Dual Energy X-Ray Absorptiometry (DXA) – Science, Technology, and Practice

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Disclosures

- I am a (minor) GE stockholder
- I was involved in the design of two DXA machines (Expert and Achilles) when working for Lunar Corporation (now GE Lunar)
- My only clinical experience with DXA has been as a patient (no QA experience!)
- I grew up in Bedford MA, 2 miles from Hologic HQ
**DXA Bone Densitometers**

Image courtesy GE Healthcare

Image courtesy Hologic Corporation

**Effective dose**

<table>
<thead>
<tr>
<th>Exam</th>
<th>GE Prodigy</th>
<th>Hologic QDR 4500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbar spine</td>
<td>0.7 uSv</td>
<td>1.8 uSv (?)</td>
</tr>
<tr>
<td>Proximal femur</td>
<td>0.7 uSv</td>
<td>6 uSv</td>
</tr>
<tr>
<td>Whole body</td>
<td>0.6 uSv</td>
<td>4 uSv</td>
</tr>
</tbody>
</table>

Uses of DXA machines

- Bone densitometry
  - Diagnosis (accuracy)
  - Therapy response (precision)
  - Fracture prediction (FRAX application)
- Body composition
  - Total bone, total lean, total adipose
- Vertebral morphology

Dual Energy X-ray Absorptiometry

Science
Technology
Practice
Monoenergetic x-rays

\[ \ln \left( \frac{I_0(E)}{I(E)} \right) = \mu_{PMMA}(E)t_{PMMA} + \mu_{Al}(E)t_{Al} \]

Log attenuation

\[ LA(E) = \ln \left( \frac{I_0(E)}{I(E)} \right) \]

Mass attenuation coefficient

\[ \mu_{M,mat}(E) = \frac{\mu_{mat}(E)}{\rho_{mat}} \]

Areal density (g/cm²)

\[ \sigma_{mat} = t_{mat}\rho_{mat} \]
Dual energies

\[ L_{A_L} = \mu_{M,PMMA}(E_L)\sigma_{PMMA} + \mu_{M,Al}(E_L)\sigma_{Al} \]
\[ L_{A_H} = \mu_{M,PMMA}(E_H)\sigma_{PMMA} + \mu_{M,Al}(E_H)\sigma_{Al} \]

\[ \sigma_{PMMA} = f_{PMMA}(L_{A_L}, L_{A_H}) \]
\[ \sigma_{Al} = f_{Al}(L_{A_L}, L_{A_H}) \]

Dual energies

\[ \mu_{M,mat}(E) = a_{PE,mat} \mu_{M,PE}(E) + a_{CS,mat} \mu_{M,CS}(E) \]
Material Decomposition

![Graph showing Mu/Rho vs Photon energy for Aluminum and PMMA with different decomposition types.]
Material Decomposition

- Coefficient of photoelectric absorption
- Coefficient of Compton scattering

Bone
Aluminum
Lean
Adipose

PMMA

Material Decomposition

- Aluminum equivalence (g/cm²)

Bone
Aluminum
PMMA
Adipose
Lean

PMMA Equivalence (g/cm²)
Material Decomposition

Bone

Aluminum

PMMA

Bone equivalence (g/cm²)

Lean equivalence (g/cm²)

Example

Detector

25 g/cm²
75% lean
25% adipose

1 g/cm² bone
Calcium hydroxyapatite

X-ray tube
Example

Bone equivalence (g/cm²) vs. Lean equivalence (g/cm²)

Example

Bone equivalence (g/cm²) vs. Total equivalence (g/cm²)
Fat content correction

Image courtesy Hologic Corporation
Fat content estimation

Soft tissue (25% fat) Equivalence

Bone equivalence

Dual Energy X-ray Absorptiometry

Science
Technology
Practice
Technologies - History

• Single Photon Absorptiometry
  • 1963 – Cameron and Sorenson
• Dual Photon Absorptiometry
  • ~1970, Cameron, Mazess, et al
• Dual X-Ray Absorptiometry
  • ~1980s (?); Stein, Mazess, et al

