Helical Multidetector Row Quantitative Computed Tomography (QCT) Precision[1]

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Rationale and Objectives. The impact of varying image acquisition parameters on the precision of measurements using quantitative computed tomography is currently based on studies performed before the advent of helical image acquisition and multidetector-row scanners. The aim of this study was to evaluate helical multidetector-row quantitative computed tomography to determine the factors contributing to the overall precision of measurements on quantitative computed tomography conducted using current vintage computed tomographic (CT) scanners.

Materials and Methods. The effects of CT protocol parameters (x-ray tube voltage and current, pitch, gantry rotation speed, detector configuration, table height, and reconstruction algorithm) and short-term scanner variation were examined on two commercially available quantitative CT (QCT) systems (ie, a combination of reference phantoms and analysis software) using seven multidetector-row CT scanners (available from a single vendor) operated in helical mode. Combined with simulated patient repositioning using three ex vivo spine specimens, precision (coefficient of variation) estimates were made on the basis of three scenarios: ‘‘best case,’’ ‘‘routine case,’’ and ‘‘worst case.’’

Results. The overall best-case QCT precision was 1.4%, provided that no changes were permitted to the bone mineral density (BMD) scan protocol. Routine-case examination (with a BMD reference phantom in place) that permitted some variation in the x-ray tube current and table speed produced a precision of 1.8%. Without any constraints on the clinical QCT examinations, the worst-case precision was estimated at 3.6%.

Conclusions. Although small in appearance, these errors are for single time points and may increase substantially when monitoring changes through QCT measurements over several time points. This calls for increased caution and attention to detail whenever using helical multidetector-row quantitative computed tomography for the assessment of BMD change.

Key Words. Quantitative computed tomography; QCT; bone densitometry; quantitation; density calibration

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Dual-energy x-ray absorptiometry (DXA) has become the standard clinical method of screening for osteoporosis (1). For some patients and under certain circumstances, quantitative computed tomography is an attractive alternative to DXA and is often used to assess osteoporosis and metabolic bone disease (2–5). Quantitative computed tomography can be helpful to place mineral mass value in a broader context, as with spinal metastases, fractures, or arthritis (6). The calibration of computed tomographic (CT) images is not unique to quantitative computed tomography and may be required for other specific quantification tasks, such as the assessment of coronary artery calcification (7,8), detection of the progression of emphysema (9), the characterization of lung nodules (10), and the development of finite element models for bone strength prediction (11–14).

No systematic studies have yet investigated how acquisition parameters can influence the precision of quantitative CT (QCT) measurements conducted using modern helical multidetector-row CT (MDCT) scanners. Several investigators

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have shown DXA to be superior or equal to single-slice quantitative computed tomography in terms of accuracy and the precision of bone mineral density (BMD) measurements (15–22). In addition to the basic technique parameters of x-ray tube voltage, current, and rotation speed, additional parameters that must be controlled for MDCT scanners include overall x-ray beam width, detector configuration (how detector elements are assigned to individual data channels), table speed, and reconstructed image thickness.

In this study, we evaluated the effect of helical MDCT acquisition parameters on QCT values in phantoms with known simulated BMD values. We also assessed short-term QCT precision using seven MDCT scanners and estimated the effects of patient repositioning. The primary goal of the study was to estimate helical multidetector-row QCT precision under the following three clinical conditions. First, we sought to establish the best possible achievable helical multidetector-row QCT precision (‘‘best case’’) and to determine which constraints must be in place to perform measurements at that optimal level. Second, current QCT systems require the use of a reference phantom, and there are obvious advantages to permanently installing a reference phantom for quantitative computed tomography in a table for all routine CT imaging examinations (‘‘routine case’’), that is, with reasonable variability for typical acquisition parameters. In a facility such as ours, this setup would provide the potential to collect, without additional radiation exposure or scan time, a very large database of QCT results for patients being followed with computed tomography while undergoing a wide variety of cancer treatments. Third, it was also important to determine the ‘‘worst-case’’ scenario, which could occur if no attention were focused on the possible sources of QCT measurement variability.

It is important to note that QCT accuracy was not assessed in this study; the numerical result of a BMD measurement was not the primary focus of this study. Instead, we assessed the variability of the numerical BMD value as specific factors associated with the image acquisition technique were altered on helical MDCT scanners.

MATERIALS AND METHODS

BMD Phantoms

Two commercially available QCT BMD measurement systems were used in this study: Image Analysis (Image Analysis Corporation, Columbia, KY) and Mindways (Mindways Software, Inc., Austin, TX). Each system includes two phantoms: a quality assurance (QA) calibration phantom and a density-reference phantom that provides a means for transforming Hounsfield units (HUs) to absolute BMD values in every reconstructed image.

The Image Analysis QA torso phantom simulates a 4.5-cm-thick section of an adult torso and is made of a water-equivalent epoxy-resin material. It contains a single 3-cm-diameter central chamber with a nominal BMD of 100 mg/cm^3 calcium hydroxyapatite (23). The 72-cm-long density-reference phantom, which is intended to be scanned with the QA phantom or patient, is composed of three square rods with nominal BMD values of 0, 75, and 150 mg/cm^3 calcium hydroxyapatite (QCT-3D Plus Bone Densitometry system version 7).

The Mindways QA torso phantom also simulates a 4.5-cm-thick section of an adult torso using a water-equivalent plastic material. It contains a 3-cm-diameter central chamber with a nominal BMD equivalence of 200 mg/cm^3 K_2HPO_4 and three smaller cylinders for additional QA calibration (24). The crescent-shaped density-reference phantom (model 3) is 45.5 cm long, is intended to be placed under the QA phantom or patient, and contains five reference materials, all of which are calibrated against the densities of water and K_2HPO_4 and range from −51.8 to 375.8 mg/cm^3 K_2HPO_4 (QCT PRO Bone Mineral Densitometry version 4.0).

QCT Phantom Scan Acquisition

The QA and reference phantom combination was positioned according to manufacturer specifications (23,24). The QA torso phantom was placed on top of the reference phantom, with no air gap between the two phantoms (Fig 1). A scan length (along the *z* axis, defined as the table motion direction) of 10 mm was planned, and CT images of varying thicknesses were reconstructed to represent the central transverse section of the QA torso phantom. A volume of interest (VOI) was defined on the images acquired along the 10-mm scan length, and the HU average was converted to BMD. The same QA torso phantoms and reference phantoms were used throughout the entire data acquisition period. More than 20,000 images were collected, and >2,000 VOIs were defined to provide data to determine the variance in the BMD measurement associated with the individual variables of interest.

QCT Phantom Image Data Analysis

To determine BMD for QA, the QCT software computes the average HU value of all image voxels composing a cylindrical volume that is 10 mm thick through the central chamber in the QA torso phantom. In the Image Analysis system, four regions of interest were placed semiautomatically (manual placement was necessary in some instances): three within the density-reference phantom calibration rods and one within the QA torso phantom 100 mg/cm^3 cylinder. The output was the measured BMD of the QA torso phantom chamber in milligrams per cubic centimeter. In the Mindways system, the automated QA phantom was operated to place all of the 12 regions of interest used in calibration and monitoring measurements in the correct positions; no failures of

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