Clinical Investigations

A Comparison of Two Dual-Energy X-Ray Absorptiometry Systems for Spinal Bone Mineral Measurement

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Received July 31, 1991

Summary. Two dual-energy X-ray absorptiometry (DEXA) systems—the Hologic QDR-1000 and the Norland XR-26 bone densitometers—were evaluated in terms of precision, accuracy, linearity of response, X-ray exposure, and correlation of in vivo spinal measurements. In vitro precision and accuracy studies were performed using the Hologic anthropomorphic spine phantom; linearity of response was determined with increasing thicknesses of aluminum slabs and concentrations of Tums E-X in a constant-level water bath. Both systems were comparable in precision, achieving coefficients of variation (CVs) of less than 1% in bone mineral content (BMC, g), bone area (cm²), and bone mineral density (BMD, g/cm²). Both were accurate in their determination of BMC, bone area, and BMD with reference to the Hologic spine phantom. Both systems also showed good BMC and BMD linearity of response. Measured X-ray skin surface exposures for the Hologic and the Norland systems were 3.11 and 3.02 mR, respectively.

In vivo spinal measurements (n = 65) on the systems were highly correlated (BMC: r = 0.993, SEE = 1.770 g; area: r = 0.984, SEE = 1.713 cm²; BMD: r = 0.990, SEE = 0.028 g/cm²). In conclusion, both systems are comparable in terms of precision, accuracy, linearity of response, and exposure efficiency.

Key words: Dual-energy X-ray absorptiometry – Bone mineral content – Bone mineral density – Linearity – Exposure.

Due to its relatively low cost, low radiation dose, high precision, and accuracy, dual photon absorptiometry (DPA) has become the most widespread technique for bone mass measurement. The recently developed dual-energy X-ray absorptiometry (DEXA) systems, which utilize X-ray tubes as photon sources, represent an improvement over the radioisotope-based DPA systems. The numerous advantages of DEXA over DPA systems include higher precision, better resolution, and faster scanning time [12–14]. Currently, there are three principal DEXA manufacturers in the United States: Hologic Inc. (Waltham, MA), Lunar Radiation (Madison, WI), and Norland Corporation (Fort Atkinson, WI). The two DEXA systems evaluated in this study were the Hologic QDR-1000 and the Norland XR-26 bone densitometers.

Although the essential operating principles of DEXA systems are similar to conventional DPA, they differ in methods of calibration, methods for the generation of dual-energy photon spectra, operating voltages, and in edge-detection algorithms. These differences may complicate standardization of bone mass measurements among DEXA systems [15]. Although there are currently no established standards and calibration procedures for these systems, an in vivo study [16] has shown that the Lunar DPX (Lunar Radiation, Madison, WI) and the Hologic QDR-1000 (Hologic Inc., Waltham, MA) are highly correlated (n = 220, for L2-L4: QDR = 0.01 + 0.90 DPX, r = 0.97, SEE = 0.04 g/cm² for bone mineral density—BMD). In assessing in vitro precision, and in comparing different systems and measurement methods, geometrically complex standards may be more appropriate [15], and this is the basis for selecting the Hologic anthropomorphic spine phantom as the standard.

The objectives of this study were to compare (1) the two DEXA systems in terms of in vitro precision and accuracy (consistency with specified values) of bone mineral content (BMC, g), bone area (cm²), and BMD (g/cm²) using a geometrically complex standard; (2) BMC and BMD linearity of response using simple-shaped objects; (3) radiation exposure; and (4) in vivo spinal BMC and BMD measurements.

