Bone as a Structural Material

Iwona Jasiuk
Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign
Contact: ijasiuk@illinois.edu

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Education

B.S. 1980; M.S. 1982 Univ. of Illinois at Chicago (Civil Engrg.)
Ph.D. 1986 Northwestern Univ. (Theor. & Applied Mechanics)

Research Interests

Mechanics of Materials

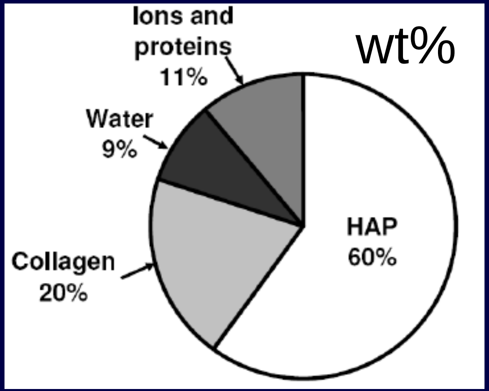
Phenomena:

- Multiscale Characterization and Modeling of Materials
- Structure-property relations in materials
- Interfaces (slipping, functionally graded …)
- Randomness in materials microstructure
- Size effects (micro vs. nano)
- Scale and boundary conditions effects

Context: Composite, nanocomposite, and biological materials
Applications: health, energy, transportation, defense, …

Bone: An Introduction

- Bone is a structural material with excellent mechanical properties; it is stiff, strong, tough and light

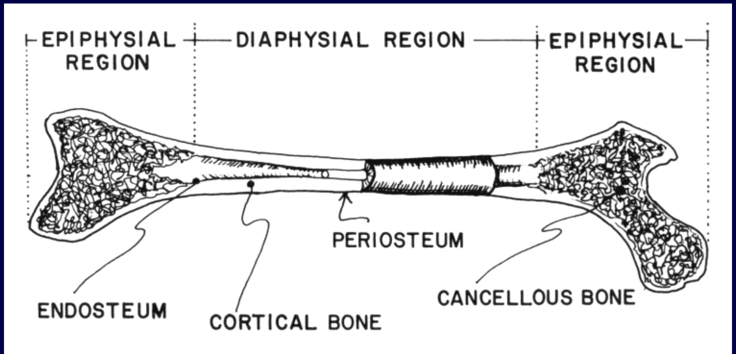


- Bone is a (nano)composite material
  - Collagen – soft and deformable
  - Minerals – stiff, strong, but brittle (nanoscale)
  - Non-collagenous proteins
  - Fluids

- Bone has a complex, hierarchical and heterogeneous structure at several different length scales

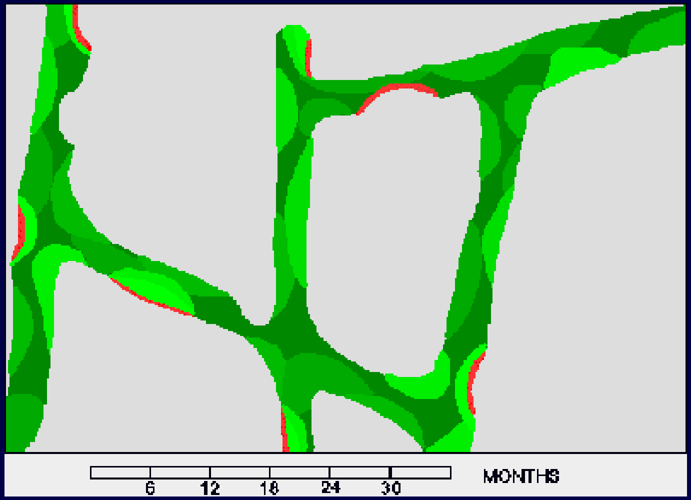
- Bone is a biological material: a living tissue with evolving structure (due to mechanical, biological & chemical factors)
  - age, diet, medications, hormones, exercise, disease

Long bone



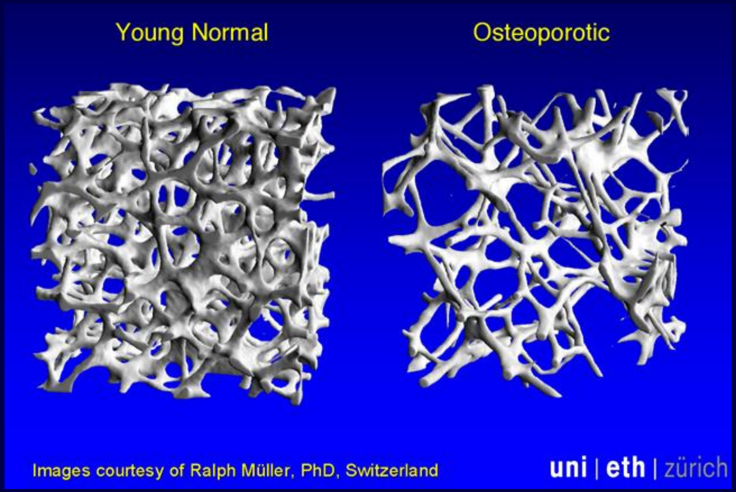
Bone is a living tissue

Normal bone



Osteoporotic bone

Susan Ott, University of Washingtonhttp://courses.washington.edu/bonephys/opmovies.html

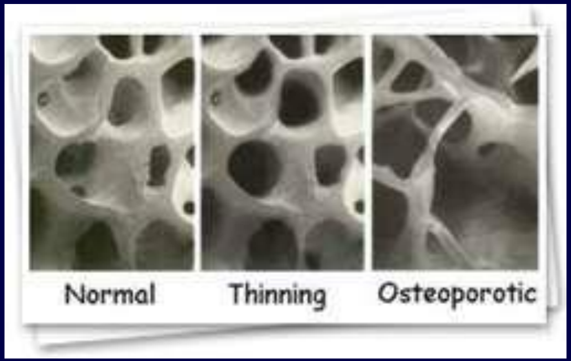


Research Objectives

- Determine multi-scale structure-composition-property relations for bone (orthopedics, biomimetics); methodology applies to other biological materials

