Development and assessment of 3-dimensional computed tomography measures of proximal humeral bone density: a comparison to established 2-dimensional measures and intraoperative findings in patients undergoing shoulder arthroplasty

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Background: The purpose of this study was to develop novel three-dimensional (3D) measures of bone density from computed tomography (CT) scans and to compare them with validated two-dimensional (2D) radiographic assessments of bone density. Patient demographic data were also analyzed to see if there were any predictors of bone density (age, sex, etiology).
Methods: The study group consisted of 290 consecutive patients undergoing primary shoulder arthroplasty surgery (total anatomic, reverse, and hemiarthroplasty). All underwent preoperative CT imaging. Three 3D CT measurements (metaphysis cancellous, metaphysis cortical, and proximal diaphysis) were developed and automated into software. The developed 3D measurements were compared with validated 2D measures (Tingart and Gianotti Index). Patient demographic data were correlated with these measurements. The difference between the size of the final sounder and of the final stem was calculated as Delta.
Results: There was moderately strong correlation between Tingart and Gianotti measures (0.674, $P < .001$), as well as between 3D metaphysis cancellous measurements and Tingart (0.645, $P < .001$). Decreased bone density was highly correlated with female sex. Tingart (area under the curve [AUC]: 0.87, 95% confidence interval [CI]: 0.82-0.91) and 3D metaphysis cancellous (AUC: 0.78, 95% CI: 0.72-0.84) had the highest correlation. These were significantly more than other measures of bone density ($P < .01$). Decreased bone density measured with Tingart also had moderate correlation with advanced age (AUC: 0.67, 95% CI: 0.6-0.73), but less so for etiology (AUC: 0.62, 95% CI: 0.55-0.69). The 3D metaphysis cancellous measure had lower correlation with age (AUC: 0.59, 95% CI: 0.52-0.66) and etiology (AUC: 0.59, 95% CI: 0.52-0.65). The highest correlation with Delta (the difference between the final sounder and the stem size) was with the 3D metaphysis cancellous measure (AUC: 0.67, 95% CI: 0.59-0.73), followed by Tingart (AUC: 0.647, 95% CI: 0.57-0.671). A multiple regression model to predict Delta demonstrated the stronger prediction using 3D metaphysis cancellous (analysis of variance F-ratio of 42.6, $P < .001$) than Tingart (35.9, $P < .001$).
Conclusion: This study demonstrates that automated measures of bone density can be obtained from 3D CT scans. Of the three novel 3D measurements of bone density, the humeral metaphysis cancellous measurement was most correlated to the known 2D measures and most correlated to the intraoperative assessment of bone density (delta).

Over the last decade, software-based presurgical planning has become more frequently used in shoulder arthroplasty. Most of the literature, however, has focused on the glenoid. Preoperative software planning and patient-specific guides have demonstrated accurate and reproducible positioning and orientation of the glenoid component in shoulder arthroplasty.[4,7,18] Glenoid bone density has also been determined using computed tomography (CT).[12] Unfortunately, a paucity of literature exists on CT-based software templating for the humeral component.

Overall, there has been a trend in shoulder arthroplasty to move to shorter stemmed implants and stemless implants. These sorts of implants, however, no longer rely on diaphyseal fixation but rather obtain intraoperative time zero stability from metaphyseal bone. When templating a diaphyseal fit implant, the diameter of the canal is typically utilized and is easily measured on radiographs, two-dimensional (2D) CT and three-dimensional (3D) CT. However, with metaphyseal fixation implants, the fixation is obtained from cancellous bone and the density of this bone is an important determinate of implant size.

An accurate and reproducible method of assessing proximal humeral bone density is important for the development of automated software templating for predictable sizing of the humeral implant. As such, the purpose of this study was to reproduce validated 2D radiographic assessments of bone density using CT and to correlate these with novel 3D measures of bone density in patients undergoing total shoulder arthroplasty (TSA). Our primary hypothesis was that there would be high correlation between 2D and 3D measures. Our secondary hypothesis was that patient demographic data (age, sex, etiology) would correlate with bone density. Finally, the correlation of humeral stem size selection with radiographic and demographic variables was assessed.