Materials and Methods

System Descriptions

The Hologic QDR-1000 utilizes an X-ray tube as the radiation source, which is mounted beneath the tabletop. The two excitation
voltages at which this X-ray tube operates are 70 and 140 kVp. The photon beam first passes through a rotating calibration disk or filter wheel. This disk is divided into three major segments: one consists of air, a second consists of an epoxy-resin-based material simulating bone mineral (areal density of 1.0 g/cm²), and a third consists of an epoxy-resin-based material simulating soft tissue (areal density of 1.0 g/cm²). Each segment in turn includes a low and a high energy subsection, the latter incorporating an additional brass filter to harden the photon spectra. The filter wheel makes a complete rotation in 1.20 second (i.e., 1/60 second for each of the three segments at each pixel point) and the system is pulsed at 70 and 140 kVp to generate the required low- and high-energy X-ray photon spectra. Finally, a pencil beam of photons is generated by passage through a collimator 2.3 mm in diameter. The pixel size of the Hologic QDR-1000 system in the spine mode is 1.0 by 1.0 mm. The full width at half maximum (FWHM), as specified in the operator's manual, is 1.5 mm. The scanning speed is 60 mm/second. The X-ray beam diameter at table-top, determined by interpolating between measured diameters on films exposed at the collimator and detector positions, was approximately 2.7 mm.

The Hologic system measures a lumbar spine in a rectilinear fashion similar to conventional DPA systems. The rapid kVp switching method enables the use of a single detector assembly because only one energy source is present at a time and energy discrimination is therefore not required. At each pixel point, the transmitted photons are detected by a cadmium-tungstate scintillator, coupled to a photomultiplier tube, which operates in the current mode to produce a signal proportional to the total energy absorbed in the detector.

The configuration and scanning motions of the Norland XR-26 are similar to those of the Hologic QDR-1000. The pixel size for the Norland lumbar spine mode is 1.5 by 1.5 mm; preliminary assessment of the FWHM in our laboratory provides a value of 2.5 mm. The collimator size is 2.0 mm in diameter, and the scanning speed is 60 mm/second. The X-ray beam diameter at the table-top, as determined from a film exposure, was approximately 4.0 mm. Unlike the Hologic system, the Norland system operates at a single excitation voltage of 100 kVp and utilizes a K-edge filtering technique to selectively shape the broadband spectrum emitted from the source into low-energy and high-energy components. The principles of K-edge filtering have been described elsewhere [12].

The K-edge filter material used in this system is Samarium, which has a K-absorption edge at 4.7 keV. Altogether there are four Samarium filters (1 fixed and 3 selectable), each with a different thickness and areal density. The areal density of the fixed filter is 0.05 g/cm²; the areal densities of the second, third, and fourth filters are 0.10, 0.20, and 0.40 g/cm², respectively. Combinations of these filters yield eight possible areal densities ranging from 0.05 to 3.15 cm², each with a surface area of 106 cm². Thus, the range in g/cm² was 0.4–8.5, and the range in g was 43–901. Measurements were performed in a water bath, 20.5 cm deep, to simulate the abdominal thickness in a typical spine scan. The aluminum slabs were aligned with the aid of lasers each time during and after stacking. To insure adequate statistical precision in the simulated soft tissue attenuation, a scan area was selected which included a margin of at least 1 inch of water about all sides of the aluminum slab.

An additional linearity test was performed using known amounts (ranging from 2 to 56 g) of ground Tums E-X tablets (Norcliff Thayer Inc., Tarrytown, NY) which were poured into 10.2 cm² plastic Petri dishes. Tums represent an inexpensive and readily available source of mineral-simulating material. Each Tums E-X weighs 1.988 ± 0.018 g, with 0.75 g of calcium carbonate, adipic acid, mineral oil, sodium polyphosphate, starch, sucrose, and talc in unspecified quantities. As we did not chemically determine the mineral content of each Tums tablet, our measurements were related to the mass of the ground tablets. The Petri dishes were sealed with plastic mender for waterproofing so that they could be immersed in the water tank. The experimental setup was similar to that for the aluminum slabs.

