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

David M. Gauntt, Ph.D.
UAB Medical Center

UAB MEDICINE
Knowledge that will change your world

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

UAB MEDICINE
Knowledge that will change your world

DXA Bone Densitometers

Image courtesy GE Healthcare

Image courtesy Hologic Corporation

UAB MEDICINE
Knowledge that will change your world

Effective dose

Exam	GE Prodigy	Hologic QDR 4500
Lumbar spine	0.7 uSv	1.8 uSv (?)
Proximal femur	0.7 uSv	6 uSv
Whole body	0.6 uSv	4 uSv

Source: CRCPD Bone Densitometry White Paper (2006)

UAB MEDICINE
Knowledge that will change your world

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

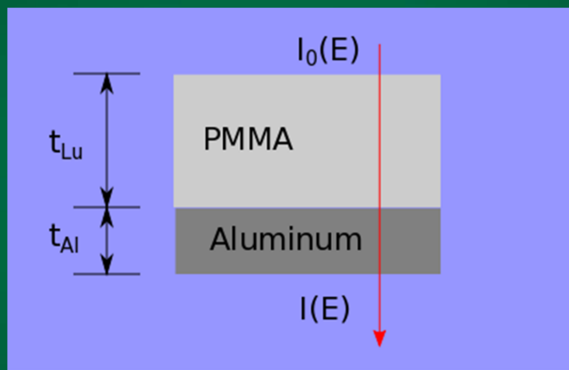
UAB MEDICINE
Knowledge that will change your world

Dual Energy X-ray Absorptiometry

Science
Technology
Practice

UAB MEDICINE
Knowledge that will change your world

Monoenergetic x-rays



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

UAB MEDICINE
Knowledge that will change your world

Monoenergetic x-rays

$$LA(E) = \mu_{M,PMMA}(E)\sigma_{PMMA} + \mu_{M,Al}(E)\sigma_{Al}$$

Log attenuation $LA(E) = \ln\left(\frac{I_0(E)}{I(E)}\right)$

Mass attenuation coefficient $\mu_M, mat(E) \equiv \frac{\mu_{mat}(E)}{\rho_{mat}}$

Areal density (g/cm^2) $\sigma_{mat} \equiv t_{mat}\rho_{mat}$

UAB MEDICINE
Knowledge that will change your world

Dual energies

$$LA_L = \mu_{M,PMMA}(E_L)\sigma_{PMMA} + \mu_{M,Al}(E_L)\sigma_{Al}$$

$$LA_H = \mu_{M,PMMA}(E_H)\sigma_{PMMA} + \mu_{M,Al}(E_H)\sigma_{Al}$$

$$\sigma_{PMMA} = f_{PMMA}(LA_L, LA_H)$$

$$\sigma_{Al} = f_{Al}(LA_L, LA_H)$$

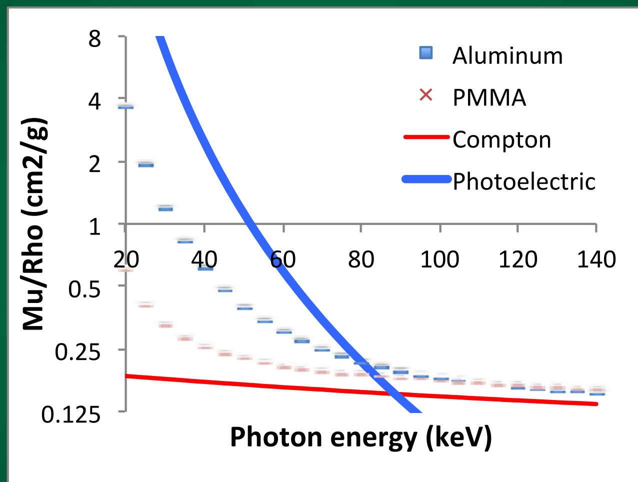
UAB MEDICINE
Knowledge that will change your world

