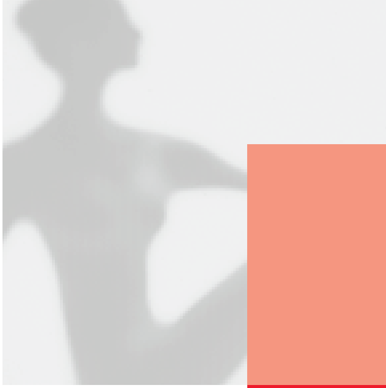

Number Three in a Series

Review

# Body Composition Determinations Using High Speed Fan-Beam Technology

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The continued refinement of DXA has lead many investigators to adopt it in place of chemical analysis and hydrodensitometry as the method of choice for BCA. DXA has been shown to accurately measure fat and lean mass in test objects, human subjects, and animal models.

Measurements of body composition have become more commonplace in both clinical medicine and in research. Studies investigating various growth disorders, wasting diseases, aging and neuromuscular changes, and the effects of physical training employ body composition measurements as a primary outcome variable. Pharmaceutical researchers utilize body composition analysis to develop therapeutic interventions to treat obesity and to develop new and improved infant formulas. For these applications, accuracy, precision, and high speed scanning are critical. Many high volume scenarios such as animal studies, clinical trials, and observational studies demand short exams times. Rapid scanning is an absolute requirement for studies involving infants and children too young to follow verbal instruction.

Among the various methodologies for measuring body composition, many consider chemical analysis to be the "gold standard" for accuracy. However, the method is destructive, time consuming, and expensive. Hydrodensitometry, considered by others to be the gold standard, also has several significant technical and practical limitations. For example, formulas for deriving %Fat results from hydrodensitometry are based on assumed densities of the body compartments, which are not always appropriate. Further, skeletal mass is often erroneously assumed to be a constant fraction of lean mass, and errors in determining residual lung volume may influence the measured results. Also, the technique is impractical for high volume scenarios. It requires subject cooperation, and does not provide regional measurements of body composition.

Over the last several years the continued refinement of dual energy x-ray absorptiometry (DXA) technology has led many investigators to adopt it in place of chemical analysis and hydrodensitometry as the method of choice for BCA. DXA has been shown to accurately measure fat and lean mass in test objects, human subjects, and animal models.[1,2,3]

**Table 1. Fan-beam & pencil-beam whole body comparison (Bath, 1998)**

| | Fan beam | Pencil beam |
|---|---|---|
| Data Acquisition | Isocentric fan-beam; Subject fully sampled | Conical beam, raster scan, Under-sampled |
| Scan Time | 3 minutes | 15-25 minutes |
| Pixel Size | 2 mm x 4 mm | 4 mm x 10 mm |
| Radiation Dose | < 1 mrem | << 1 mrem |
| Precision Error | 0.005 g/cm² for BMD; 300 g for Fat & Lean | 0.010 g/cm² for BMD; 600 g for Fat & Lean |
| Fan/Pencil Correlation | Better than r=0.98 for BMD, Fat Mass, Lean Mass, and %Fat | |
| Accuracy | Both agree well with CT, hydrodensitometry, and chemical analysis | |

## Technical Considerations

Currently both fan-beam and pencil-beam DXA scanners are available in the marketplace. Modern fan-beam scanners have largely replaced pencil-beam scanners due to their superior speed, image resolution, and precision.[4] Table 1 provides a comparison of the two DXA technologies for body composition determinations.

Pencil-beam scanners typically require 20 minutes per measurement as a consequence of moving a small x-ray beam over a very large area. Although reasonably accurate at slower speeds, faster exam times produce unreliable results because the subject is under-