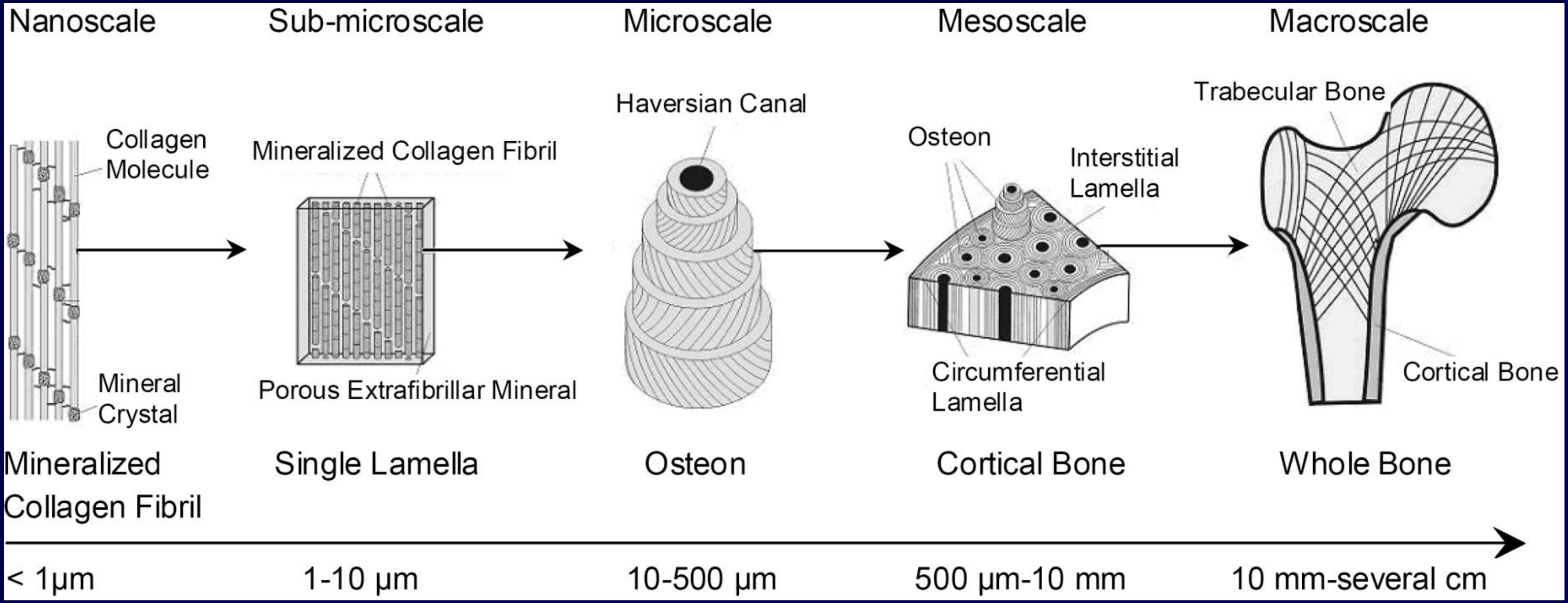
- Develop predictive tools for assessing bone quality
(healthy, diseased, developing, aging, effect of medications, exercise, diet, and other factors)

- Develop non-invasive tools for early detection of osteoporosis
(disease characterized by bone fragility)



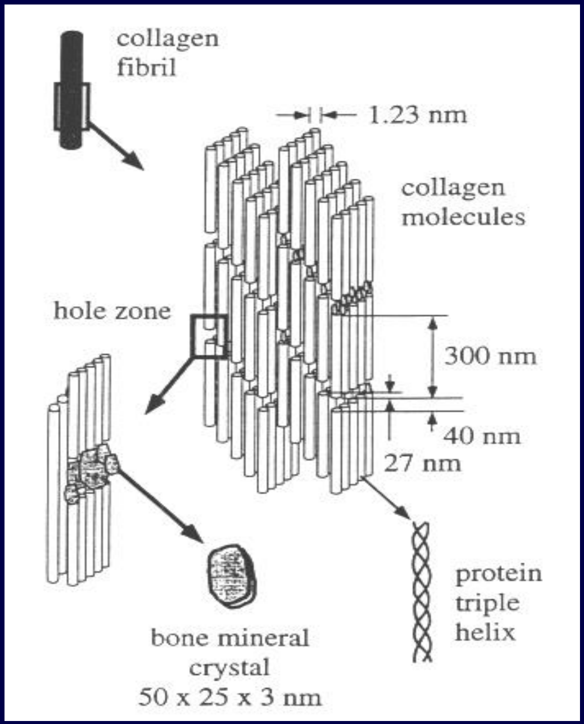
Hierarchical Structure of Cortical Bone

- Mesostructure **(0.5 – 10 cm) –** cortical bone
- Microstructure **(10 – 500 μm)** – single osteon
- Sub-microstructure **(1 – 10 μm) –** single lamella
- Nanostructure **(below 1 μm) –** collagen fibrils, apatite crystals



E. Hamed, Y. Lee and I. Jasiuk (2010) *Acta Mechanica*, **213**, 131.

Nanoscale – mineralized collagen fibrils



Rho *et al*. (1997)

