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Quantitative Computed Tomography—Current Status and New Developments

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Abstract

This review focuses on new developments and current controversies in the field of quantitative computed tomography. Recent positions of the International Society for Clinical Densitometry acknowledged the clinical value of quantitative computed tomography of the spine and the hip using clinical whole-body computed tomography (CT) scanners. Opportunistic screening summarizes a number of new approaches describing the dual use of clinical CT scans. For example, CT scans may have been taken for tumor diagnosis but may also be used for the prediction of high or low fracture risks as an additional benefit for the patient. The assessment of the cortical parameters is another topic of current research. In CT images of the spine and the hip, a number of techniques have been developed to determine the thickness, mass, and bone density of the cortex. In higher-spatial resolution peripheral CT images of the radius and tibia obtained from special purpose scanners, 1 focus is the measurement of cortical porosity. Two different approaches, one based on the direct segmentation of the pores and one based on cortical density, will be reviewed.

Key Words: Asynchronous calibration; cortical bone; cortical porosity; opportunistic screening; quantitative computed tomography (QCT).

Introduction

In osteoporosis, dual-energy X-ray absorptiometry (DXA) remains the standard to measure bone mineral density (BMD), although in recent years quantitative computed tomography (QCT) has been (re)established as a complementary or even alternative approach *(1,2)*. QCT is a true 3-dimensional (3D) method; thus, trabecular and cortical bone compartments can be assessed separately. BMD is measured as physical bone mineral density in gram per cubic centimeter (volumetric bone mineral density [vBMD]) compared to a projected or areal density in gram per square centimeter as measured by DXA (areal bone mineral density [aBMD]). QCT is also the basis for finite element analysis (FEM) to determine bone strength. A number of recent reviews *(3–6)* have been dedicated to FEM. Therefore, it is not a topic of this contribution.

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QCT scans of the spine and the hip are acquired on clinical whole-body multipurpose computed tomography (CT) scanners, which, in contrast to DXA scanners, are not specifically dedicated to osteodensitometry. CT scanners do not offer 1-button push acquisition protocols to measure BMD. Acquisition and reconstruction parameters vary quite widely among studies. Several commercial and noncommercial QCT programs exist, which apply different bone segmentation and analysis algorithms. In addition, the multitude of outcome parameters may be confusing to the nonexpert. QCT is less standardized than DXA *(7)*, and one of the aims of this review was to explain differences among QCT acquisition and analysis techniques.

An exciting development is the use of clinical CT scans for the diagnosis of osteoporosis or fracture risk prediction. For "standard" QCT, an in-scan calibration phantom is used to calculate BMD from the measured CT values. In routine clinical CT scans, however, such a phantom is not used. Another obstacle is the current World Health Organization (WHO) definition of osteoporosis, which only applies to *T*-scores of DXA aBMD but not QCT vBMD values. A number of approaches summarized under the term

Table 1
QCT Analysis Software

	Analysis options				
	Spine	Hip	CTXA[a]	Geometry	Comment
QCT Pro: Mindways Inc	trab BMD of central elliptical VOI	int, trab, cort, BMD/BMC/vol of neck, trochanter, IT, and total hip	Yes	Hip: cortical thickness	BIT: analysis of 2D slices in the neck and the trochanter
VirtuOst: O.N. Diagnostics	trab BMD of central elliptical VOI	int BMD of the total hip	Yes		FEM analysis software that outputs few BMD values
MIAF: University of Erlangen	int, trab, cort, subcort BMD/BMC/vol of multiple VOIs of the vertebral body	int, trab, cort, subcort BMD/BMC/vol of head, neck, trochanter, IT, shaft, and total hip	No	Hip and spine: cortical thickness, moments of inertia	Analysis of 2D slices in the neck and the trochanter
Stradwin: University of Cambridge		trab/cort BMD, cortical mass per projected surface area of the total hip		Hip: cortical thickness	Cortical thickness mapping[b]
UCSF QCT analysis software	int, trab, cort, BMD/BMC/vol of multiple VOIs of vertebral body	int, trab, cort, BMD/BMC/vol of the neck and the trochanter	Yes		

Note: Web pages for the analysis programs are listed in the Appendix.
Abbr: 2D, 2-dimensional; BIT, bone investigational toolkit for QCT Pro; BMC, bone mineral content; BMD, bone mineral density; cort, cortical; CTXA, computed tomography X-ray absorptiometry; FEM, finite element analysis; int, integral; IT, intertrochanter; QCT, quantitative computed tomography; subcort, subcortical (VOI between cortical and trabecular compartments); trab, trabecular; VOI, volume of interest; vol, volume.
[a]CTXA details are discussed in the section "CTXA–DXA Equivalent *T*-Scores From QCT."
[b]Details are discussed in the section "Cortical Bone-Continuing Challenges."

"opportunistic screening" addressing these issues will be discussed.

Another focus of the current review is QCT of the cortical bone *(8)*. Because of the limited spatial resolution of clinical whole-body CT scanners, accuracy errors of cortical measurements in the femoral neck and the vertebral body may be high. Different analysis techniques for cortical bone exist, and it is important to understand their strengths and limitations. High-resolution peripheral QCT scanners improve spatial resolution approximately by a factor of 5, but are limited to the distal tibia and radius. This finding is highly relevant for cortical measurements such as cortical porosity. Again, different analysis concepts exist, and it is important to understand their respective assumptions and outcomes *(9)*.

Spine and Hip QCT—Established Techniques to Measure Integral and Trabecular BMD

Table 1 lists QCT analysis software for spine and hip that is either commercially available or has been used more widely in the analysis of clinical trials or scientific projects. Siemens still supports their older Osteo™ software, which provides BMD in single slices through the vertebral bodies from L1 to L3 or L4 *(10)*. For Osteo™, a standardized acquisition and analysis protocol is installed on Siemens CT scanners. Philips offers a dedicated QCT analysis option on their Brilliance scanners. VirtuOst is a program for FEM analysis but also outputs an integral BMD of the femur and a trabecular BMD of the spine.

Table 2 lists QCT acquisition and reconstruction parameters that provide a good balance between noise, spatial resolution, and radiation exposure. This protocol was used in most of the recent clinical trials in osteoporosis *(12–16)*. Effective dose estimates for the 2 protocols are listed in the table. Differences compared to earlier estimates *(17)* can be explained with updated tissue weighing factors (ICRP report 103 *(11)*), lower milliampere-second for the femur scan, improved Monte Carlo simulations, and improved dose efficiency of current CT equipment but also by smaller effects of automated exposure control than assumed earlier. Very early QCT techniques of the spine