Instrumentation for Measuring Bone Mineral Density (Emphasis on Dual Energy X-Ray Absorptiometry)

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Director of Nuclear Medicine Physics
Emory University School of Medicine
Instrumentation for Measuring Bone Mineral Density

- Instrumentation for Measuring Bone Mineral Density
- Principles of DEXA (Dual Energy X-Ray Absorptiometry)
- Quality Control for DEXA
Instrumentation for Measuring Bone Mineral Density

- Radiographic Absorptiometry
- Single Photon Absorptiometry
- Dual Photon Absorptiometry
- Dual Energy X-Ray Absorptiometry
- Quantitative Computed Tomography
- Quantitative Ultrasound
Radiographic Absorptiometry (Photodensitometry)

• Technique
  – X-ray of the Hand
  – Calibration with an Aluminum Wedge
  – Analysis of Film with Photodensitometer

• Advantages
  – Low Cost
  – Low Radiation Dose

• Disadvantages
  – Technical (non-uniformity of x-ray intensity, etc.)
  – Limited to Peripheral Skeleton

MetriScan™, ALARA Inc.

Digital Radiographic Absorptiometry

MetriScan features include:

* less than one second scan
* radiation dose less than 5% of dental x-ray
* total clinical precision error = 1% vs. ultrasound systems (1.5% - 2.0%)
* no gel or patient preparation required
* automatic calibration check
* small footprint: 16” x 16”

http://www.alara.com/
Single Photon Absorptiometry (SPA)

• Technique
  – Semi-Permanent Radioactive Source
    » I-125, 27.5 keV photon, 60 day half life
    » Am-241, 59.5 keV photon, 432 year half life
  – Collimated Beam and Sodium Iodide Detector
  – Water Bag or Bath to Compensate for Soft Tissue

• Advantages
  – Stability of Source

• Disadvantages
  – Radioactive Decay
  – Detector Stability
  – Limited to Peripheral Skeleton

Dual Photon Absorptiometry (DPA)

• Technique
  – Semi-Permanent Radioactive Source
    » Gd-153, 40 and 100 keV photon, 242 day half life
  – Collimated Beam and Sodium Iodide Detector
  – Rectilinear Scanning

• Advantages
  – Stability of Source
  – Dual-photon technique Compensates for Soft Tissue

• Disadvantages
  – Radioactive Decay
  – Detector Stability

Dual Energy X-ray Absorptiometry (DEXA)

- **Technique**
  - X-ray Tube Produces Intense Beam of Radiation
  - High and Low Energy X-Rays
  - Pencil or Fan Beam Scanning

- **Advantages**
  - Dual-Energy Technique Compensates for Soft Tissue
  - High Photon Flux from X-ray Tube
  - Higher Resolution than Dual Photon Absorptiometry

- **Disadvantages**
  - Technical: Stability of X-ray Generator
Quantitative Computed Tomography (QCT)

- **Technique**
  - CT Images of Spine
  - Calibration Phantom Included in Image
  - Regions of Interest Drawn over Selected Area of Bone

- **Advantages**
  - Allows Separation of Trabecular and Cortical Bone

- **Disadvantages**
  - Cost
  - Availability of Quantitative CT Scanners

Quantitative Ultrasound

• Technique
  – Ultrasound Transducers Coupled to Heel
  – Sound Passes Through Heel
  – Measures Broadband Ultrasonic Attenuation (BUA) and Velocity of Sound (SOS)

• Advantages
  – Low Cost/Small Size
  – Radiation Free
  – Measurements Relate to Bone Structure

• Disadvantages
  – Shows Promise (Particularly for Screening)
  – Not Completely Accepted
Quantitative Ultrasound

• Speed of Sound (SOS)
  – Density

• Broadband Ultrasonic Attenuation (BUA)
  – Elasticity

• Stiffness
  – Combination of BUA and SOS that improves reproducibility
Precision and Accuracy

• **Accuracy**
  – How does the measurement deviate from the true value?