**Pencil-beam scanners typically require 20 minutes per measurement. Fan-beam instruments require only three minutes.**

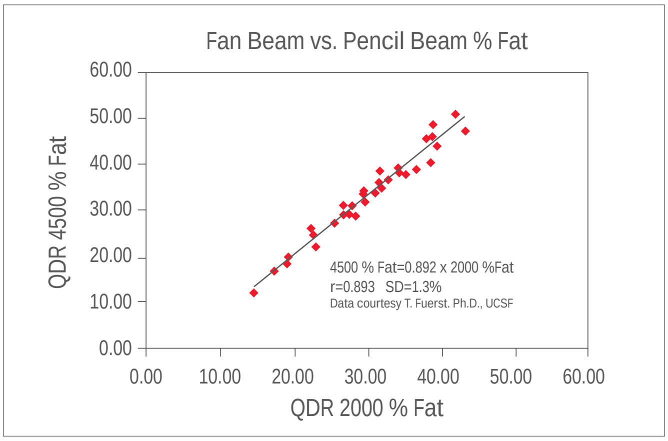


Figure 1. Fan-beam vs. Pencil-beam measurements of %Fat

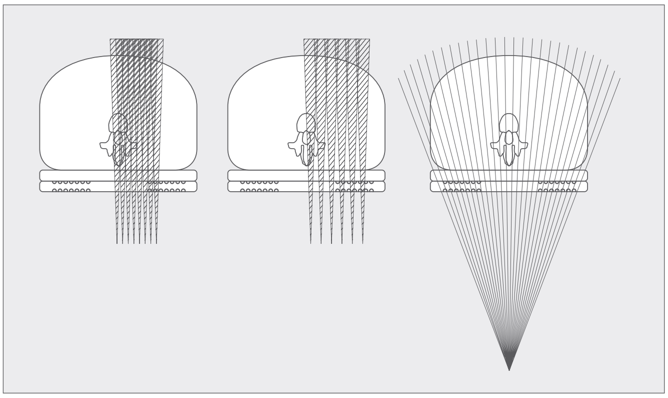

Figure 2. Pencil and fan bean data acquisition. Pencil beam geometry either overlaps (left) or under-samples (center) the subject, causing inaccuracies. Isocentric fan beam geometry (right) uniquely samples each volume element.

sampled and the image is photon-starved. Fan-beam instruments acquire accurate whole body measurements with superior spatial resolution in three minutes. It has been known for some time that fan-beam measurements of bone mineral and body composition are very highly correlated (r = 0.98 or higher) and linearly related in human subjects.[5]

**Fan-beam and pencil-beam measurements of BCA are highly correlated in humans.**

Fan-beam measurements may actually be inherently more accurate than pencil-beam measurements because the poor resolution of pencil-beam scanners limits it's ability to accurately segment the body into bone and non-bone containing regions. During data acquisition, pencil-beam scanners employ a single x-ray detector and a small cone-shaped beam translated in a raster pattern. Ideally, subjects are over-sampled and the average result of the cone-beam overlaps are measured. More typically, to avoid excessive scan times, subjects are under sampled and missing data is estimated by linear extrapolation. In either case, conical divergence distorts the measured data, and this distortion cannot be corrected because it is not a constant function of subject position within the raster scan.

Fan-beam technology, on the other hand, employs several hundred detectors operating in parallel to provide complete sampling of the entire subject with no overlap between adjacent pixels. Thus, it is a superior sampling method for whole body measurements. Using known fan-beam geometry, high-energy attenuation, and the fact that the body is uniquely sampled, fan-beam systems accurately integrate mass along each ray of the beam.

There are some image projection differences between fan-beam and pencil-beam whole body scanners that should be taken into consideration whenever measurements from the two different systems are being compared. The pencil-beam image is projected perpendicular to the plane of the table, whereas the fan-beam projection depends upon the position of the object within the fan-beam. The ROI cutlines, which are placed on the projected image, encompass different physical regions of tissue when projected back to the x-ray source. This relatively small difference is one of ROI definition, not magnification. DXA ROI definitions are arbitrary and both projections and measurements are equally valid.

The QDR 4500A has several significant technical and practical advantages over competitive whole body scanners. The QDR 4500A scan field is 1.5 inches wider than its nearest competitor, substantially increasing the number of subjects that fit within the QDR 4500A imaging window. Inadequate scan field width represents a significant limitation of competitive designs; it is particularly problematic in the field of obesity research, where subjects larger than 200 lbs. cannot be accommodated within the active scan area.

**Inadequate scan fields are problematic; subjects larger than 200 lbs. frequently cannot be accommodated on existing pencil-beam densitometers.**

The QDR 4500A records more data in a 3-minute scan than pencil-beam systems record during a 16-minute scan. This extra information is exploited to improve spatial resolution, accuracy, precision, and signal-to-noise ratios. Investigators do not use the "survey" or "fast" pencil-beam whole body scan modes because they produce measurements that are under-sampled and photon-starved, resulting in poor spatial resolution and unreliable results in obese subjects. The QDR 4500A x-ray source is 25-times more intense than competitive designs, dramatically reducing x-ray noise and improving measurement precision.

Also, the QDR 4500A whole body image is superior to images produced by pencil-beam scanners. Spatial resolution and image quality are important considerations for studies of regional changes in body composition. Visual inspection of the QDR 4500A whole body image immediately reveals additional information content not available on images produced by pencil-beam whole body scanners.

## Body Composition Calibration

Hologic scientists have given careful consideration toward the development of a comprehensive calibration and quality control program for body composition measurements.