Dual energies

$$\mu_{M,mat}(E) = a_{PE,mat}\, \mu_{M,PE}(E) + a_{CS,mat}\, \mu_{M,CS}(E)$$

UAB MEDICINE
Knowledge that will change your world

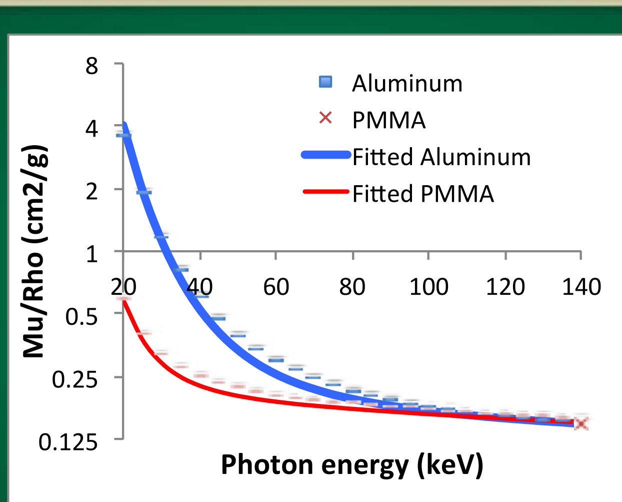
Material Decomposition



UAB MEDICINE

Knowledge that will change your world

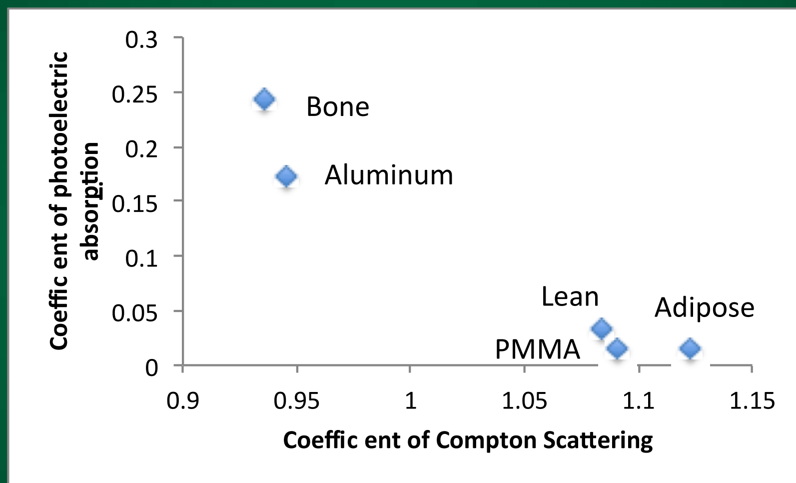
Material Decomposition



UAB MEDICINE

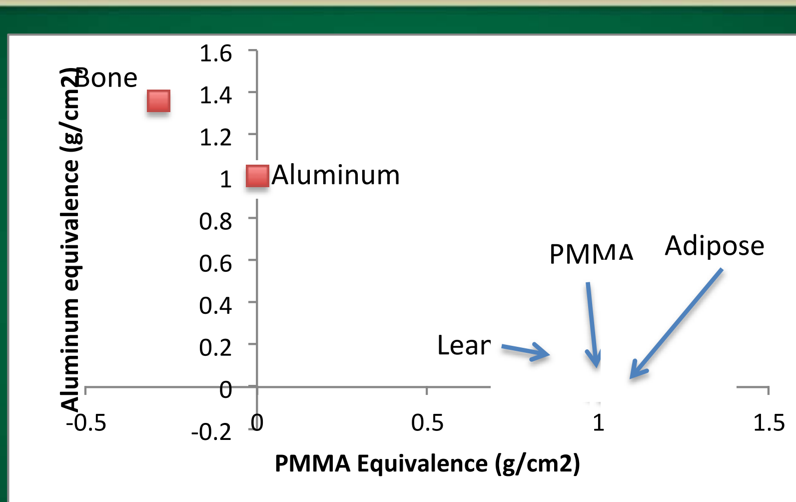
Knowledge that will change your world

Material Decomposition



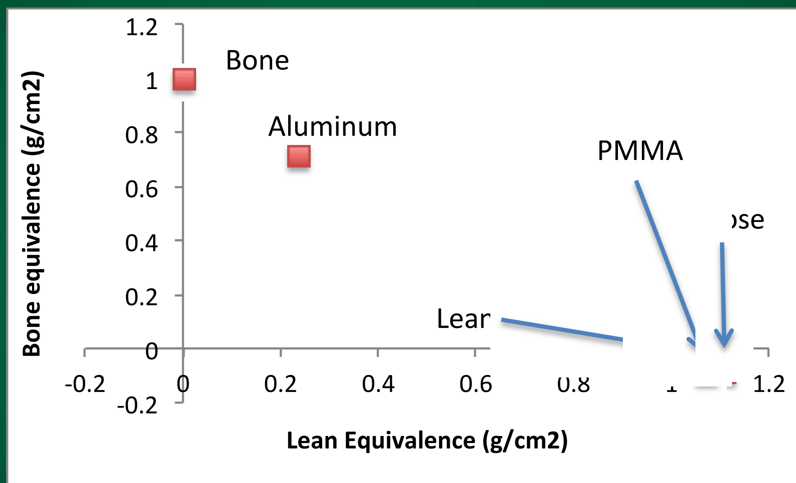
UAB MEDICINE
Knowledge that will change your world

Material Decomposition



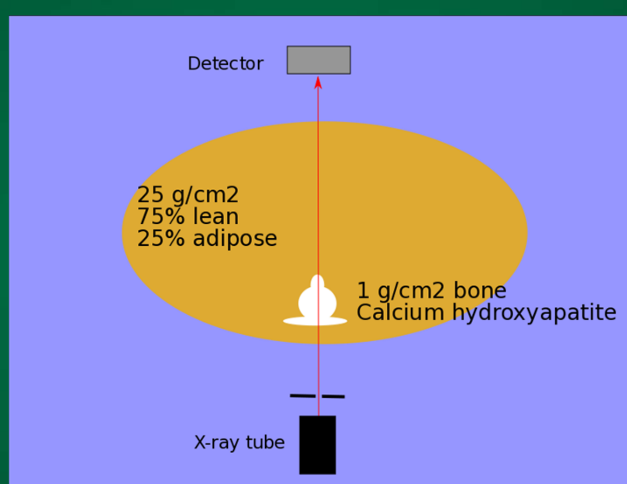
UAB MEDICINE
Knowledge that will change your world

Material Decomposition



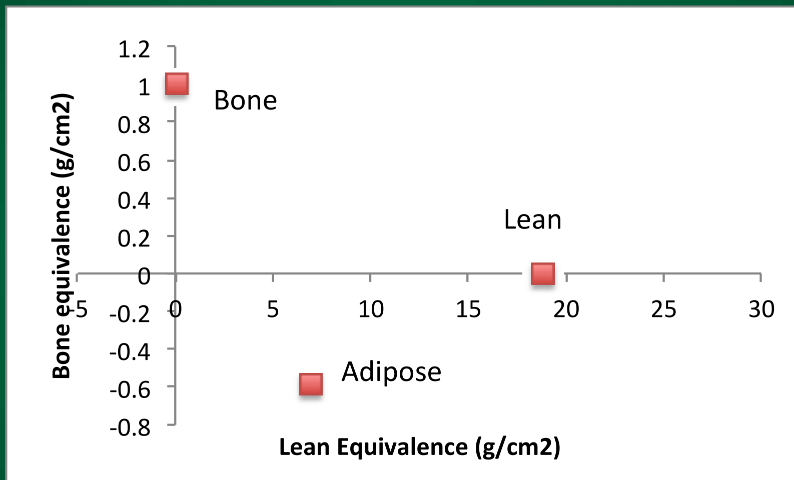
UAB MEDICINE
Knowledge that will change your world