• **Precision**
  – How does the measurement vary when done repeatedly?
  – Percent Coefficient of Variation:

\[
CV = \left( \frac{\text{Standard Deviation (}X\text{)}}{\text{Mean (}X\text{)}} \right) * 100\%
\]
**Characteristics of Different Bone Densitometry Techniques**

<table>
<thead>
<tr>
<th>Technique</th>
<th>ROI</th>
<th>Units</th>
<th>Precision (%CV)</th>
<th>Dose (µSV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEXA</td>
<td>Spine (AP)</td>
<td>BMD (g/cm²)</td>
<td>1%</td>
<td>1-10</td>
</tr>
<tr>
<td></td>
<td>Femur</td>
<td></td>
<td>1-2%</td>
<td>1-10</td>
</tr>
<tr>
<td></td>
<td>Total body</td>
<td></td>
<td>1%</td>
<td>3</td>
</tr>
<tr>
<td>QCT</td>
<td>Spine</td>
<td>BMD (g/cm³)</td>
<td>3%</td>
<td>50-500</td>
</tr>
<tr>
<td>RA</td>
<td>Phalanx</td>
<td>BMD (g/cm²)</td>
<td>2-5%</td>
<td>10</td>
</tr>
<tr>
<td>QUS</td>
<td>Calcaneous</td>
<td>BUA (db/MHz)</td>
<td>2-5%</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Calcaneous</td>
<td>SOS (m/s)</td>
<td>0.1-1%</td>
<td>None</td>
</tr>
</tbody>
</table>

Precision in Monitoring BMD Change

<table>
<thead>
<tr>
<th>System Precision</th>
<th>Significant BMD Change</th>
<th>Expected BMD Change Per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>1.4%</td>
<td>1.4</td>
</tr>
<tr>
<td>1.0%</td>
<td>2.8%</td>
<td>2.8</td>
</tr>
<tr>
<td>2.0%</td>
<td>5.5%</td>
<td>5.5</td>
</tr>
<tr>
<td>3.0%</td>
<td>8.3%</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Years Required to see a Significant Change

<table>
<thead>
<tr>
<th>1%</th>
<th>2%</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>2.8</td>
<td>1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>5.5</td>
<td>2.8</td>
<td>1.1</td>
</tr>
<tr>
<td>8.3</td>
<td>4.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Instrumentation for Measuring Bone Mineral Density

• Instrumentation for Measuring Bone Mineral Density

• Principles of DEXA (Dual Energy X-Ray Absorptiometry)

• Quality Control for DEXA
Dual Energy X-Ray Absorptiometry

- Dual Energy (High and Low) Photons
  - Rare Earth Filter (~40 and ~80 keV)
  - Switching the X-ray Tubes High Voltage (70 and 140 keV)

- High and Low Energy Intensity Profiles
  - Low Energy Photons Attenuated More
  - Difference in Attenuation Greater in Bone

- Attenuation of Bony Components Calculated Manually
  - Projection Measurement (mass/area)
  - Typically gm/cm²
Filtering to Produce Dual Energy X-Rays

• K-Absorption Edge Filter
  – Splits Beam into High and Low Energy Components
  – Narrow Spectral Peaks Minimize Beam Hardening

• Lunar DPX
  – Cerium Filter
  – Photomultiplier Tube and Pulse Height Analysis

• Norland XR
  – Samarium Filter (Thickness Varies to Control Exposure)
  – Separate Detectors for High and Low Energy X-Rays
High Voltage Switching to Produce Dual Energy X-Rays

• Switch the X-Ray Tubes High Voltage
  – Low and High kVp
  – Spectral Distribution > K-Absorption Edge Filtering

• Hologic QDR
  – Beam Hardening Corrected by Calibration Wheel (Cylinder in Fan Beam Systems)
  – Pulse Height Analysis is not Required

Calibration Wheel
  – Internal Reference Standard
  – Contains Bone, Soft Tissue and Air Segments
  – Each Segment has Brass Filter to Give High and Low Energy X-Ray Sectors
  – BMD of Bone Filter is 1.006 g/cm²

Taken from Blake and Fogelman, Seminars in Nuclear Medicine, Vol XXVII, No 3, 1997: pp 210-228.
DEXA
Pencil Beam vs Fan Beam

Hologic
DEXA
Pencil Beam vs Fan Beam

- Narrow angle fan-beam
- Reduced distortion due to magnification
- High efficiency CZT detector (1/5th the dose)
- Automatic scan positioning