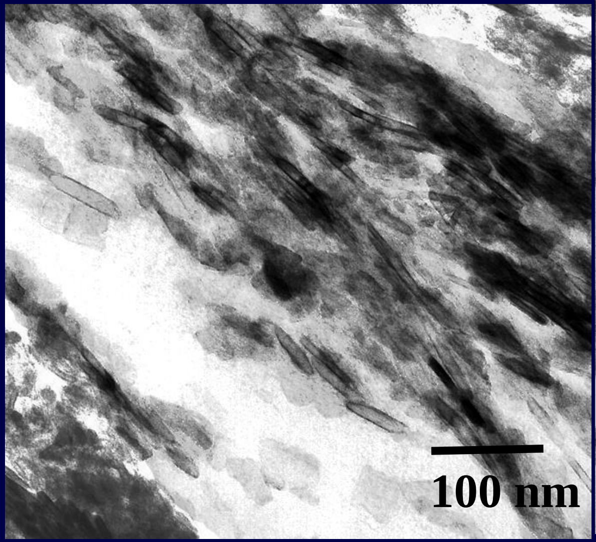
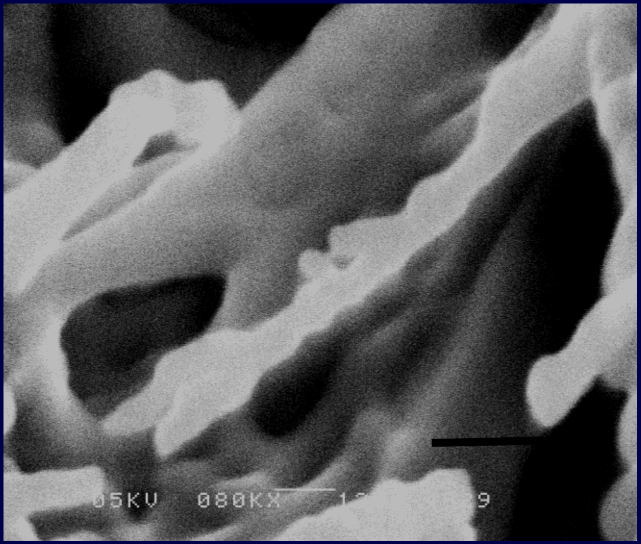


Plate-like HAP crystals



Collagen fibrils with HAP

Mineralized collagen fibrils (~ 100 nm in diameter) are building blocks of bone.

M. A. Rubin, I. Jasiuk, J. Taylor, J. Rubin, T. Ganey, R. Apkarian (2003), *Bone*, **33**, 270.

E. Hamed and I. Jasiuk (2012), *Materials Science and Engineering R* **73**(3-4), 27-49.

Characterization of Cortical Bone

(focus on age related changes, bone development)

SEM: Scanning Electron Microscopy

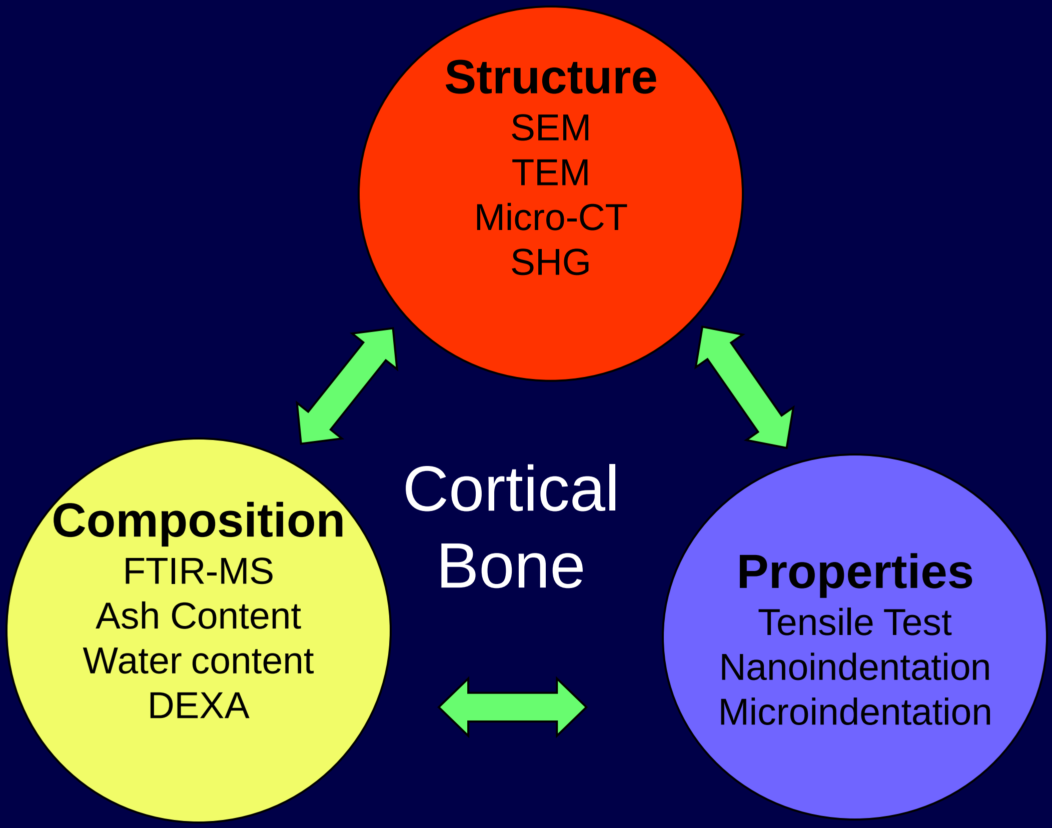
Micro-CT: Micro Computed Tomography

TEM: Transmission Electron Microscopy

FTIR-MS: Fourier Transform Infrared Microspectroscopy

DEXA: Dual-Energy X-ray Absorptiometry

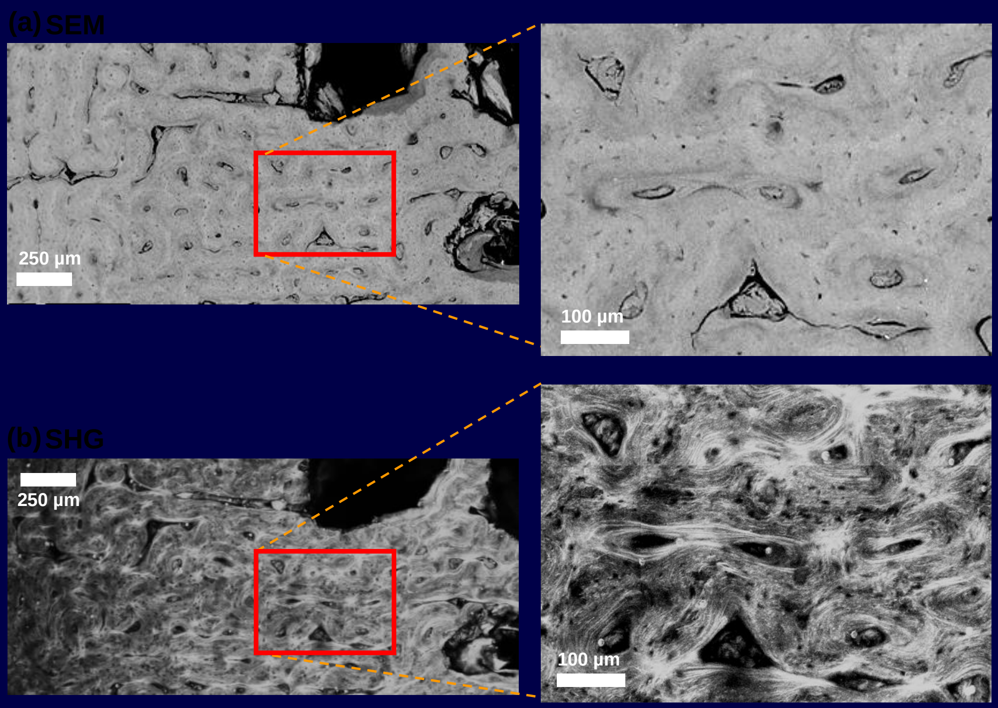
SHG: Second Harmonic Generation microscopy