Example



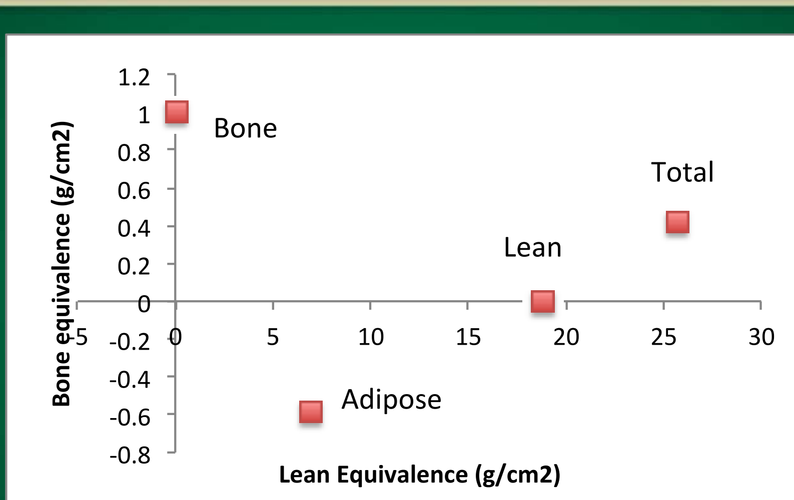
UAB MEDICINE
Knowledge that will change your world

Example



UAB MEDICINE
Knowledge that will change your world

Example



UAB MEDICINE
Knowledge that will change your world

Fat content correction

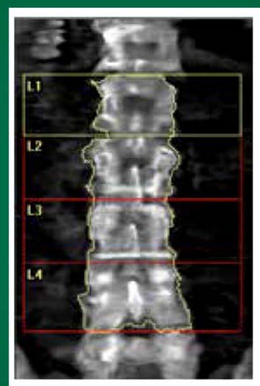
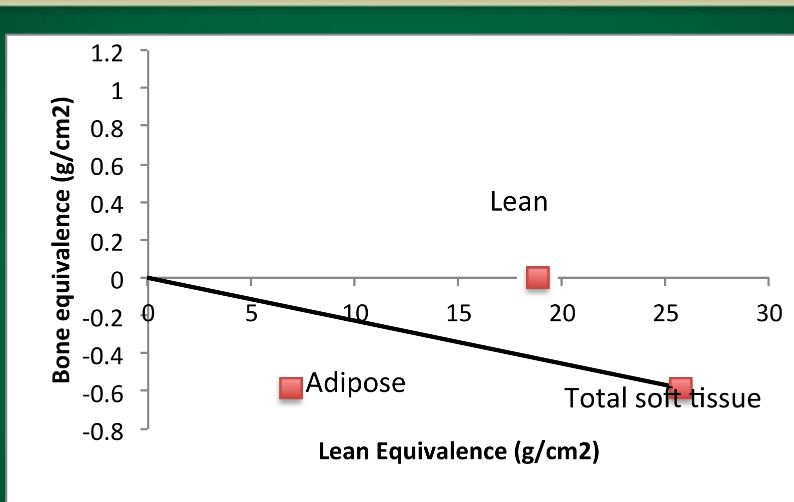


Image courtesy Hologic Corporation

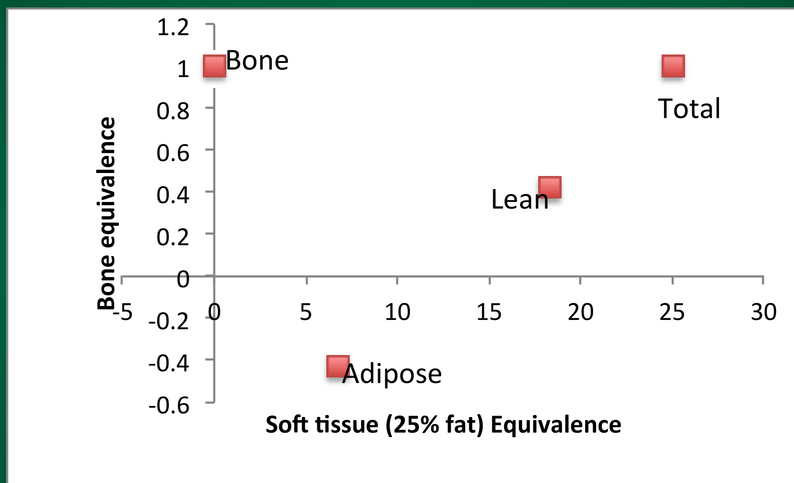
UAB MEDICINE
Knowledge that will change your world