Methods

This was an imaging study to compare novel 3D measures of proximal humeral bone density obtained on CT scans with known 2D measures, in patients undergoing shoulder arthroplasty. All patients underwent standardized, preoperative CT scans, from which the measures were calculated. Demographic and intra-operative data were collected from the same cohort.

Patients

Two hundred ninety consecutive patients undergoing primary shoulder arthroplasty surgery (total anatomic, reverse, and hemi-arthroplasty) were included. Patient demographics are summarized in Table I. All surgeries were performed by a single, experienced shoulder arthroplasty surgeon (G.W.). The same uncemented short-stem humeral prosthesis (Tornier Ascend Flex, Bloomington, IN, USA) was used for all patients. Patients with the following etiologies were included: primary osteoarthritis, massive rotator cuff tear, and cuff tear arthropathy.

Surgery

Surgery was performed using the surgeon's standard technique. After glenoid component placement, the humeral canal was identified and sized with canal sounders. The purpose of the sounders is to size the internal dimensions of the humeral diaphysis. Then, the humeral canal is progressively broached until rotational stability in the metaphysis is achieved. With greater density of the metaphyseal bone, the final stem will achieve rotational stability with a smaller size than the sounder's diaphyseal fit. At the time of

Table I
Demographics.

Age, mean(range)	73 (34-99)
Sex	
Male	109
Female	181
Surgery	
Hemiarthroplasty	6
Reverse TSA	174
Anatomic TSA	110
Aetiology	
Cuff tear arthropathy	50
Massive rotator cuff tear	48
Primary osteoarthritis	192

TSA, total shoulder arthroplasty.

surgery, the size of the final sounder and of the final stem utilized was recorded. The difference between these two numbers was calculated as Delta.

The definitive implant with a 1-mm press-fit was then impacted into place. After all components were inserted, the arm was reduced and checked for stability and range of motion.

Radiological measurements

CT imaging protocol: Included the entire shoulder and scapula-240 mA, slice thickness 0.625 mm, pitch to 0.9, rotation time 1.0 sec.

All measurements were made using Glenosys planning software (Imascap, Brest, France) as follows.

Humeral distal cortical index (Giannotti)

Gianotti et al developed the cortical index of the humerus to quantify in a reproducible way the humeral bone density.[5] It was defined as the ratio between the thickness of the cortex and the total diameter of the humeral diaphysis measured at a level 10 cm below the greater tuberosity. They found it to be predictive of osteoporotic fracture.

This measure was replicated on the CT scan with the following steps:

1. The 2D cut level was defined at 11 cm below the highest humeral point, perpendicular to the axis of the diaphysis.
2. At this 2D cut level, 2 measures were defined:
   a. N_{cort}: the number of humerus voxels with a Hounsfield value greater than 220
   b. N_{canal}: the number of humerus voxels with a Hounsfield value lesser than 220
3. The Gianotti cortical index was then calculated:

$$\frac{N_{cort}}{N_{cort} + N_{canal}}$$

Humeral proximal diaphysis cortical thickness (Tingart)

Tingart demonstrated a positive correlation between the average cortical thickness of the proximal humeral diaphysis measured on conventional radiographs and the bone mineral density.[19] Cortical thickness is measured at 2 levels. The first level is the most proximal point on the humerus where the outer medial and lateral cortical borders become parallel. The second level is at 20 mm distal to level 1. These two levels were replicated in this study, but the mean cortical thickness of the entire cylinder portion between the two levels was calculated. The steps were as follows:

1. *TingartNeck$_{sup}$* was defined as the plane perpendicular to the diaphyseal axis, at the highest level where the humeral cortices are parallel.
2. *TingartNeck$_{inf}$* was defined as the plane 20 mm below *TingartNeck$_{sup}$*.
3. The distance between the two planes is *h* (20 mm).
4. Between *TingartNeck$_{sup}$* and *TingartNeck$_{inf}$*, the following values inside the humerus were calculated:
    a. *N$_{bone}$*, the number of voxels, and *V$_{bone}$*, the corresponding volume in mm^3.
    b. *N$_{cancellous}$*, the number of voxels with a Hounsfield Unit value lesser than 220, and *V$_{cancellous}$*, the corresponding volume in mm^3.
5. Assuming a cylindrical shape of the humerus between the two planes, the Tingart cortical thickness was calculated as the average external thickness of the cylindrical portion:

$$\sqrt{\frac{V_{bone}}{\pi h}} - \sqrt{\frac{V_{cancellous}}{\pi h}}$$

Metaphyseal bone density

This is a newly proposed measure to assess the bone density in the metaphysis region, where short-stem stability occurs. This measure was developed to utilize available CT data in the zone of interest. It was calculated as follows:

1. The humeral metaphysis was defined as the part between the anatomical neck and the surgical neck (see Fig. 1)
2. Inside the humeral metaphysis, two average values were computed:
    a. *3D Mean metaphysis cancellous* is the average of Hounsfield Units lesser than 220
    b. *3D mean metaphysis cortical* is the average of Hounsfield Units greater than 220

Proximal diaphyseal bone density

This is a newly proposed measure to assess the bone density in the proximal diaphyseal region:

1. The humeral proximal diaphysis was defined as the part of the humerus between the Tingart neck superior measurement and the Tingart neck inferior measurements (see Fig. 2)
2. Inside the humeral proximal diaphysis, *3D_Proximal Diaphysis* was calculated as the average of Hounsfield Units greater than 220.

Statistics

Data are presented as mean (standard deviation [SD], minimum-maximum) for continuous variables and frequencies for categorical variables. The Pearson correlation coefficient was used for comparisons between the different measures of bone density.

A correlation coefficient of 0.3-0.5 was considered low, 0.5-0.7 was considered moderate, and >0.7 was considered high. Receiver operator characteristic curves were used to compare radiologic measures with patient demographics. The area under the curve (AUC) was used to compare the different radiologic measures. Analysis of variance was used to determine the relationship between Delta and the radiologic measures.
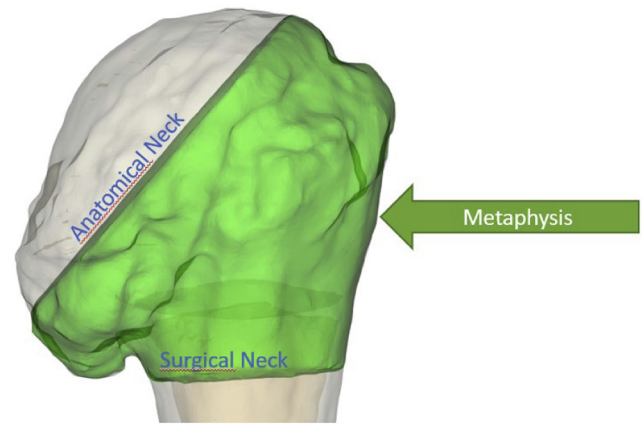

Figure 1 Humeral metaphyseal zone.

Results

Correlation of CT bone density measures

There was moderately strong correlation between Tingart and Gianotti measures (0.674, $P < .001$), as well as between 3D metaphysis cancellous measurements and Tingart (0.645, $P < .001$). However, there was a low correlation of 3D metaphysis cancellous measurement with Gianotti (0.417, $P < .001$). There was low correlation between 3D proximal diaphysis bone density and Gianotti (0.314, $P < .001$). All comparisons are presented in Table II.