Swine femurs (three age groups)
- 0, 1, 3 months (young)
- 6, 12, 18, 30, 42 months (developing)

Second Harmonic Generation (SHG) Microscopy

- SHG is well suited to characterize collagen fibril orientations.
- Provides high contrast due to high specificity to collagen fibrils.



Scanning Electron Microscopy (SEM) image of cortical bone

SHG image of the same region of cortical bone, collagen fibrils orientations are more visible.

R. Ambekar, M. Chittenden, I. Jasiuk, and K.C. Touissant (2012) *Bone* **50**, 643-650

Chemical Composition-FTIR-MS Imaging

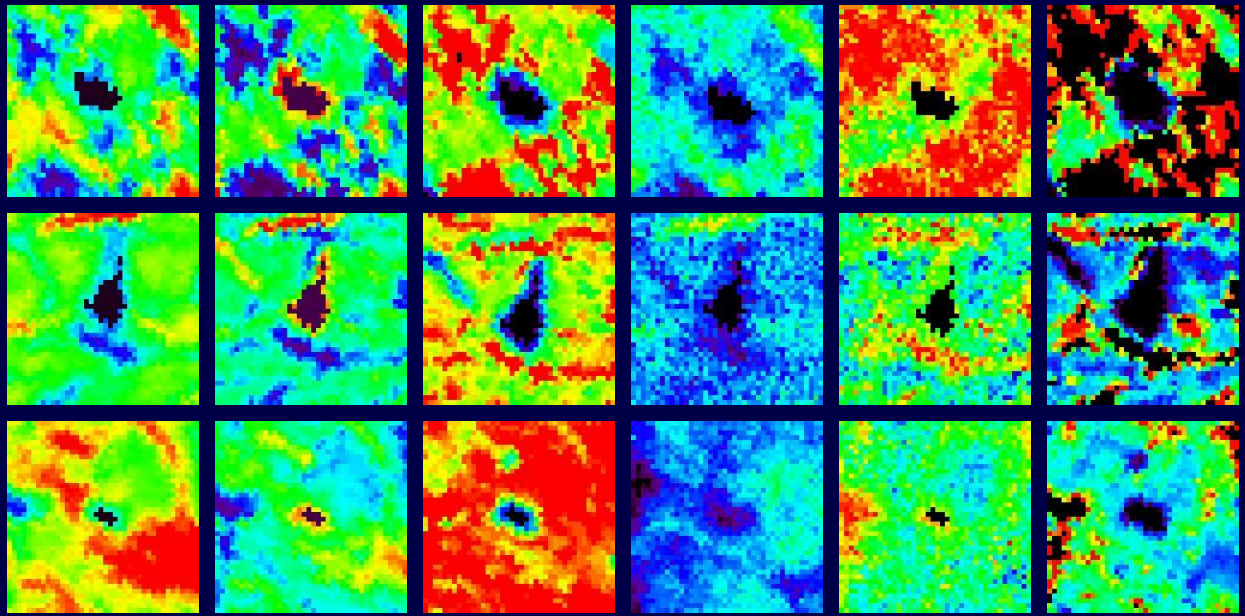
In collaboration with R. Bhargava

M O M:O C Cr CC

6 months

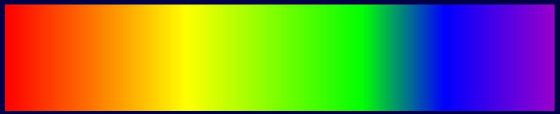
12 months

42 months



M: Mineral; O: Organic; M:O Mineral: Organic ratio C: Carbonate Cr: Crystallinity

CC: Nonreducible: reducible collagen crosslink ratio



- Mineral content increases with age
- Mineral: organic ratio increases as bone matures

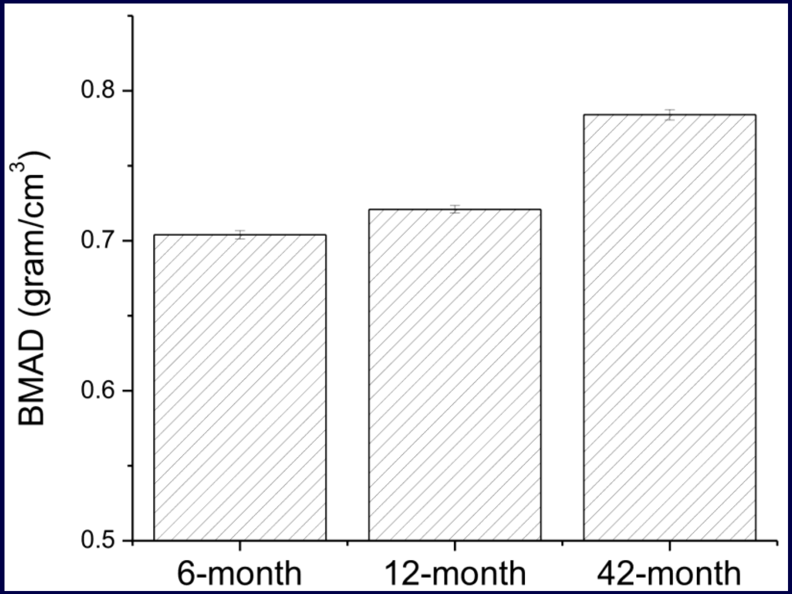
L. Feng, I. Jasiuk (2010), *Journal of Biomechanics*, **44**, 313-320.