Source: Thorson and Wahner, JNuMed Vol 14, pp163-171
US Patent Office

Single Photon Absorptiometry

![Diagram of Single Photon Absorptiometry](image)


Courtesy of Society of Nuclear Medicine and Molecular imaging.
Dual Photon Absorptiometry

Detector

Gd153 spectrum

Yield (%)

Photon energy (keV)

20 40 60 80 100 120 140

20 40 60 80 100 120 140

Gd-153

44 keV, 100 keV

Photon energy (keV)

Yield (%)

Detector

Discriminators

Counters

Photomultiplier tube

Sodium iodide crystal

Collimator

X-rays

Computer
Pulse height spectrum

With 20cm water

PMT Pulse Height

Raster scan

Pencil Beam Technique

Image courtesy GE Healthcare
**DXA Technologies**

**X-ray source**
- K-edge filter (GE)
- kV switching (Hologic)

**Beam geometry**
- Pencil beam (1st generation)
- Partial fan beam
- Fan beam
  - Cone Beam

**Photon counting Detectors (GE)**
- Na-I / PMT
- CdTe (direct detection)
- LYSO / SSPM

**Energy integrating detectors**
- Scintillator/photodiode array (Hologic)
- Sandwich detector

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**Beam geometries**

- **Pencil beam**
- **Narrow fan beam**
- **Wide fan beam**
Beam Geometries

- Pencil Beam Technique
- Lunar’s Patented Narrow Fan Beam Technique
- Wide Fan Beam Technique

Image courtesy GE Healthcare

X-ray source technologies

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>GE/Lunar</th>
<th>Hologic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube voltage</td>
<td>76 kV</td>
<td>60kV, 120kV or 100kV, 140kV</td>
</tr>
<tr>
<td>Filtration</td>
<td>K-edge</td>
<td>Spinning filter wheel*</td>
</tr>
</tbody>
</table>

* Six sector wheel with the following filter combinations
  - Air
  - Bone equivalent
  - Soft tissue equivalent
  - Copper
  - Copper + bone
  - Soft tissue + bone
Detector technologies

Photon counting (GE)
- NaI with PMT
- CdTe with direct conversion
- LYSO with solid state PMT

Energy integrating
- Ceramic detectors with photodiode array (Hologic)
- Sandwich detector (obsolete)
**K-edge filtration**

*20 cm Water 1.0 mm Lanthanum*

- Relative photon flux
- Photon energy (keV)

**Sandwich detectors**

- X-rays
- LaOS
- Photodiode array
- Copper
- Photodiode array
- GdOS
Sandwich detectors

20 cm Water 0.2 mm Tungsten

- Incident on detector
- La2O2S (100 mg/cm2)
- Transmitted by 1.0mm Copper

Relative photon flux

Photon energy (keV)

Dual Energy X-ray Absorptiometry

Science Technology Practice
Clinical report

\[ T = \frac{BMD - BMD_{ref}}{\sigma_{BMD}} \]

\[ Z = \frac{BMD - BMD_{ref}}{\sigma_{BMD}} \]

- \( BMD_{ref} \) is the average for young healthy adults
- \( BMD_{ref} \) is the average for adults of the same age and sex

Diagnosis

<table>
<thead>
<tr>
<th>T-Score</th>
<th>WHO Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1 or higher</td>
<td>Normal</td>
</tr>
<tr>
<td>-2.5 to -1.5</td>
<td>Osteopenia</td>
</tr>
<tr>
<td>-2.5 or lower</td>
<td>Osteoporosis</td>
</tr>
</tbody>
</table>
Lumbar Spine and Proximal Femur Bone Mineral Density, Bone Mineral Content, and Bone Area: United States, 2005-2008