GE/Lunar

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# Dual Energy X-Ray Absorptiometry

## Patient Dose for DEXA Spine and Hip

<table>
<thead>
<tr>
<th>DEXA System</th>
<th>Beam Geometry</th>
<th>Effective Dose</th>
<th>Scan Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar DPX*</td>
<td>Pencil</td>
<td>0.06 µSv</td>
<td>5 min</td>
</tr>
<tr>
<td>Hologic QDR-1000*</td>
<td>Pencil</td>
<td>0.3 µSv</td>
<td>3 min</td>
</tr>
<tr>
<td>Hologic QDR-4500*</td>
<td>Fan</td>
<td>2.6 µSv</td>
<td>30 sec</td>
</tr>
<tr>
<td>Lunar Prodigy**</td>
<td>Fan</td>
<td>37 µSv</td>
<td>30 sec</td>
</tr>
</tbody>
</table>

*Blake and Fogelman, Seminars in Nuclear Medicine, Vol XXVII, No 3, 1997: pp 210-228.

** GE/Lunar Product Literature
DEXA Scan Analysis

- Place ROI Over Desired Area
- Measure Area and Bone Mineral Content (from intensity profiles)
- Calculate Bone Mineral Density as Mass per Area (gm/cm²)
- Compare to Normal Database

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International Society for Clinical Densitometry (ISCD): OFFICIAL POSITIONS

DXA Nomenclature

• DXA – not DEXA.
• T-score - not T score, t-score, or t score
• Z-score - not Z score, z-score, or z score

DXA Decimal Digits

Preferred number of decimal digits for DXA reporting:

• BMD: 3 digits (example, 0.927 g/cm$^2$)
• T-score: 1 digit (example, -2.3)
• Z-score: 1 digit (example, 1.7)
• BMC: 2 digits (example, 31.76 g)
• Area: 2 digits (example, 43.25 cm$^2$)
• % reference database: Integer (example, 82%)

International Society for Clinical Densitometry (ISCD): OFFICIAL POSITIONS

Precision Assessment

- Each DXA center should determine its precision error and calculate the LSC. The precision error supplied by the manufacturer should not be used.
- If a DXA center has more than one technologist, an average precision error, combining data from all technologists, should be used …
- At the present time, in the absence of an industry-wide competency threshold, the center’s discretion must be used to define acceptable performance.
- An industry-wide competency threshold (expressed as the %CV) should be established to define the minimum skill level. This competency threshold could be used to verify that the skill level of different technologists is similar.
- Every technologist should perform an in vivo precision assessment using patients representative of the clinic’s patient population.


http://www.iscd.org/Visitors/official.cfm
International Society for Clinical Densitometry (ISCD): OFFICIAL POSITIONS

Precision Assessment (Continued)

• Each technologist should do one complete precision assessment after basic scanning skills have been learned (eg, manufacturer training) and after having performed approximately 100 patient scans.

• A repeat precision assessment should be done if a new DXA system is installed.

• A repeat precision assessment should be done if a technologist’s skill level has changed.

• To perform a precision analysis:
  – Measure 15 patients 3 times, or 30 patients 2 times, repositioning the patient after each scan.
  – Calculate the root mean square standard deviation (RMS-SD) for the group.
  – Calculate LSC for the group at 95% confidence interval.

• Precision assessment should be standard clinical practice...

Instructions and calculators for determining precision may be found at the ISCD Website: http://www.iscd.org/


http://www.iscd.org/Visitors/official.cfm
Quality Control for DEXA

• Instrumentation Quality Control
  – Daily Imaging and Analysis of QC Phantoms

• Imaging Quality Control
  – Patient Positioning
  – Removal of External Attenuation
  – Other Photon Sources

• Processing Quality Control
  – Correct Placement of Regions of Interest (ROIs)
  – Careful Checking of Automated ROIs
Phantom Scanning and Calibration

The Quality Control (QC) program at a DXA center should include adherence to manufacturer guidelines for system maintenance. In addition, if not recommended in the manufacturer protocol, the following QC procedures are advised:

- Perform periodic (at least once per week) phantom scans for any DXA system as an independent assessment of system calibration.
- Plot and review data from calibration and phantom scans.
- Verify the phantom mean BMD after any service performed on the densitometer.
- Establish and enforce corrective action thresholds that trigger a call for service.
- Maintain service logs.
- Comply with government inspections, radiation surveys and regulatory requirements.