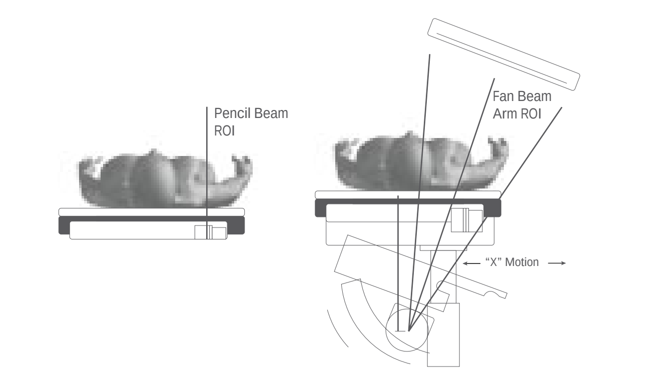


Figure 3. Schematic representation of pencil-beam and fan-beam image projections. The pencil-beam image is projected perpendicular to the plane of the table; the fan-beam projection depends on the position of the object within the beam.

Calibration of body composition measurements is achieved by direct comparison of the subject's dual energy attenuation values to those produced by a step phantom composed of soft tissue and lean tissue equivalent materials. The fat mass and lean mass of each soft tissue element in the image is calculated by direct comparison to the step phantom on a pixel-by-pixel basis, providing the most reliable calibration in the industry. A detailed description of the QDR calibration method is described elsewhere.[6]

QDR 4500A body composition results were calibrated to provide measurements of %Fat which are equivalent to %Fat results generated by a multi-component model of hydrodensitometry. The model included body water estimates by deuterium dilution, bone mass measurements by DXA, and body density measurements by hydrodensitometry.[7] Cross-calibration studies between QDR 4500A and QDR-1000/W scanners have shown close agreement for bone mineral and body composition determinations.[8] Other studies have since confirmed the close agreement between the QDR 4500A and a QDR-2000 system.[9]

Because of the calibration of QDR 4500A and QDR 4500W scanners described above, %Fat results are 2-3% lower than previous generations of QDR scanners at a nominal %Fat value of 25%. A recent 4500A DXA validation study, described below, confirmed that the QDR 4500A produces %Fat results that are 2-3% lower than pencil-beam scanners and that the QDR 4500A is more accurate. This study has been submitted as a separate full publication; however, preliminary results from the study have appeared in abstract form.[7]

**A recent validation study concluded that QDR4500A results are more accurate than pencil-beam scanners, yielding %Fat results 2-3% lower.**

## Current Research Studies

The National Institutes of Health (NIH) has been investigating the performance of the QDR 4500A fan-beam whole body scanner in a series of cross-sectional and longitudinal validation studies. These studies compared QDR 4500A measurements of body composition to 4-compartment hydrodensitometry, computed tomography, and pencil-beam measurements of body composition in human subjects. Independent researchers at several renowned U.S. institutions, using state-of-the-art equipment and techniques, conducted these studies. Several abstracts describing the studies have appeared in print[7,8] and two manuscripts describing the work have been submitted for publication. The NIH conducted the above studies as part of their process for selecting DXA whole body scanners for a large, multi-center longitudinal study on Health, Aging, and Body Composition (the Health ABC study).

**Table 2. Fan beam (n=58) and pencil beam (n=13) total body fat mass compared to hydrodensitometry**

| Hydrodensitometry | Fan Beam DXA | Diff. | $R^2$ | SEE |
|---|---|---|---|---|
| 24.2 kg | 23.5 kg | -.07 kg ±1.7 | 0.96 | 1.5 |
| **Hydrodensitometry** | **Pencil Beam DXA** | **Diff.** | **$R^2$** | **SEE** |
| 29.5 kg | 32.7 kg | 3.2 kg ±1.5 | 0.95 | 1.4 |

*Preliminary results from a DXA Validation protocol conducted by the Health, Aging, and Body Composition Study. See also abstract #826: Visser M et al, 1998 Measurement of body composition by fan beam DXA: a validation in elderly persons. Med Sci Sports Exer 30:s146*

**Table 3. Fan beam (n=58) and pencil beam (n=14) leg fat mass compared with computed tomography**

| Computed Tomography | Fan Beam DXA | Diff. | $R^2$ | SEE |
|---|---|---|---|---|
| 6.7 kg | 7.0 kg | 0.2 kg ±0.4 | 0.98 | 0.4 |
| **Computed Tomography** | **Pencil Beam DXA** | **Diff.** | **$R^2$** | **SEE** |
| 8.5 kg | 9.4 kg | 0.9 kg ±0.7 | 0.96 | 0.6 |

*Preliminary results adapted from the DXA Validation Protocol conducted by the Health, Aging, and Body Composition Study. See also Fuerst T et al, 1998, Body composition by dual x-ray absorptiometry: comparison with CT of the mid-thigh. Abstract: 13th Intnl BMD Workshop, Delevan, WI, USA*

When QDR 4500A fan-beam and pencil-beam %Fat measurements were compared to a 4-compartment model of hydrodensitometry, the QDR 4500A outperformed the pencil-beam scanner in terms of absolute accuracy verses the criterion method. The results, courtesy of the Health ABC DXA validation study, are shown in Table 2.