Fat content correction



UAB MEDICINE
Knowledge that will change your world

Fat content estimation



UAB MEDICINE
Knowledge that will change your world

Dual Energy X-ray Absorptiometry

Science
Technology
Practice

UAB MEDICINE
Knowledge that will change your world

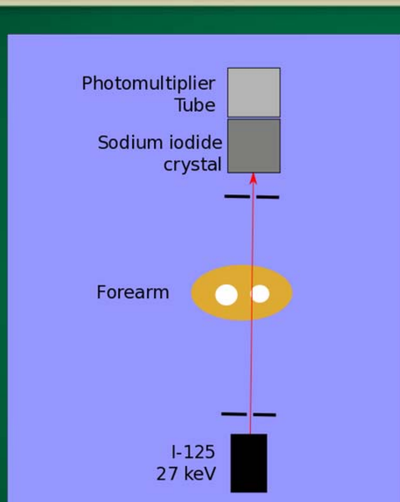
Technologies - History

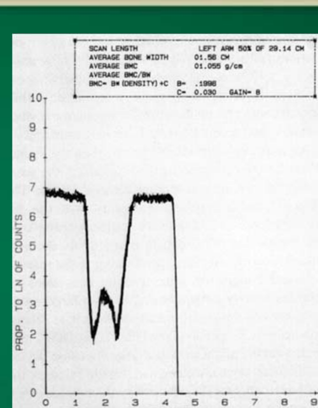
- Single Photon Absorptiometry
  - 1963 – Cameron and Sorenson
- Dual Photon Absorptiometry
  - ~1970, Cameron, Mazess, et al
- Dual X-Ray Absorptiometry
  - ~1980s (?); Stein, Mazess, et al

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

UAB MEDICINE
Knowledge that will change your world

Single Photon Absorptiometry



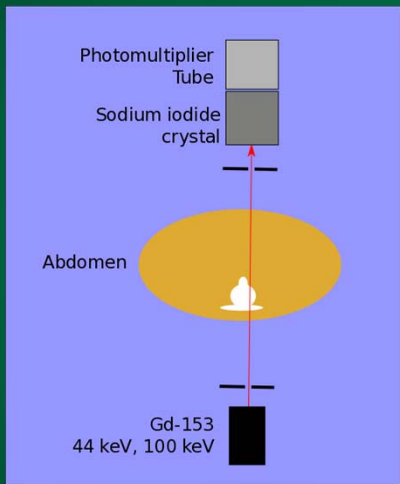


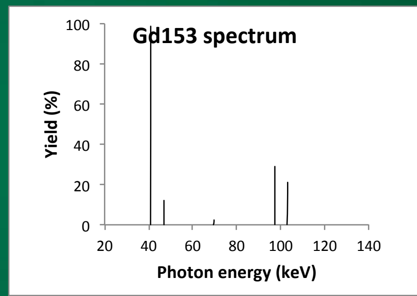
LM Thorson, HW Wahner, "Single and Dual Photon Aborptiometry...", J Med Vol 14, Sept 1986, pp163-171

Courtesy of Society of Nuclear Medicine and Molecular imaging.

UAB MEDICINE
Knowledge that will change your world

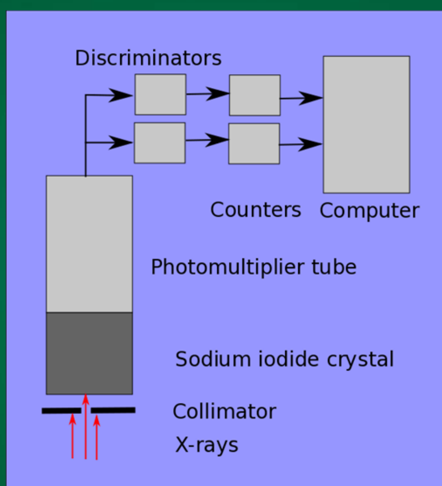
Dual Photon Absorptiometry





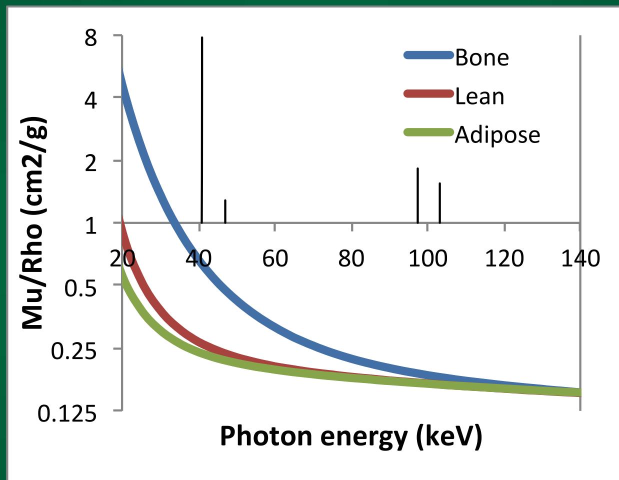
UAB MEDICINE
Knowledge that will change your world

Detector



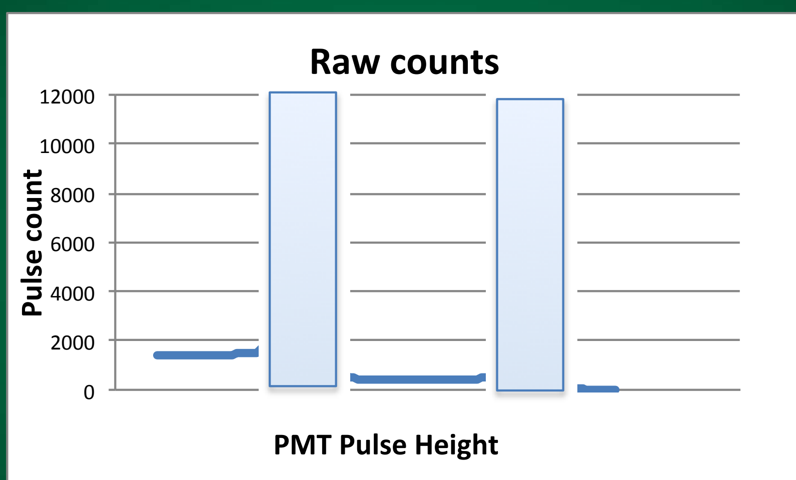
UAB MEDICINE
Knowledge that will change your world