### Accuracy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute accuracy</td>
<td>+/- 10%</td>
</tr>
<tr>
<td>Inter-model variation</td>
<td>+/- 15%</td>
</tr>
<tr>
<td>Inter-unit variation</td>
<td>+/- 2%</td>
</tr>
</tbody>
</table>

Source: International Society for Clinical Densitometry (ICSD) white paper “Precision Assessment and Radiation Safety for Dual-Energy X-ray Absorptiometry

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### Therapy response

- **Precision**
  - Scanner stability
  - Technologist skill
    - Positioning
    - Tissue segmentation
Scanner QA

Shewhart Chart

Avg + 2 Std. Dev.

Avg - 2 Std. Dev.
Shewhart Rules

Machine failure if
• Single BMD outside average ± 3 standard deviation
• Two consecutive BMD on same side of average outside avg ± 2 S.D.
• Four consecutive BMD on same side of average outside avg ± 1 S.D.
• Ten consecutive BMD on same side of average
• Two consecutive BMD differing by more than 4 S.D.

Sources
SYDNEY LOU BONNICK, Bone Densitometry in Clinical Practice: Application and Interpretation, Springer, p.115 (2009)

Technologist Precision

Least Significant Change (LSC)
95% confidence interval

\[ LSC \equiv 2.77 \sigma_{\text{in vivo}} \]

In-vivo Precision Measurements
• Measure BMD in 30 patients 2 times, or
• Measure BMD in 15 patients 3 times

Written consent recommended
IRB approval not needed
BMD Precision

<table>
<thead>
<tr>
<th>Site</th>
<th>Coefficient of variation</th>
<th>Least significant change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbar spine</td>
<td>1.0-1.2%</td>
<td>~3%</td>
</tr>
<tr>
<td>Total hip</td>
<td>0.8-1.7%</td>
<td>~3.5%</td>
</tr>
<tr>
<td>Femoral neck</td>
<td>1.1-2.2%</td>
<td>~4.5%</td>
</tr>
<tr>
<td>Trochanter</td>
<td>1.2-1.5%</td>
<td>~3.8%</td>
</tr>
</tbody>
</table>

Therapy response

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lumbar spine</th>
<th>Femoral neck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>0.850 g/cm²</td>
<td>0.865 g/cm²</td>
</tr>
<tr>
<td>2 years later</td>
<td>0.865 g/cm²</td>
<td>0.858 g/cm²</td>
</tr>
<tr>
<td>Difference</td>
<td>+0.015 g/cm²</td>
<td>-0.007 g/cm²</td>
</tr>
<tr>
<td>LSC for this technologist</td>
<td>0.027 g/cm²</td>
<td>0.030 g/cm²</td>
</tr>
</tbody>
</table>
Accreditation - ISCD

International Society of Clinical Dosimetry
Accreditation Program

- Follow manufacturer’s QA recommendations
- Periodic (at least once/week) phantom scans
- In-vivo precision test for every technologist
  - Upon completion of training
  - When a new DXA system is installed
  - When the technologist’s skill level has changed.

Accreditation - CBMD

Canadian Bone Mineral Density Facility Accreditation Program
(Ontario Association of Radiologists)

- “Approved” medical physicist
- Weekend long workshop on DXA QA
- At initial visit
  - Establish “Shewhart” baselines
  - Determine LSC for facility/technologist
  - Measure entrance skin exposure
  - Measure scatter
- Annual review by physicist
- Establish LSC for new staff

Source: Jeff Frimeth, MSc, MCCPM, CIIP
Accreditation - ANZBMS

Australian and New Zealand Bone and Mineral Society

Periodic tests
  • Daily phantom accuracy tests
  • Long term stability tests
Acceptance tests and after major repair
  • Laser light positioning
  • Scan line and step spacing
  • Scan time indication
  • Entrance skin exposure
Other
  • Staff scatter exposure measurements

Acknowledgements

Jeff Frimeth
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