DEXA and Radionuclide Studies


Phantom Setup

- Hologic BMD Spine Phantom Taped to Fillable Liver Phantom
- BMD Measurements with Activity Levels
  - 0 mCi
  - 0.5 mCi
  - 1 mCi
  - 5 mCi
  - 10 mCi
  - 20 mCi
- Procedure
  - Image on Scanner A
  - Image on Scanner B
  - Add and Mix Activity
  - Image on Scanner B
  - Image on Scanner A
  - Add and Mix Activity
  - Etc.

Hatton et al. Effect of diagnostic radionuclide studies on bone mineral density values measured by DEXA. *J Nucl Med* 2002; 1370:341(P)
The image shows graphs comparing BMD deviation (gm/cm²) against activity (mCi) for Tc-99m. The graphs are labeled with the names of the imaging systems: Hologic and GE/Lunar. The data points indicate a decreasing trend in BMD deviation with increasing activity for both systems.
DEXA and Radionuclide Studies

- In the presence of an administered radionuclide DEXA systems that utilize energy discrimination are effected more that those that use energy switching.

- A 24-hour delay following the administration of a diagnostic dose of Tc-99m should be sufficient to avoid spurious DEXA BMD values

Hatton et al. Effect of diagnostic radionuclide studies on bone mineral density values measured by DEXA. *J Nucl Med* 2002; 1370:341(P)
Instrumentation for Measuring Bone Mineral Density

“I think that for now and in the foreseeable future, central DEXA measurements of the spine and hip will remain the gold standard for both diagnoses of osteoporosis and for monitoring treatment.”

Nelson Watts, MD
Director, U. of Cincinnati Bone health and Osteoporosis Center
Past President, International Society for Clinical Densitometry
Medical Imaging Magazine, May 2003
Cooper Surgical/Norland pDEXA

- Scans Forearm
- 60 kV, X-ray Source
- Tin Filtered
- 28 and 48 keV X-Rays
- 2 Cadmium Telluride Detectors
- 1-4 Minute Scan Times
- < 3 mRem Radiation Dose
Schick
AccuDEXA

Dedicated Finger DXA

Small Footprint
Requires less that 2 feet of counter space and weighs less that 70 lbs.

• **Low radiation**
  Effective radiation to the patient is a low 0.0003 uSv, just 1/150,000th of a chest X-ray

• **High Precision**
  Patient precision error is less than 1%

http://www.schicktech.com
DEXA Lateral Spine

• **Pro**
  – Better isolation of vertebral bodies from posterior elements
  – Better separation of trabecular and cortical bone

• **Con**
  – Curvature of spine difficult to reproduce (pt on side)
  – Soft tissue attenuation may be greater than PA scan
  – Ribs may interfere with ROIs over spine

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In an 81 year old female, AP spine T-score indicates osteopenia (-1.2), while her lateral spine T-score shows evidence of osteoporosis (-3.0). The AP measurement may be artificially elevated due to arthritis or other degenerative changes.
Vertebral Morphometry

- Measures Vertebral Heights and Ratios
- Examine for Deformation
DEXA Whole Body

• Option on High End Scanners
• Body Composition
  – DEXA Scan
  – Eliminate Bone
  – Determine 2 Densities: Fat Muscle
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• Imaging Quality Control
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  – Removal of External Attenuation
  – Other Photon Sources

• Processing Quality Control
  – Correct Placement of Regions of Interest (ROIs)
  – Careful Checking of Automated ROIs
Quality Control for DEXA

• Image Phantom
• Analyze
• Track
Quality Control for DEXA

- Patient Positioning
Quality Control for DEXA

• Patient Positioning
Quality Control for DEXA

• ROI Placement
  – Override Automated ROIs if Necessary
Quality Control for DEXA

• ROI Placement
  – Override Automated ROIs if Necessary

Thick Patient
Quality Control for DEXA

- Other Attenuation
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