**Although Health ABC has pencil-beam whole body scanners available, they have selected the QDR4500A for their study.**

Further studies comparing fan-beam and pencil-beam measurements of leg fat mass versus computed tomography were undertaken to assess the accuracy of regional DXA body composition measurements. Leg lean and fat mass are important outcome variables for Health ABC, since they may predict morbidity and mortality in the elderly. As Table 3 shows, the fan-beam scanner was consistently more accurate than the pencil-beam system in comparisons with computed tomography, an alternative method for regional body composition assessment.

Based on the results of the above comparisons, the Health ABC study selected QDR 4500A fan-beam scanners for their study. Health ABC also has pencil-beam whole body scanners available at their clinical sites, but the superior accuracy, scan speed, and ease of use of the QDR 4500A

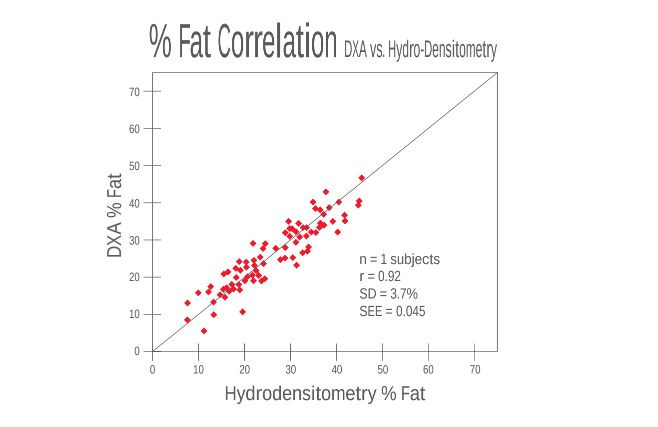


Figure 4. DXA %Fat results versus hydrodensitometry. Data courtesy of Oregon State University, Corvallis, Oregon. (See Reference 7)

indicate that fan-beam technology will be the method of choice for the duration of the longitudinal study.

The other large NIH study is the National Health and Nutrition Examination Survey (NHANES IV). The NHANES group recently published an important and comprehensive hip BMD reference database for DXA scanners. NHANES is not considering pencil-beam whole body scanners because of their unacceptably long scan times. Consultants to the NHANES study group evaluated the "survey" pencil-beam whole body scan mode supplied with competitive equipment and determined that it does not work reliably. NHANES IV reviewed the results of the Health ABC studies described above and sponsored additional comparisons between the QDR 4500A and a Lunar DPX at the University of California, San Francisco and the Mayo Clinic in Rochester, Minnesota.

Preliminary data from these studies were favorable. The results demonstrated highly correlated linear relations between the bone mineral and body composition results provided by the two DXA systems. As a result of these studies and the Health ABC DXA validation study, NHANES IV has also selected several QDR 4500A scanners for its next national survey of whole body BMD and body composition that began in the summer of 1998. The body composition data provided by the next NHANES IV survey and the Health ABC study will represent a valuable pool of information for investigators involved in body composition research. The two studies will provide extensive cross-sectional and longitudinal data, population-based reference data, and prospective data on how body composition measurements can be used to predict morbidity and mortality in elderly populations.

**NHANES IV has also selected the QDR4500A for its next national survey of whole body BMD and BCA.**

## Summary

Experimental and clinical evidence has demonstrated that QDR 4500A body composition measurements are superior to pencil-beam measurements in terms of overall accuracy. Fan-beam precision and spatial resolution are superior despite five to ten-fold reductions in exam time.

As a result of these substantial practical and technical advantages, the two leading NIH studies on human body composition have both selected Hologic QDR 4500A fan-beam scanners for their landmark investigations.

Fan-beam technology produces accurate mass measurements over a wide range of weight and body composition in human subjects and in test objects of varying mass and composition. The development of an algorithm that combines high energy attenuation, pixel position, and fan-beam geometry has resolved issues of fan-beam mass magnification.[1] This development, along with improvements in accuracy, spatial resolution, and exam times, has led to the rapid acceptance of fan-beam technology in the field of *in vivo* body composition measurements.

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