Chemical Composition

DEXA: Dual-Energy X-ray Absorptiometry

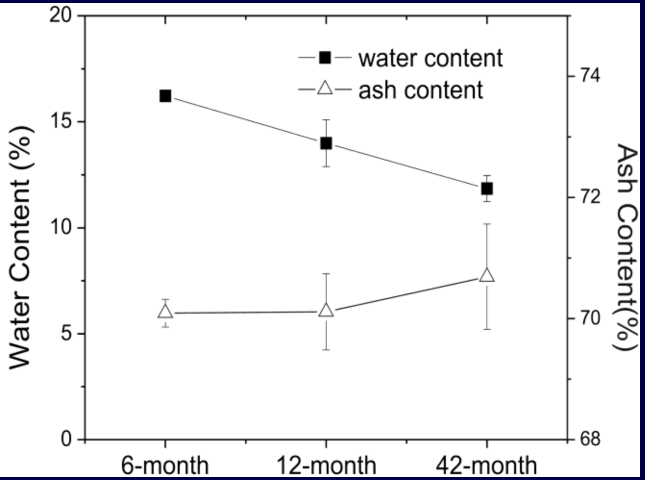
Hologic QDR 4500 Elite Bone Densometer

BMAD – bone mineral apparent density



- BMAD increases as bone develops

Water & Ash content



$$Moisture\% = \frac{W_{wet} - W_{dry}}{W_{wet}} \times 100\%$$

$$Ash\ contents\% = \frac{W_{dry} - W_{ashed}}{W_{ashed}} \times 100\%$$

As bone matures:

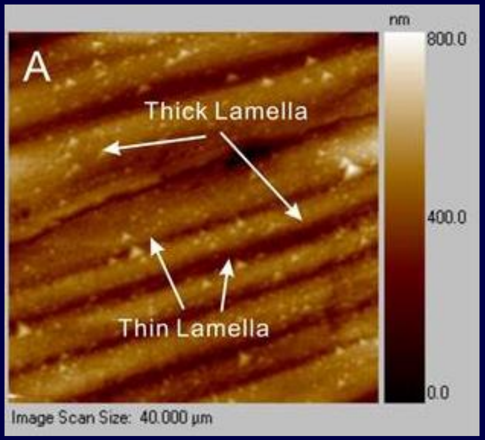
- Water content decreases
- Mineral content increases

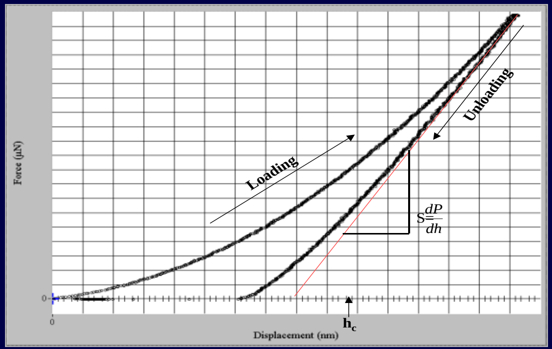
L. Feng, I. Jasiuk (2010), *Journal of Biomechanics*, **44**, 313-320.

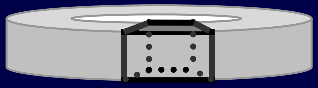
Mechanical Properties-Nanoindentation

- TI 900 TriboIndenter (Hysitron)
- Diamond fluid cell Berkovich

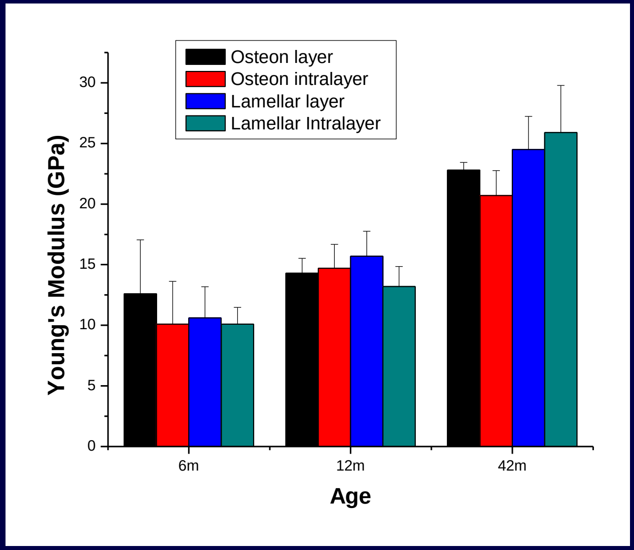
$$\frac{1}{E_r} = \frac{\left(1-\nu_i^{\,2}\right)}{E_i} + \frac{\left(1-\nu_s^{\,2}\right)}{E_s}$$







Transverse specimen



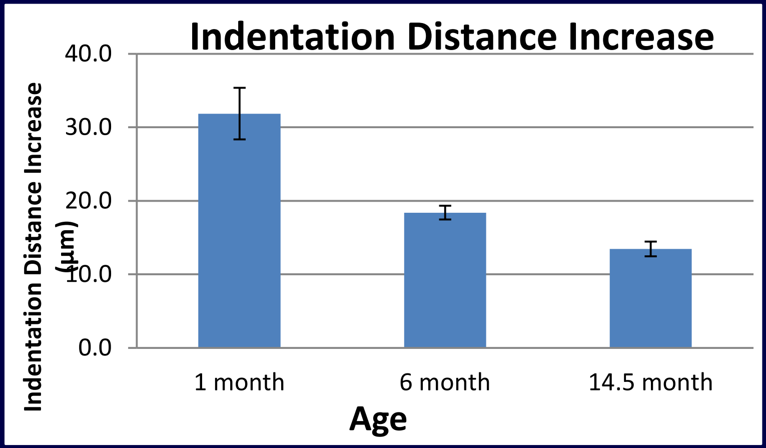
- Elastic moduli and hardnesses increase as bone matures

