar joint. *J Hand Surg Am.* 1998;23(5):909-913.
- Pidgeon TS, DaSilva KA, Crisco JJ, et al. Three-dimensional characterization of trabecular bone mineral density of the distal radius utilizing quantitative computed tomography [published online ahead of print July 18, 2018]. *Hand.* doi:10.1177/1558944718789407.
- Johnson CC, Gausden EB, Weiland AJ, et al. Using Hounsfield units to assess osteoporotic status on wrist computed tomography scans: comparison with dual energy x-ray absorptiometry. *J Hand Surg Am.* 2016;41(7):767-774.
- Wagner SC, Dworak TC, Grimm PD, et al. Measurement of distal ulnar Hounsfield units accurately predicts bone mineral density of the forearm. *J Bone Joint Surg Am.* 2017;99(8):e38.
- Schreiber JJ, Anderson PA, Rosas HG, et al. Hounsfield units for assessing bone mineral density and strength: a tool for osteoporosis management. *J Bone Joint Surg Am.* 2011;93(11):1057-1063.
- Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med.* 2016;15(2):155-163.
- Horne LT, Murray PM, Saha S, et al. Effects of distal radius bone graft harvest on the axial compressive strength of the radius. *J Hand Surg Am.* 2010;35(2):262-266.
- Chamay A, Tschantz P. Mechanical influences in bone remodeling. Experimental research on Wolff's law. *J Biomech.* 1972;5(2):173-180.
- Cummings SR, Browner W, Black DM, et al. Bone density at various sites for prediction of hip fractures. *Lancet.* 1993;341(8837):72-75.
- Majumdar S, Genant HK, Grampp S, et al. Correlation of trabecular bone structure with age, bone mineral density, and osteoporotic status: in vivo studies in the distal radius using high resolution magnetic resonance imaging. *J Bone Miner Res.* 1997;12(1):111-118.
- Biddulph SL. Bone donor site: iliac crest or distal radius? *J Hand Surg Am.* 1999;24(6):645-646.