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Technical Issues

A Trimodality Comparison of Volumetric Bone Imaging Technologies. Part I: Short-term Precision and Validity

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Abstract

In vivo peripheral quantitative computed tomography (pQCT) and peripheral magnetic resonance imaging (pMRI) modalities can measure apparent bone microstructure at resolutions 200 μm or higher. However, validity and in vivo test-retest reproducibility of apparent bone microstructure have yet to be determined on 1.0 T pMRI (196 μm) and pQCT (200 μm). This study examined 67 women with a mean age of 74 ± 9 yr and body mass index of 27.65 ± 5.74 kg/m^2, demonstrating validity for trabecular separation from pMRI, cortical thickness, and bone volume fraction from pQCT images compared with high-resolution pQCT (hr-pQCT), with slopes close to unity. However, because of partial volume effects, cortical and trabecular thickness of bone derived from pMRI and pQCT images matched hr-pQCT more only when values were small. Short-term reproducibility of bone outcomes was highest for bone volume fraction (BV/TV) and densitometric variables and lowest for trabecular outcomes measuring microstructure. Measurements at the tibia for pQCT images were more precise than at the radius. In part I of this 3-part series focused on trimodality comparisons of precision and validity, it is shown that pQCT images can yield valid and reproducible apparent bone structural outcomes, but because of longer scan time and potential for more motion, the pMRI protocol examined here remains limited in achieving reliable values.

Key Words: MRI; pQCT; segmentation; short-term precision; validity.

Introduction

Bone volumetric structure has proven useful in monitoring treatment success of bone formation agents beyond changes in areal bone mineral density (BMD) *(1,2)*. Over the last decade, several noninvasive techniques for quantifying volumetric bone outcomes have been developed including the peripheral quantitative computed tomography (pQCT) *(3)*, high-resolution pQCT (hr-pQCT) *(4)*, and magnetic resonance imaging (MRI) *(5)*. Although the first 2 modalities had been constructed for the investigation of bone, MRI has mostly been used for soft tissue investigations. The 2 computed tomography (CT)−based modalities hinge on the linear attenuation of X-ray photons to determine density and structure by calibration. With MRI, however, bone structure can be measured by virtue of the lack of proton signals in solid bone. Application of full body MRI to bone structure quantification is limited by poor accessibility, but dedicated high-field (>1.0 T) peripheral MRI (pMRI) units have been developed. These 3 peripheral modalities (pQCT, hr-pQCT, and pMRI) enable the examination of trabecular bone at the ultradistal radius and tibia.

In vivo short-term precision error for volumetric bone outcomes has been quantified from test-retest images obtained

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by hr-pQCT but not by either pQCT or pMRI. Boutroy et al (4) demonstrated that all hr-pQCT image−derived bone outcomes yielded root mean square coefficients of variation (RMSCV) below 5% (2.5%−4.4%). Short-term precision error for bone volume fraction (BV/TV), trabecular separation (Tb.Sp), and trabecular thickness (Tb.Th) derived from 1.5 T MRI of the calcaneus was between 1% and 2% in vivo (6). One study quantified the test-retest precision for trabecular, cortical, and integral bone density (0.8%−1.6%) using pQCT imaging at the radius (7). The manufacturer software of pQCT does not yield bone microstructural outcomes, although at an in-plane resolution of 200 μm, apparent structural measurements can be obtained. Such outcome measures have formerly been reported in the Osteoporotic Fractures in Men Study by Sheu et al (8), but the test-retest precision of these measurements remains unknown in this or any of the Osteoporotic Fractures in Men Study studies using pQCT. The validity of these pQCT apparent bone structure measurements has been demonstrated ex vivo using specimens by Lala et al (9) (R^2 = 0.61−0.98), but in vivo validity is important to ensure that soft tissue attenuation and participant motion do not significantly interfere with the accuracy of measurements. Similar to pQCT, 1.0 T pMRI is capable of imaging at 195 μm in-plane resolution, but measurements derived from this modality have not been validated. Apparent bone microstructure from other MRI modalities has been validated using cadavers, and externally validated using BMD derived from dual-energy X-ray absorptiometry and vertebral fractures. However, there is a lack of construct validity data. To date, hr-pQCT−derived bone outcomes have been validated against μCT (R^2 = 0.59−0.96) at 19 μm resolution on ex vivo specimens (10).