X-ray exposures were measured with an MDH model 1015c Radiation Monitor (Radiocal Corp., Monrovia, CA) equipped with a model 1025-180 (180ec) ionization chamber. The scan parameters were chosen such that the entire ionization chamber was within the field of the scan. The systems were set at the spine acquisition mode, and exposures were measured (n = 2) at the tabletop distance for a patient thickness of approximately 1/60 inch. This is accomplished by measuring the number of photons at a non-bone site in the patient prior to actual scanning. A thicker subject will require higher photon flux, and consequently less filtration.

The system utilizes a dual detector system to register the transmitted high- and low-energy photons. The first detector, a thin sodium iodide crystal, detects predominantly the low-energy photons and transmits the high-energy photons to the second NaI crystal, where they in turn are detected. A low level discriminator is used to limit the electronic noise in the low-energy detected signal and a second lower level discriminator is used to limit the electronic noise in the high-energy detected signal. Discriminator settings are automatically determined during the daily calibration procedure. Energy windows are not employed with either detector in this system.

Determination of BMD is based upon the basis function decomposition or transformation process [17–21]. The calibration procedure involves the use of double step wedges (one made of aluminum alloy and the other of acrylic). Calibration is performed on a daily basis to adjust for any drift in the machine.

**Procedures**

For all of the procedures that follow, lumbar spine analysis software version 4.20 on the Hologic system and version 2.01 on the Norland system were used to process the raw data and to analyze the scan data.

The Hologic anthropomorphic spine phantom represents the geometrically complex standard that was used to evaluate in vivo precision and accuracy. Precision is defined as system stability over time in measuring the phantom bone area, BMC, and BMD. Accuracy, in our context, is defined as the ability of each system to correlate results with the specification of the Hologic phantom. This phantom (serial number 59) was molded with an accurately weighed (57.5 g) mixture of calcium hydroxyapatite (i.e., tribasic calcium phosphate) and epoxy-resin material. It was then measured repeatedly (n = 20) at the Hologic corporate headquarters on a calibrated Hologic QDR-1000. The resulting BMC, area, and BMD (L1-L4, excluding the transverse processes) were 57.72 ± 0.29 g, 55.83 ± 0.20 cm², and 1.034 ± 0.005 g/cm², respectively. These are the reference values to which we compared our measurements. Lumbar vertebral sections L1 through L4 were measured on the same day on both the Hologic and the Norland systems at our institution for precision and accuracy comparisons. System stabilities were studied over a period of 306 days.

As aluminum has physical properties similar to bone, it can be used as a surrogate for bone mineral. One test of the system linearity of response involved measurements of increasing thicknesses of six aluminum slabs (1.08 alloy; density = 2.7 g/cm³), with slab thicknesses ranging from 0.15 to 3.15 cm, each with a surface area of 106 cm². Thus, the range in g/cm² was 0.4–8.5, and the range in g was 43–901. Measurements were performed in a water bath, 20.5 cm deep, to simulate the abdominal thickness in a typical spine scan. The aluminum slabs were aligned with the aid of lasers each time during and after stacking. To insure adequate statistical precision in the simulated soft tissue attenuation, a scan area was selected which included a margin of at least 1 inch of water about all sides of the aluminum slab.

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For the in vivo comparison, 65 human subjects (aged 6–73) had their lumbar spine scanned on the Hologic QDR-1000 and the Norland XR-26 systems. Measurements were performed on each person on the same day. For consistency, spine sections L1 through L4 were measured using techniques as specified in the user manuals of each system.

**Statistical Methods**

The sample size was determined for detecting a 1% difference in phantom BMC, bone area, and BMD, with a significance level of 0.05 and a power of 0.90. Differences between means were analyzed using one-way analysis of variance (ANOVA) with a significance level of 0.05 (RS/1 statistical package, BBN Software Product Corporation, Cambridge, MA). Linear regression analyses (Cricket- graph, Cricket Software, Malvern, PA and StatView-II, Abacus Concepts Inc., Berkeley, CA) were performed to examine the linearity of response and to correlate the in vivo spinal BMC and BMD measurements.