Dual Photon Absorptiometry



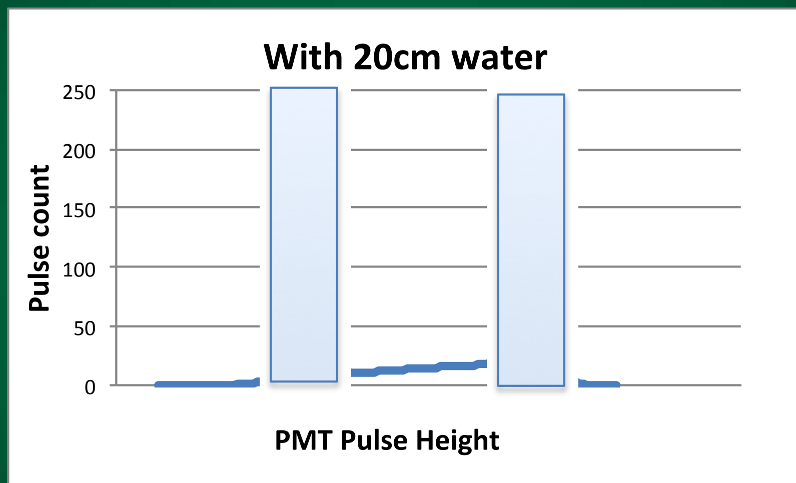
UAB MEDICINE
Knowledge that will change your world

Pulse height spectrum



UAB MEDICINE
Knowledge that will change your world

Pulse height spectrum



UAB MEDICINE
Knowledge that will change your world

Raster scan

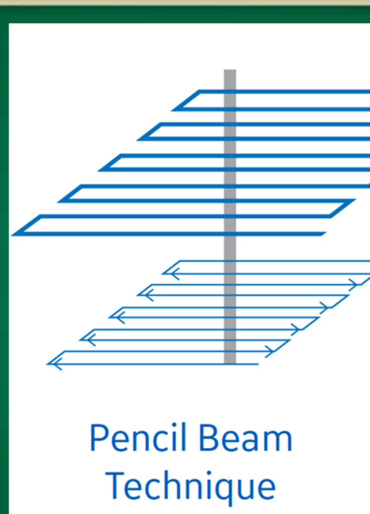


Image courtesy
GE Healthcare

UAB MEDICINE
Knowledge that will change your world

DXA Technologies

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

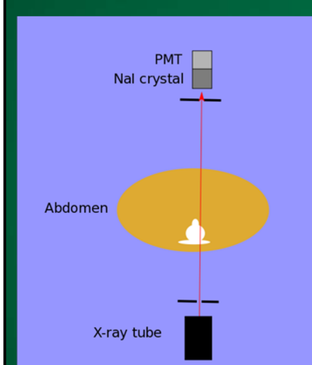
Beam geometry
- Pencil beam (1st generation)
- Partial fan beam
- Fan beam
- ~~Cone Beam~~

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

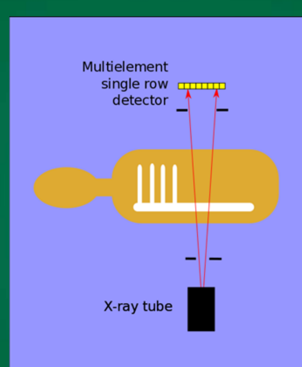
Energy integrating detectors
- Scintillator/photodiode array (Hologic)
- ~~Sandwich detector~~