An appreciation of the differences among these modalities by characterizing their short-term precision and validity will assist in selecting one vs another for specific applications. The present study aimed to compare short-term precision error of apparent volumetric bone measures computed from images obtained by pQCT and 1.0 T pMRI vs hr-pQCT. In addition, outcomes quantified from pQCT and pMRI were validated against hr-pQCT equivalents.

This tri-modality comparison is presented as the first component of a three-part series discussing intermodality differences in technological limitations versus advantages for in vivo volumetric bone imaging.

Methods

This study was designed as a cross-sectional observational analysis comparing the short-term technical precision of 3 in vivo technologies for imaging bone volumetrically. All study procedures were performed within 1.5 yr in a cohort of women ≥50 yr of age enrolled in the Canadian Multicentre Osteoporosis Study (CaMOS) and living within a 50 km radius of the Hamilton (Ontario, Canada) CaMOS site (sampling pool N = 340). CaMOS is an ongoing, prospective cohort study of community-dwelling, randomly selected women and men ≥25 yr of age at 9 major Canadian cities. The main CaMOS objectives, methodology, and sampling framework are described in detail elsewhere (11). Those having valid contraindications to MRI (pacemaker and insulin pumps) were excluded from 1.0 T pMRI procedures. Participants weighing more than 250 lbs were excluded from hr-pQCT and 1.0 T pMRI procedures because of the chair weight limit. Women with self-reported tremors were also excluded to avoid significant motion artifact.

Participants volunteered in the completion of a pQCT, hr-pQCT, and 1.0 T pMRI ultradistal radius scan. For pQCT and pMRI, scans were repeated once within the same day. A second scan was not completed for hr-pQCT within this cohort because this procedure has already been completed on the same scanner by the same technician previously. Repeated imaging was also performed at the ultradistal tibia for pQCT. Because of the limitations of the gantry diameter and depth, ultradistal tibia scans were not completed using the pMRI. All study procedures were approved by the St. Joseph's Healthcare Research Ethics Board in Hamilton and the University Health Network in Toronto (Ontario, Canada).

hr-pQCT

The standard hr-pQCT imaging protocol was followed (4). Briefly, a region of interest located 9.5 and 22.5 mm proximal to the end plate of the radius and tibia, respectively, was scanned on the hr-pQCT (XtremeCT v1; Scanco Medical AG, Bassersdorf, Switzerland) machine acquiring 110 transaxial CT slices in the proximal direction at an isotropic voxel resolution of 82 μm. Only images with motion grade 3 and below (12) were accepted for analyses. Each slice was semiautomatically segmented using Scanco software as guided by a dual-threshold edge-detection algorithm. Segmented images were reconstructed in three dimension (3D) and were used to automatically compute apparent microstructural outcomes (BV/TV, Tb.Sp, Tb.Th, Tb.N, Ct.Th, integral, cortical, and trabecular vBMD, as denoted by subscripts i, c, and tr). Hydroxyapatite rod phantoms were scanned daily for quality control.

pQCT

Limb positioning followed previous pQCT studies (13). Scans of the radius were completed using a model XCT2000 pQCT (Stratec Medizintechnik, Pforzheim, Germany) at sites 11.5 and 16.5 mm proximal to a reference line identified at the midpoint of the radial tilt. The base and tip of the radial tilt was identified as the most medial and most lateral articulating aspects of the distal radius, respectively. Tibial scans were completed at sites that were 24.5 and 29.5 mm proximal to a reference line located along the distal tibia end plate, which was defined as the outer cortical border of the plateau portion of the ultradistal tibia. At each region of interest for both radius and tibia scans, 2.5 ± 0.3 mm thick slices were acquired with an in-plane resolution of 200 μm, a CT scan speed of 10 mm/s, 38 kVp X-ray beam energy, a tube current of 0.3 mA, and reconstructed by filtered back projection on a matrix size of 256 × 256. Both slices obtained on each limb were acquired in sequence without interruption. Hydroxyapatite phantoms were assessed on days in which scans were obtained. Only