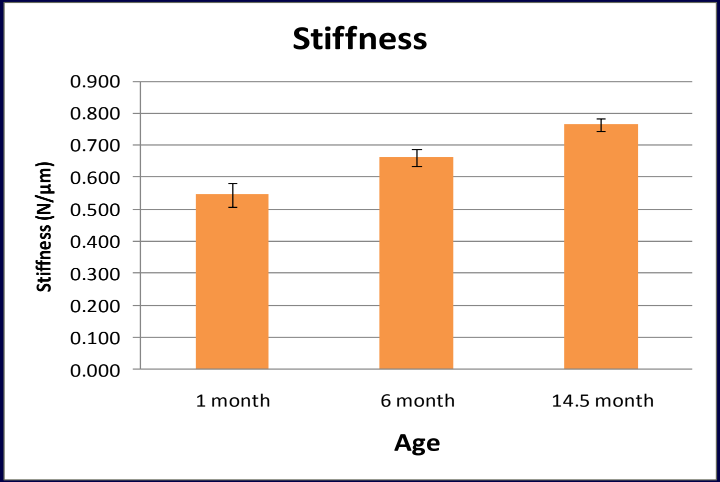
L. Feng, I. Jasiuk (2010), *J. Biomechanics*, **44**, 313-320.
L. Feng, M. Chittenden, J. Schirer, M. Dickinson, I. Jasiuk (2012), *J. Biomechanics* **45** (10), 1775-1782.

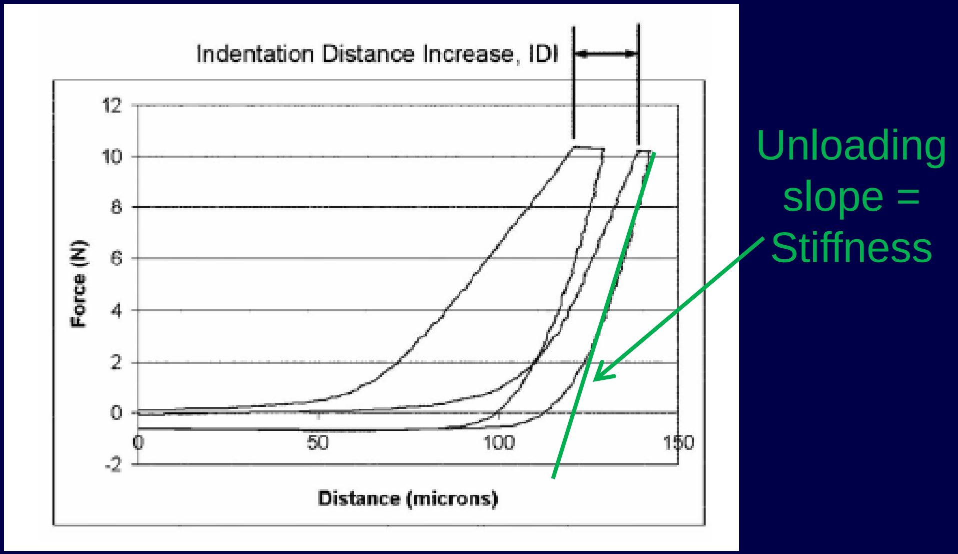
Mechanical Properties: Microindentation

Reference Point Indentation

BioDent microindenter
Active Life Scientific, Inc.







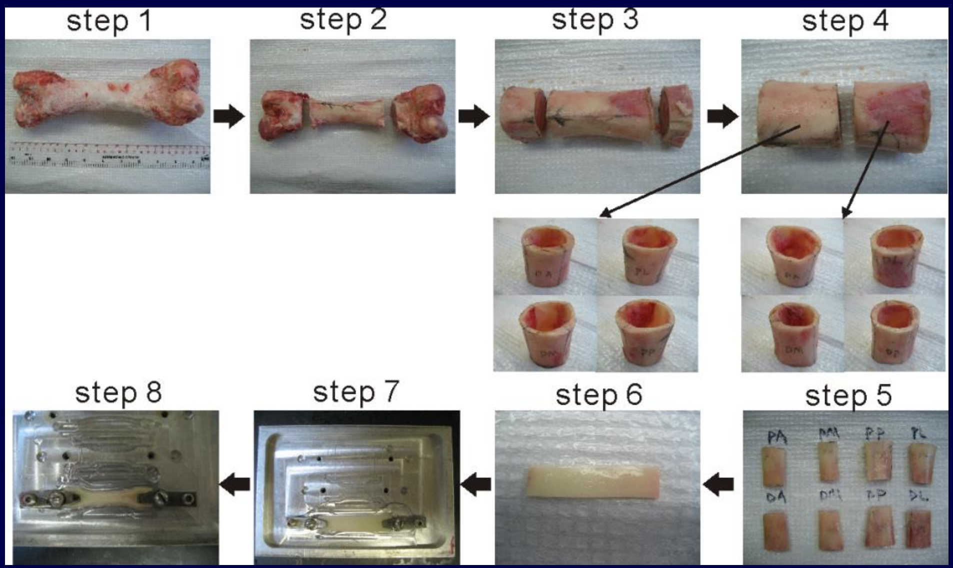
Load vs. distance

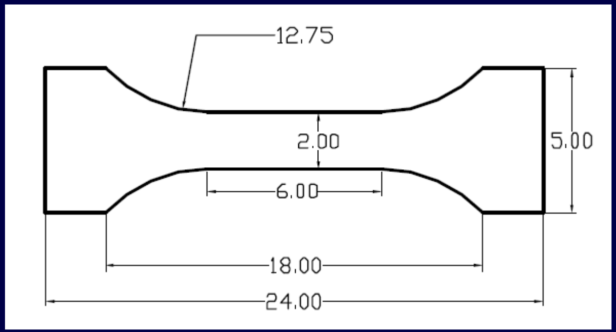
- Indentation distance is directly correlated with fracture resistance.
- Technique can be used in vivo

- The protocol includes 20 indents per location
- Only 2 are shown on the figure above

