Non-Invasive Bone Monitoring by High-Resolution pQCT: A Reproducibility Study on Structural and Mechanical Properties at the Human Radius

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Introduction: Fractures in the distal radius are amongst the most common in humans. Their incidence is increasing due to an aging population leading to a higher percentage of osteoporotic patients with an increased risk of radius fractures. Hence, an accurate prediction of bone strength in the human radius is of major interest. Bone strength depends on bone geometry and internal architecture. With the recent introduction of a new generation of high-resolution 3D peripheral quantitative computed tomography (HR-pQCT) systems, direct quantification of structural bone parameters has become feasible in longitudinal patient studies. It was recently demonstrated that bone mechanical competence can be derived from HR-pQCT-based micro-finite element modeling (μFE) [1]. A good reproducibility of the system is very important for an accurate monitoring of bone strength, because the changes in bone architecture over short periods of time are relatively small. However, the reproducibility of structural and image-based mechanical properties has not been assessed for the human distal forearm. Therefore, the aim of this study was to determine the precision error (PE) and the intraclass correlation coefficient (ICC) of morphometry and subsequent μFE analysis for three consecutive regions in the distal radius.

Materials and Methods: 164 formalin-fixed cadavers from three consecutive courses of macroscopic dissection were harvested. In line with German legislative requirements, the donors had dedicated their body to research prior to death. 14 samples were selected evenly out of the whole range of bone densities. The 14 forearms were measured three times on two different days using an XtremeCT (Scanco Medical, Switzerland) providing an isotropic nominal resolution of 82 μm in all three spatial dimensions. All scans were analyzed by a single experienced operator. Measurements were acquired for three consecutive regions (Fig. 1) of 8 mm length; region 1 started just below the distal joint space. Cortical and trabecular bone were identified by the operator who had to draw two contours using a semiautomatic tracking algorithm. The segmentation of the structure was carried out with a 3D Laplace-Hamming filter and a fixed global threshold for all samples.

Morphometric parameters were determined using a direct 3D approach for three compartments in each of the three different regions. Total bone volume (BV) and apparent volume density (AVD) were assessed for the full bone. In the trabecular compartment, bone volume (Tv.BV), volume density (Tv.BV/TV), trabecular thickness (Tb.Th), spacing (Tb.Sp), number (Tb.N), structure model index (SMI) and connectivity density (Conn.D) were computed. Finally, in the cortex, cortical bone volume (Cr.BV), volume density (Cr.BV/TV), tissue area (T.Ar), polar moment of inertia (J), and cortical thickness (Cr.Th) were determined.

μFE models of the three regions were created by a direct conversion of bone voxels to hexahedral elements. Material properties were chosen isotropic and linear-elastic; Young’s modulus (E) and Poisson’s ratio (ν) were 10 GPa and 0.3, respectively. The proximal side of the μFE models was fully constrained whereas the distal side was subjected to a prescribed axial displacement resulting in 1% apparent strain. A special-purpose element-by-element FE solver [2] was used to solve these large problems with up to 16 million degrees of freedom using an IBM P5 at the Swiss National Supercomputing Centre (CSCS, Manno, Switzerland). Approximately 4.5 hours of CPU time were necessary for each analysis. The force required to reach 1% apparent strain was calculated and used to calculate apparent bone stiffness. Bone strength was estimated as the force where 2% of all elements in the μFE model had effective strain values above 7000 microstrain [3].

For statistical analysis, precision errors (PE) were expressed as the coefficients of variation of the repeated measures given on a percentage basis. Additionally, ICC was defined as the intersubject variance divided by the population variance, where 1 indicates perfect reproducibility. Statistics were analyzed with the SPSS software package (version 15.0 for Windows; SPSS, Chicago, IL).

Results: The PE for region 1 ranged from 0.5% (Tb.Th) to 3.54% (Tb.Sp), for region 2 from 0.42% (Tb.Th) to 3.43% (Conn.D) and for region 3, from 0.48% (BV, Stiffness) to 7.0% (Conn.D). All morphometric parameters had a PE better than 3.54% in all three regions, except Conn.D which showed less reproducibility in region 3. Reproducibility values were found to be best in all three regions for the full bone compartment with an average PE of 0.79%, followed by the cortical compartment (PE=1.19%) and the trabecular compartment with an average PE of 2.31%. The mechanical parameters showed similar reproducibility. PE for bone strength was 2.62%, 1.16% and 0.55% for regions 1, 2, and 3, respectively; for bone stiffness, PE was 2.93%, 1.16% and 0.48% for those regions. The ICC for region 1 ranged from 0.982 (Tb.Sp) to 0.999 (BV, T.BV, J), for region 2 from 0.992 (Conn.D, T.BV, TV) to 1.000 (BV, J) and for region 3, from 0.994 (Conn.D, T.BV, TV) to 1.000 (AVD, BV, Cr.BV, J, T.Ar). The ICC for bone strength and bone stiffness ranged both from 0.998 to 1.000.

Discussion: In this study, we evaluated the reproducibility of HR-pQCT measurements in the distal human radius. We found that HR-pQCT has a high precision in evaluating bone structural and mechanical parameters; also when comparing to other similar studies [4]. PE values were different in the three regions of analysis. For both full and cortical bone parameters the smallest values were found in region 3, whereas PE for the trabecular compartment was smallest in region 2. ICC showed a very high reproducibility of subject-specific measurements, ranging from 0.982 to 1.000, allowing secure identification of individual donors ranging from healthy to severely osteoporotic subjects. From these results we conclude that the technique has a high potential to be used as a tool for monitoring bone quality and bone competence of individual subjects over time.


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