Correlation of CT bone density with demographics

Decreased bone density was highly correlated with female sex (see Fig. 3). Tingart (AUC: 0.87, 95% CI: 0.82-0.91) and 3D metaphysis cancellous (AUC: 0.78, 95% CI: 0.72-0.84) had the highest
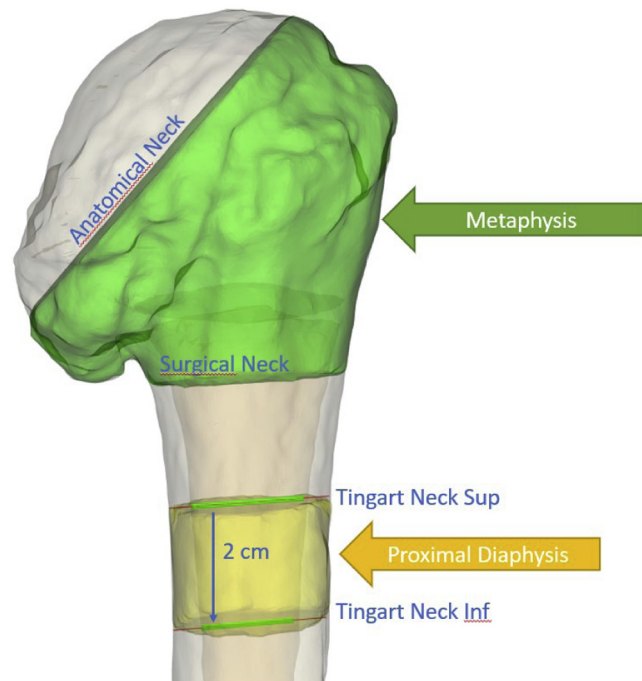

Figure 2 Humeral diaphyseal zone.

Table II
Correlation of 2D and 3D measures.

Radiological measurement		Gianotti	Tingart
Gianotti	Correlation coefficient		0.674
	Significance level *P*		<.001
	n		212
Tingart	Correlation coefficient	0.674	
	Significance level *P*	<.001	
	n	212	
3D metaphysis cortical	Correlation coefficient	0.019	0.019
	Significance level *P*	.78	.76
	n	212	257
3D metaphysis cancellous	Correlation coefficient	0.42	0.65
	Significance level *P*	<.001	<.001
	n	212	257
3D proximal diaphysis	Correlation coefficient	0.31	0.058
	Significance level *P*	<.001	<.001
	n	212	257

Pearson correlation coefficient.

correlation. These were significantly more than other measures of bone density ($P < .01$).

Decreased bone density measured with Tingart also had moderate correlation with advanced age (AUC: 0.67, 95% CI: 0.6-0.73), but less so for etiology (AUC: 0.62, 95% CI: 0.55-0.69).

The 3D metaphysis cancellous measure had lower correlation with age (AUC: 0.59, 95% CI: 0.52-0.66) and etiology (AUC: 0.59, 95% CI: 0.52-0.65).

Figures 4 and 5 demonstrate the relationship of age with Tingart and 3D metaphysis cancellous measures.

Correlation of CT bone density with intraoperative delta

The highest correlation with Delta (the difference between the final sounder and the stem size) was with the 3D metaphysis cancellous measure (AUC: 0.67, 95% CI: 0.59-0.73), followed by Tingart (AUC: 0.647, 95% CI: 0.57-0.671). A multiple regression model to predict Delta demonstrated the stronger prediction using 3D metaphysis cancellous (analysis of variance F-ratio of 42.6, $P < .001$) compared with Tingart (35.9, $P < .001$).

Discussion

This study demonstrates that surrogate measures of bone density can be accurately taken from CT scans using the study protocol and automated software programs. Of the novel 3D measurements of bone density, the humeral metaphysis cancellous measurement was most correlated to the known 2D measures and the most predictive of the intraoperative metric for bone quality "Delta."