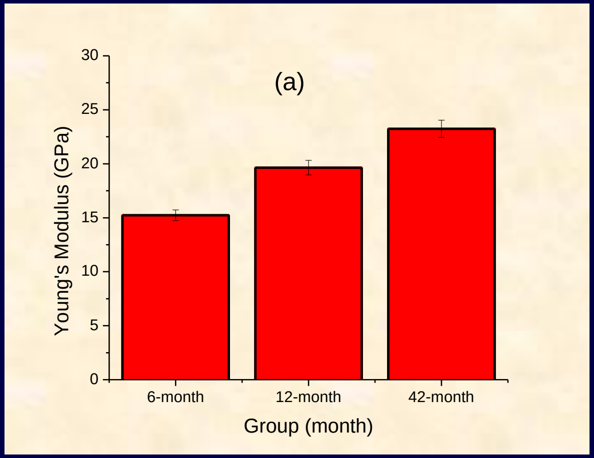
R. Rasoulian, A. Raeisi Najafi, M. Chittenden, and I. Jasiuk (2013), *J. Biomechanics* **46**, 1689-1696.

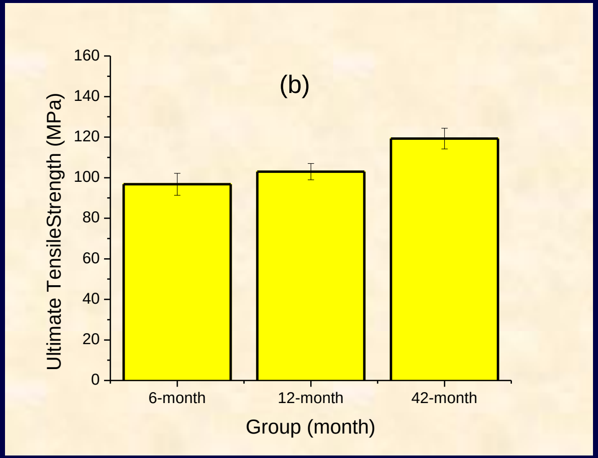
Mechanical Properties - Tensile Testing





MTS Insight 2
0.1mm/mm/min strain rate





Elastic modulus and ultimate tensile strength increase as bone matures

L. Feng and I. Jasiuk (2010) *J. Biomedical Materials Research*, **95A**, 580-587.

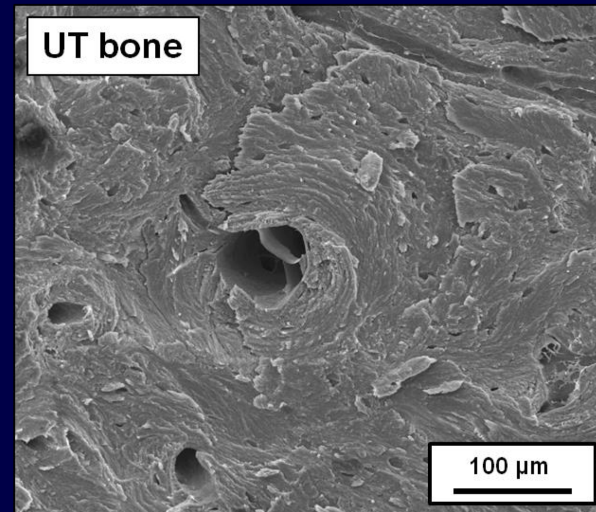
Demineralized and deproteinated bone

jointly with J. McKittrick, UCSD

Bovine cortical bone, 18 months

Self standing structures!

Earlier models assumed minerals as inclusions

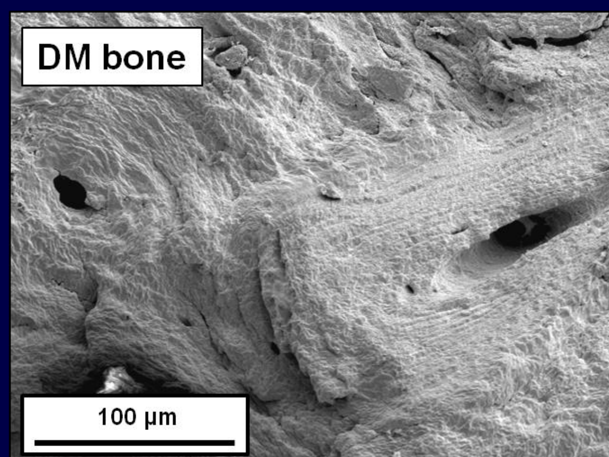


SEM Images

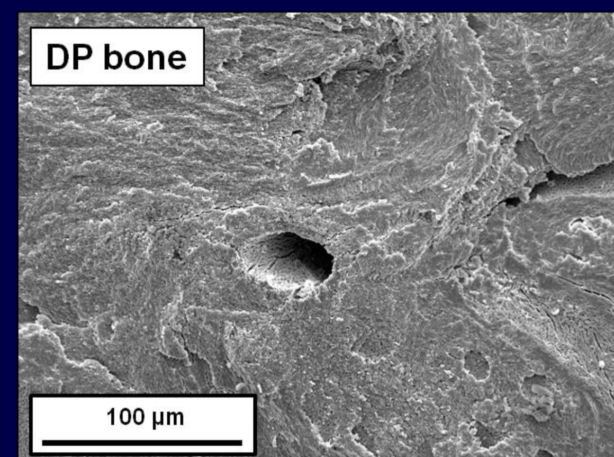
Untreated bone

(a)

- Experiments and modeling
- Validation of computational models



Proteins only



Minerals only

E. Hamed, E., E. Novitskaya, J. Li, P.-Y. Chen, I. Jasiuk, and J. McKittrick (2012) *Acta Biomaterialia*, **8**, 1080-1092.

