Automatic QCT quantification of the proximal femur: vBMD, bone volume, cortical bone thickness and finite element modeling

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QCT imaging is the basis for multiple assessments of bone quality, including compartmental vBMD analysis, finite element modeling (FEM), and statistical parametric modeling of vBMD and morphometry distribution. We integrated these approaches into an automated comprehensive proximal femoral QCT analysis. Here, we present a fully automated technique to segment hip QCT scans, which is used as a basis to: 1) prescribe volumes of interest for vQCT analysis, 2) map 3D variations in cortical bone thickness, and 3) assess FEM bone strength. In this study, we measured the accuracy of the segmentation technique and the reproducibility of the derived measurements.

This study used 179 hip vQCT scans from 2 vendors and 3 sites. Using a minimum deformation template (MDT) of the proximal femur, we developed an atlas-based segmentation algorithm consisting of 3 main steps: 1) poly-affine registration of the MDT to individual scans; 2) model-guided nonlinear registration; and 3) region growing and patch-based cleaning of the segmented boundaries obtained after applying the inverse of the registrations. Of the 179 scans, 49 were used for training of the segmentation in step 2, yielding 130 automatically segmented scans. Of these, 78 scans with manual segmentations were used for segmentation accuracy assessment, and 44 (22 scan-rescan pairs) for reproducibility of vQCT, FEM and cortical thickness measures. Cortical bone thickness was measured with a variant of the minimum line integral thickness approach: non-local fuzzy c-means was used to estimate the endocortical boundary, and cortical thickness was measured with minimum Euclidean distances, fuzzy logic, vBMD, and numerical integration. We evaluated inter-scan reproducibility (Fig. 1A) of vBMD, bone volume, cortical thickness, and nonlinear FEM strength in stance and posterolateral fall loading [Keyak Bone 2013] using RMS pairwise precision errors.

Segmentation accuracy and precision of derived measures are shown in Table 1. Figs. 1B and 1C respectively show representative examples of an automatic segmentation and scan-rescan cortical bone thickness maps.

Our automated hip segmentations had high fidelity to gold-standard manual segmentations, and were used to derive highly reproducible vQCT, FEM strength and cortical bone thickness measures. Our subjects were elderly, with scans obtained across multiple clinical sites and vendors, documenting the value of this approach for clinical trials and other multi-site studies.

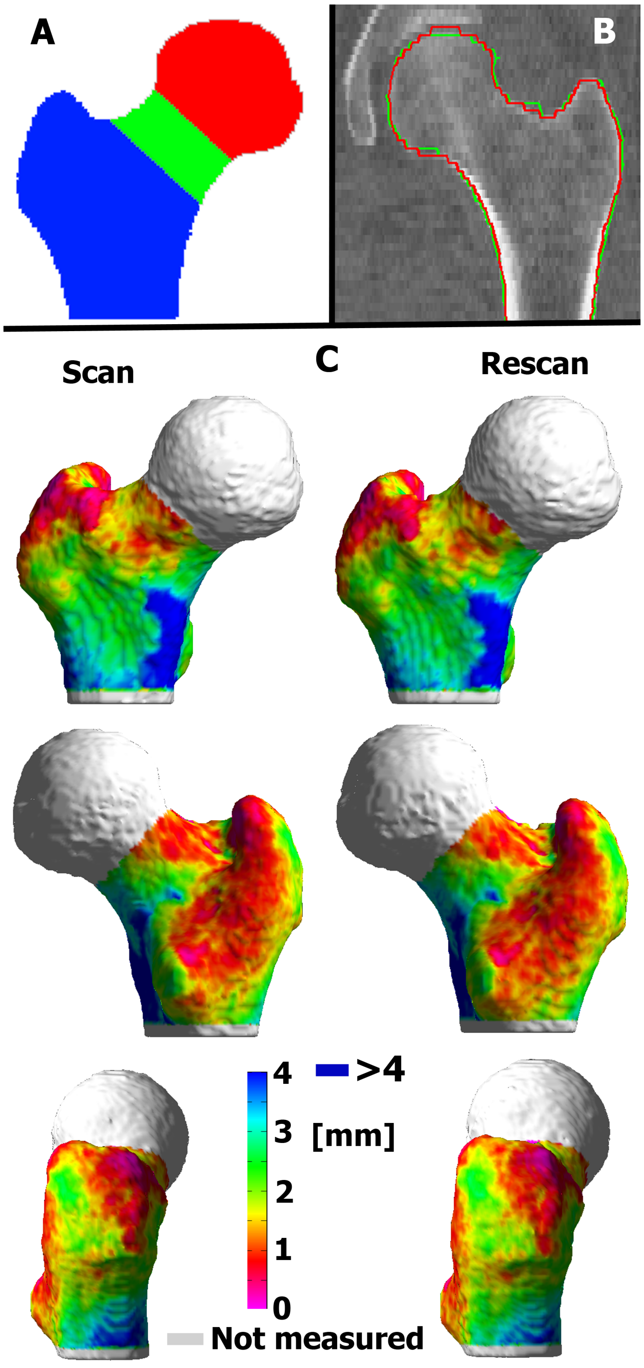

Fig. 1. A) Volumes of interest used in this study: head (red), neck (green), and trochanter (blue). B) Coronal cross-section of a representative automatic segmentation (red), also showing the manually derived contour (green). C) Anterior, posterior, and lateral views of a representative scan-rescan (left-right) 3D cortical bone thickness map.

Table 1. Segmentation Accuracy and Reproducibility of Bone Measures

Accuracy (mean±SD) (n=78)		
DSC	**FNR**	**SymDist [mm]**
0.972±0.005	**0.044±0.009**	**0.396±0.064**

DSC = Dice similarity coefficient (a value of 0 indicates no overlap; a value of 1 indicates perfect agreement; higher numbers indicate that the results match the gold standard better)
FNR = False negative rate
SymDist = Average of minimum Euclidean distances between the automatically and the manually derived surface points
10 out of 130 scans failed locally: 8 in the head and 2 in the greater trochanter (7.7%). These scans were not part of the accuracy analysis

Reproducibility (RMS pairwise precision errors [%])						
vBMD (n=22)					**Volume** (n=22)	
T	**I-Head**	**I-Neck**	**Tb-Neck**	**C-Neck**	**I-Troch**	**C-Troch**
0.90	**0.90**	**1.33**	**1.58**	**1.38**	**1.31**	**1.43**

Cortical bone thickness (n=22)		
T	**Neck**	**Troch**
0.78	**1.89**	**0.76**

Finite element modeling strength (n=19)	
Nonlinear stance loading	**Nonlinear FPL loading**
3.21	**3.40**

T = Total; **I =** Integral; **Tb =** Trabecular bone; **C =** Cortical bone
Troch = Trochanter
FPL = Posterolateral fall