In 1960, Barnett and Nordin first reported the radiographic measurement of cortical bone thickness in the femur and metacarpal as a predictor of osteoporosis.[1] Gianotti et al defined the cortical index in the humerus as the ratio between the thickness of the cortex and the total diameter of the humeral diaphysis measured at a level 10 cm below the greater tuberosity.[5] They found it to be predictive of osteoporotic fracture. Tingart et al developed a different protocol for measuring the average cortical thickness of the proximal humeral diaphysis on radiographs and reported a positive correlation with bone mineral density.[19] Using this measurement protocol, Mather et al found the average cortical bone thickness measurements correlated with DXA measurements and provided a rapid, sensitive, and inexpensive method for ruling out osteoporosis.[13]

The automatic segmentation produced by the Glenosys planning software based on 3D shape recognition algorithms has been shown to be reliable and reproducible for the glenoid bone
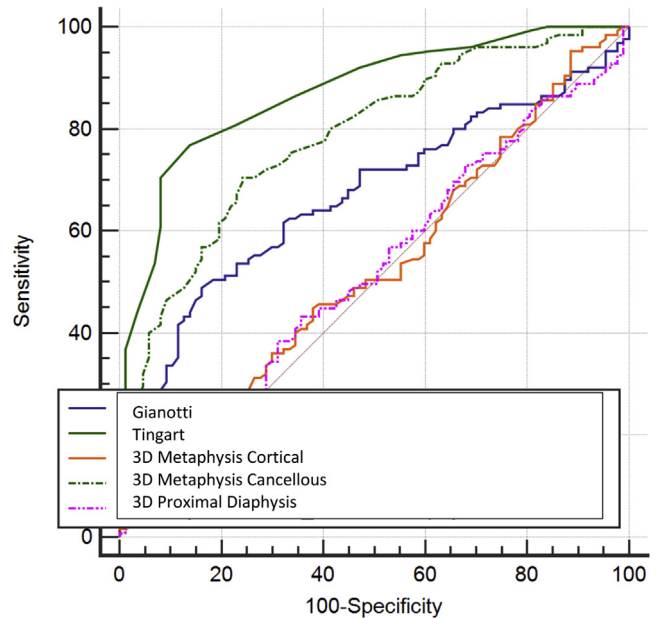

Figure 3 ROC curves for prediction of sex for all bone density measures. The higher the area under the curve (AUC), the better the predictor of sex. ROC, receiver operator characteristic.
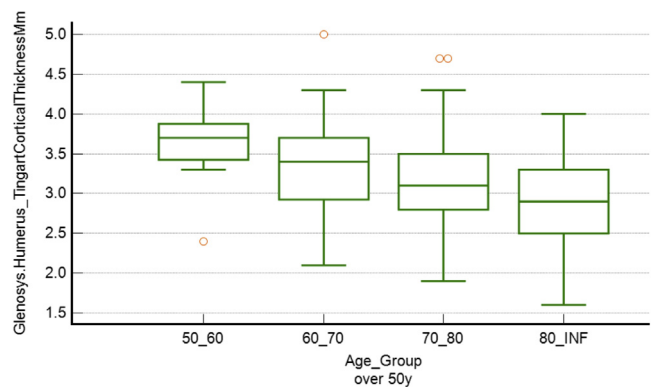

Figure 4 Box plots of Tingart cortical thickness (mm) by age (mean, standard deviation, and 95% confidence interval).

density.[12,20] Shoulder CT scans have been successfully used previously to evaluate glenoid bone quality.[3,8-10,17] Terrier et al used an automated method to quantify preoperative glenoid bone quality in different areas of interest: cortical bone, subchondral cortical plate, subchondral bone after reaming, subchondral trabecular bone, and successive layers of trabecular bone.[17] Average Hounsfield units (HU) were measured in each area on the preoperative CT scans. They found low preoperative glenoid bone quality correlated with cement stress, bone-cement interface stress, and bone strain on a finite element analysis model. The novel 3D measures of bone density used in this study should allow the same analysis of humeral arthroplasty components.