UAB MEDICINE
Knowledge that will change your world

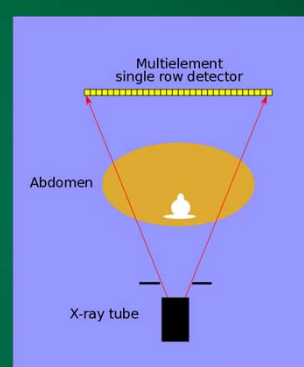
Beam geometries



Pencil beam



Narrow fan beam



Wide fan beam

UAB MEDICINE
Knowledge that will change your world

Beam Geometries

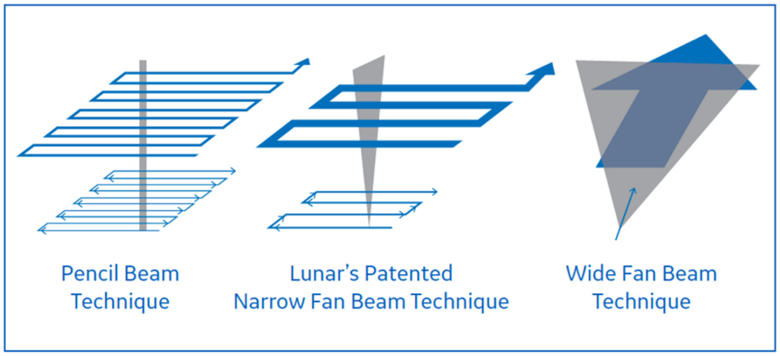


Image courtesy GE Healthcare

UAB MEDICINE
Knowledge that will change your world

X-ray source technologies

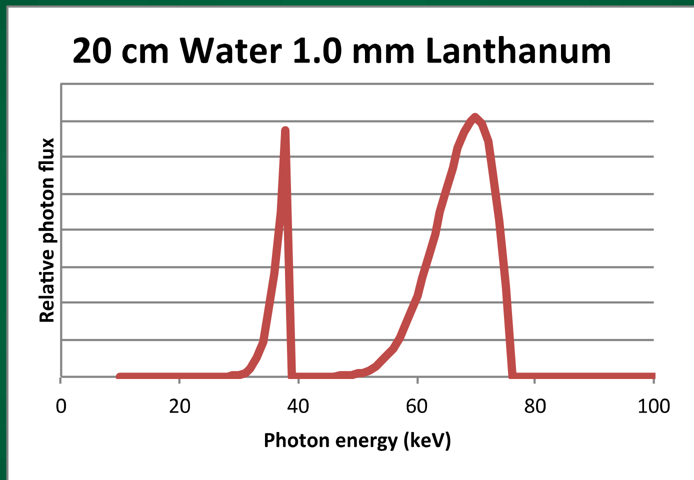
Characteristic	GE/Lunar	Hologic
Tube voltage	76 kV	60kV, 120kV or 100kV, 140kV
Filtration	K-edge	Spinning filter wheel*

* Six sector wheel with the following filter combinations

- Air
- Bone equivalent
- Soft tissue equivalent
- Copper
- Copper + bone
- Soft tissue + bone

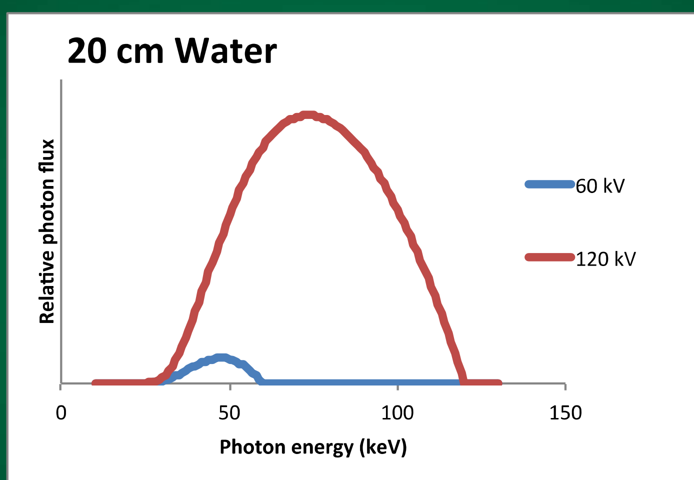
UAB MEDICINE
Knowledge that will change your world

K-edge filtration



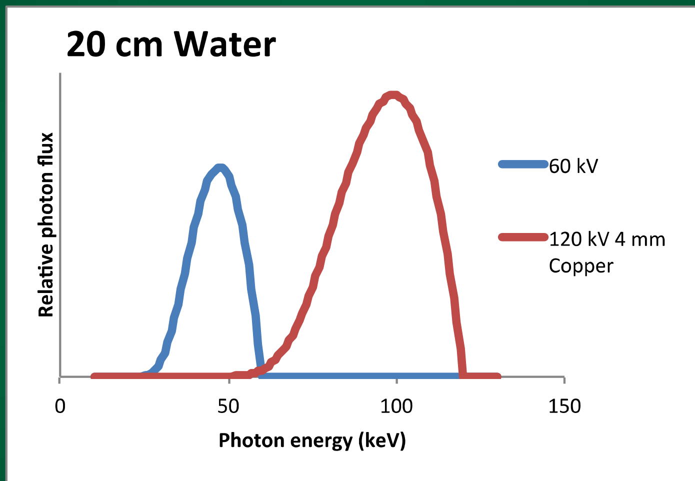
UAB MEDICINE
Knowledge that will change your world

kV switching



UAB MEDICINE
Knowledge that will change your world

kV switching

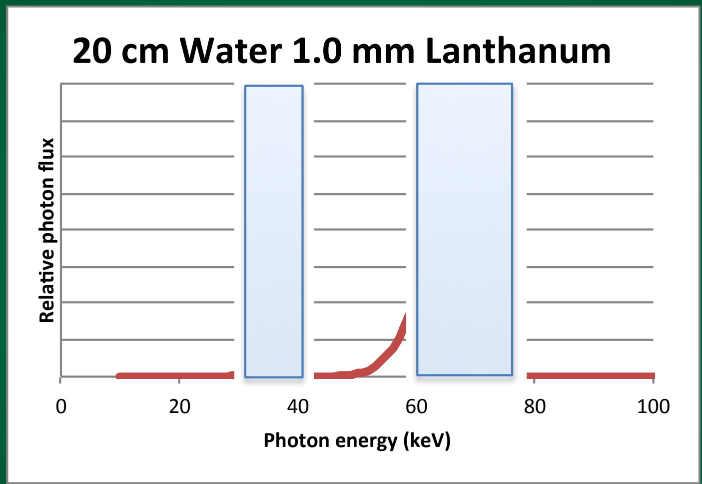


Detector technologies

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

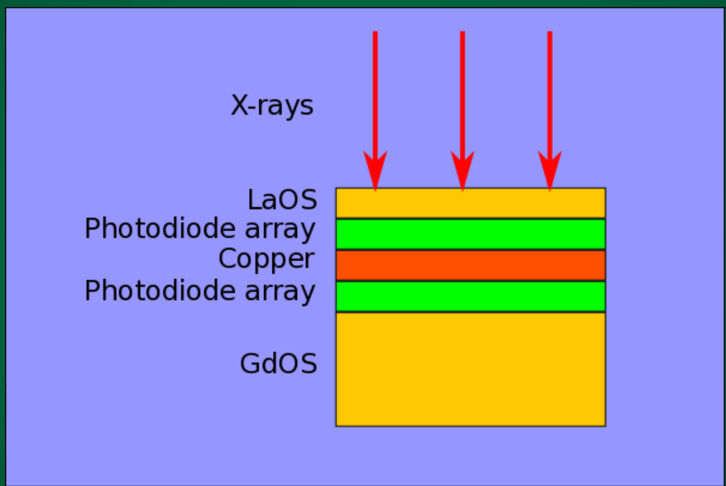
Energy integrating
- Ceramic detectors with photodiode array (Hologic)
- Sandwich detector (obsolete)

K-edge filtration



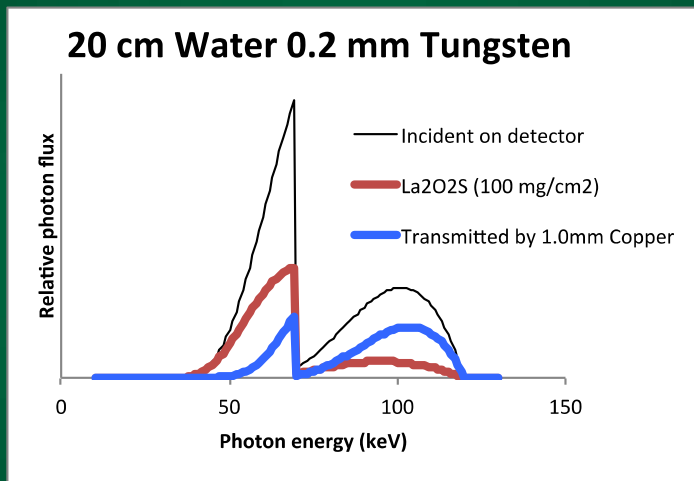
UAB MEDICINE
Knowledge that will change your world

Sandwich detectors



UAB MEDICINE
Knowledge that will change your world

Sandwich detectors



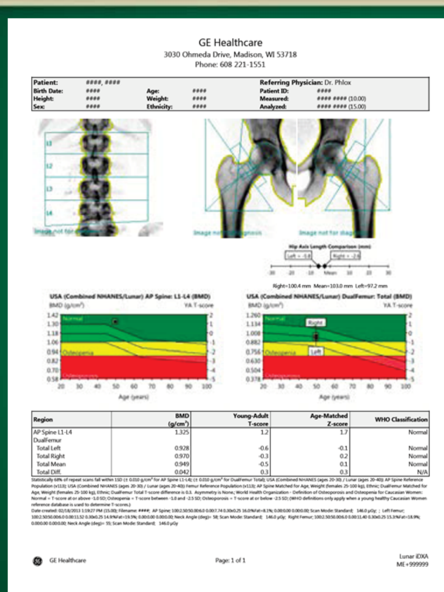
UAB MEDICINE
Knowledge that will change your world

Dual Energy X-ray Absorptiometry

Science
Technology
Practice

UAB MEDICINE
Knowledge that will change your world

Clinical report


GE Healthcare
3030 Ohmeda Drive, Madison, WI 53718
Phone: 608 221-1551

Patient:	####, ####			Referring Physician:	Dr. Phlox
Birth Date:	####	Age:	####	Patient ID:	####
Height:	####	Weight:	####	Measured:	#### #### (10.00)
Sex:	####	Ethnicity:	####	Analyzed:	#### #### (15.00)

Region	BMD (g/cm²)	Young-Adult T-score	Age-Matched Z-score	WHO Classification
AP Spine L1-L4	1.325	1.2	1.7	Normal
DualFemur				
Total Left	0.928	-0.6	-0.1	Normal
Total Right	0.970	-0.3	0.2	Normal
Total Mean	0.949	-0.5	0.1	Normal
Total Diff.	0.042	0.3	0.3	N/A

GE Healthcare Page: 1 of 1 Lunar iDXA ME+999999

$$T = \frac{BMD - BMD_{ref}}{\sigma_{BMD}}$$

BMD_{ref} is the average for young healthy adults

$$Z = \frac{BMD - BMD_{ref}}{\sigma_{BMD}}$$

BMD_{ref} is the average for adults of the same age and sex

Image courtesy GE Healthcare

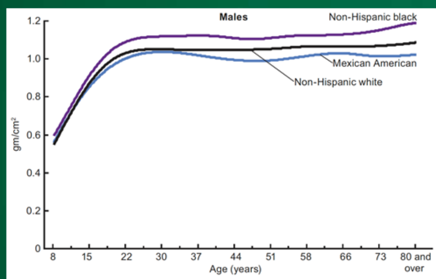
UAB MEDICINE
Knowledge that will change your world

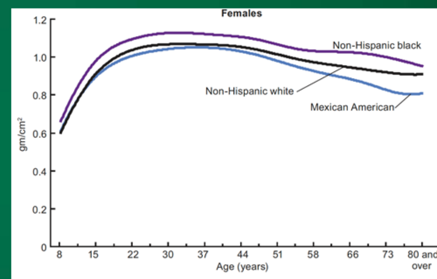
Diagnosis

T-Score	WHO Category
-1 or higher	Normal
-2.5 to -1.5	Osteopenia
-2.5 or lower	Osteoporosis