Few studies have looked at the accuracy of preoperative templating for the humeral component in shoulder arthroplasty. The use of CT scans for preoperative templating of the stem size has been shown to have higher levels of accuracy than standard 2D templating in total hip arthroplasty.[6,15,16] Buzzell et al[2] reported on analog templating on preoperative radiographs in 31 total shoulder arthroplasties. They found that preoperative templating accurately
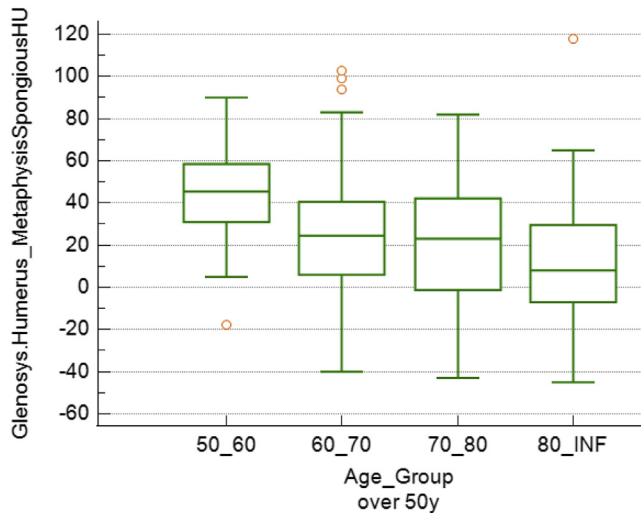
Figure 5 Box plots of 3D metaphysis cancellous measures (HU) by age (mean, standard deviation, and 95% confidence interval).

predicted stem size in 38.5% of attempts and was within one size of the actual implant 94% of the time.[2] Interobserver reliability was moderate (kappa: 0.53). Lee et al used digital templating on 25 patients undergoing TSA.[11] They accurately predicted stem size 36% of the time and were within one size variation in only 77% of the cases. They found interobserver reliability was only fair to moderate (kappa: 0.39-0.72). Both studies found no difference in accuracy between experienced surgeons and junior surgeons. These studies did not assess bone density and were looking only at diaphyseal fit. In these studies, the stems used were designed to fill the canal and were thus templated without any regard to bone density. The Ascend Flex stem (Wright Medical, USA), used in the present study, is designed to have a metaphyseal fit with the aim of a stress distribution at the proximal humerus which more closely resembles normal anatomy. The surgical technique for the Ascend Flex recommends sequential broaching with the bone compactors up until rotational stability is achieved in the metaphysis. The stem size is always smaller than the sounder size which relates to the diaphyseal fit, and thus, traditional 2D templating is of little value. This study has demonstrated that the difference between the stem and sounder size (Delta) is related to the humeral bone density and that the final stem size is therefore correlated to the metaphyseal cancellous density.

The validation of these 3D measures of bone density in the proximal humerus will also be of great usefulness for future research. For example, Raiss et al demonstrated increased stress shielding on postoperative radiographs of TSAs with a filling ratio of greater than 0.7 and suggested that these patients may be better off if given a cemented stem.[14] It is, however, difficult to estimate the filling ratio before or at the time of surgery. Preoperative templating using CT scans which includes bone density calculation may predict those that are likely to require cementation.

This study has some weaknesses. The study uses the Gianotti and Tingart indexes which are validated measures correlated with bone mineral density. The study would be stronger if bone mineral density was actually measured directly. Another weakness is that a small proportion of the CT scans did not scan low enough on the humerus to assess the Gianotti Index. This demonstrates, however, another advantage of the 3D metaphysis cancellous measure which only requires the scan to the level of the surgical neck of humerus. The strengths of this study are the large number of participants and

the accuracy of measurement that is possible with CT imaging and the software used.

Conclusion

This study has demonstrated that known 2D radiographic and novel 3D measurements of bone density can reproducibly be measured from CT scans and have moderately strong correlation. These measures of bone density also correlate with age and sex differences. The 3D metaphysis cancellous measure has greatest correlation with Delta, and future studies may use it to predict stem size.

Disclaimers:

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