UAB MEDICINE
Knowledge that will change your world

Lumbar spine BMD



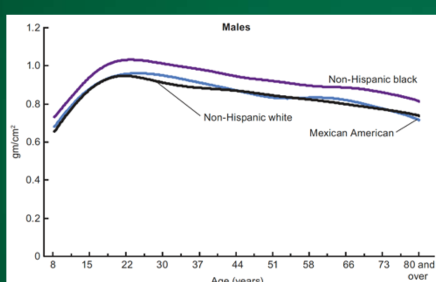


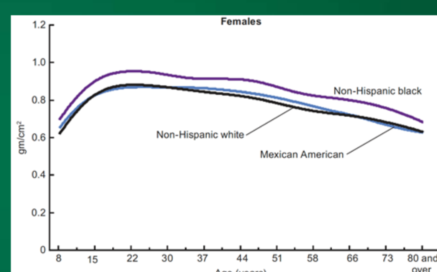
Lumbar Spine and Proximal Femur Bone Mineral Density, Bone Mineral Content, and Bone Area: United States, 2005-2008

https://www.cdc.gov/nchs/data/series/sr_11/sr11_251.pdf

UAB MEDICINE
Knowledge that will change your world

Femoral neck BMD





Lumbar Spine and Proximal Femur Bone Mineral Density, Bone Mineral Content, and Bone Area: United States, 2005-2008

https://www.cdc.gov/nchs/data/series/sr_11/sr11_251.pdf

UAB MEDICINE
Knowledge that will change your world

Accuracy

Parameter	Value
Absolute accuracy	+/- 10%
Inter-model variation	+/- 15%
Inter-unit variation	+/- 2%

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

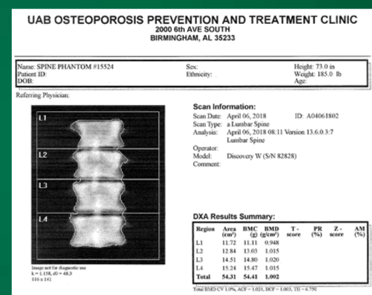
UAB MEDICINE
Knowledge that will change your world

Therapy response

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

UAB MEDICINE
Knowledge that will change your world

Scanner QA



UAB OSTEOPOROSIS PREVENTION AND TREATMENT CLINIC
2000 6th AVE SOUTH
BIRMINGHAM, AL 35233

Name: SPINE PHANTOM #15524	Sex:	Height: 73.0 in
Patient ID:	Ethnicity:	Weight: 185.0 lb
DOB:		Age:

Referring Physician:

Scan Information:
Scan Date: April 06, 2018 ID: A04061802
Scan Type: a Lumbar Spine
Analysis: April 06, 2018 08:11 Version 13.6.0.3:7
Lumbar Spine
Operator:
Model: Discovery W (S/N 82828)
Comment:

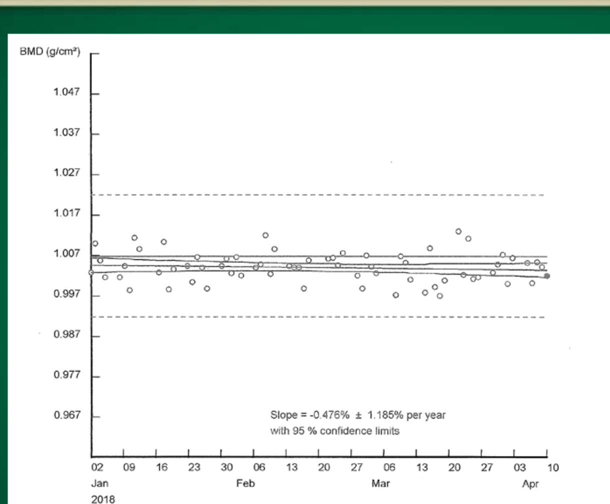
DXA Results Summary:

Region	Area (cm^2)	BMC (g)	BMD (g/cm^2)	T - score	PR (%)	Z - score	AM (%)
L1	11.72	11.11	0.948				
L2	12.84	13.03	1.015				
L3	14.51	14.80	1.020				
L4	15.24	15.47	1.015				
Total	**54.31**	**54.41**	**1.002**				

Total BMD CV 1.0%, ACF = 1.021, BCF = 1.003, TH = 6.750

UAB MEDICINE
Knowledge that will change your world

Shewhart Chart



Avg + 2 Std. Dev.

Avg - 2 Std. Dev.

UAB MEDICINE
Knowledge that will change your world

Shewhart Rules

Machine failure if

- Single BMD outside average $\pm$ 3 standard deviation
- Two consecutive BMD on same side of average outside avg $\pm$ 2 S.D.
- Four consecutive BMD on same side of average outside avg $\pm$ 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)

D.Pearson, S.A.Cawte, "Long-term quality control of DXA: A comparison of shewhart rules and cusum charts", Osteoporois International, Vol 7 (4), pp 338-343 (1997)

Technologist Precision

Least Significant Change (LSC)
95% confidence interval

$$LSC \equiv 2.77\ \sigma_{invivo}$$

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

Site	Coefficient of variation	Least significant change
Lumbar spine	1.0-1.2%	~3%
Total hip	0.8-1.7%	~3.5%
Femoral neck	1.1-2.2%	~4.5%
Trochanter	1.2-1.5%	~3.8%

UAB MEDICINE
Knowledge that will change your world

Therapy response

Parameter	Lumbar spine	Femoral neck
Baseline	0.850 g/cm^2	0.865 g/cm^2
2 years later	0.865 g/cm^2	0.858 g/cm^2
Difference	+0.015 g/cm^2	-0.007 g/cm^2
LSC for this technologist	0.027 g/cm^2	0.030 g/cm^2

UAB MEDICINE
Knowledge that will change your world

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.

UAB MEDICINE
Knowledge that will change your world

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

UAB MEDICINE
Knowledge that will change your world

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

UAB MEDICINE
Knowledge that will change your world

Acknowledgements

Jeff Frimeth

Hologic Inc. and affiliates

GE Healthcare

Society of Nuclear Medicine and Molecular Imaging

UAB Osteoporosis Clinic

UAB MEDICINE
Knowledge that will change your world