Multiscale Modeling of Cortical Bone

Bone is a natural composite material

(polymer matrix nanocomposite with a hierarchical structure)

- Nanostructure
  - Collagen fibrils, apatite crystals, water and other proteins
- Sub-microstructure
  - Fibrous network: Mineralized collagen fibrils and pores
- Microstructure
  - Laminated composite: Lamellae at different orientations
- Mesostructure
  - Cortical bone: collection of osteons, resorption cavities, interstitial bone, laminar bone

=> Experimentally-based Prediction of Elastic Moduli

E. Hamed, Y. Lee and I. Jasiuk (2010), *Acta Mechanica*, **213**, 131-154.

Conclusions

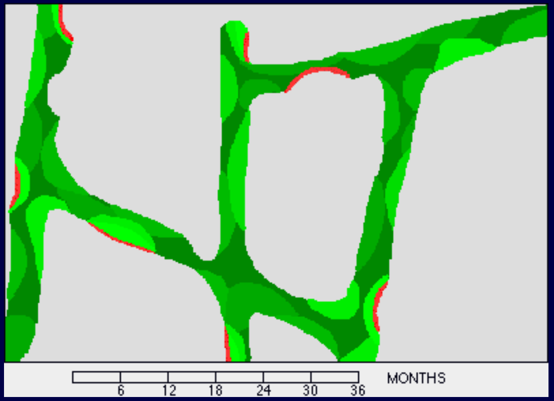
- We characterized hierarchical structure of cortical bone
- We obtained experimentally-based multiscale model of bone
- Elastic moduli were predicted

Applications/Extensions

- Experimentally-based multi-scale modeling can be used as diagnostic tool to assess bone quality
- Need to characterize bone ultrastructure and/or mechanical properties in vivo, noninvasively => RPI holds promise!

Current status

- Osteoporosis is diagnosed by
  - DEXA (scalar value)
  - History of fractures
  - Personal data (genetic, lifestyle, diet)



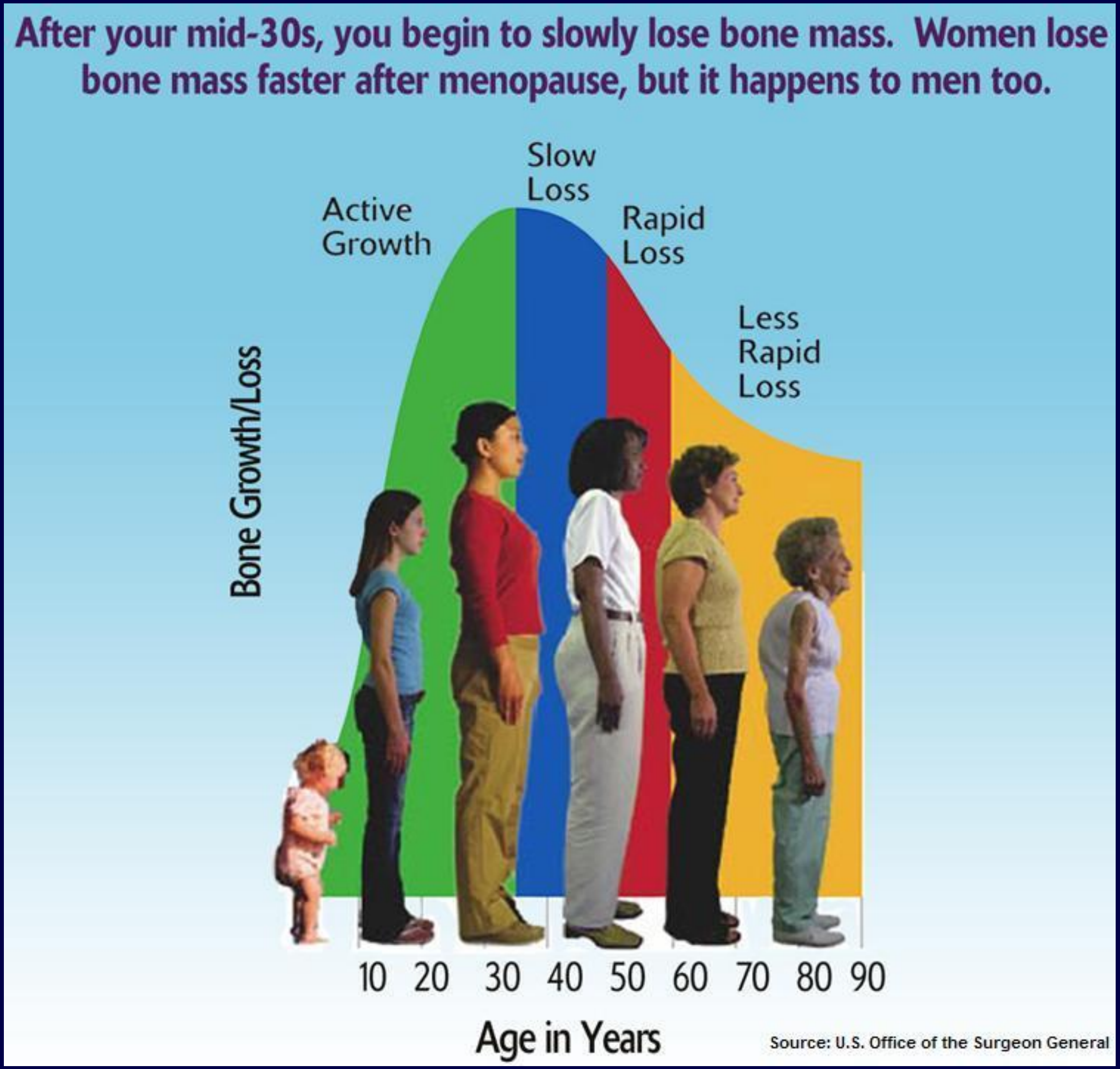
Susan Ott, U Washington: http://courses.washington.edu/bonephys/opmovies.html

Osteoporosis

- Disease (caused by abnormal bone metabolism)
  - Low bone mass
  - Microarchitectural deterioration of bone tissue
    - Consequent increase in bone fragility
    - Susceptibility to fracture
- Affects 44 million Americans
  - 10 million have disease
  - 34 million have low bone mass
- National direct expenditures for osteoporotic fractures
  - $17 billion (in 2001)
  - $47 million/day

http://www.osteo.org

Bone mass



- Age
- Gender
- Race
- Hormonal factors
- Nutritional status
- Physical activity

How can you help keep your bones healthy?

Proper nutrition and plenty of physical activity.

- Eating for healthy bones means getting plenty of foods rich in calcium and vitamin D.
- Magnesium, boron, calcium, copper, manganese, and strontium are all minerals that help strengthen bones.
- Vitamins C, D, K2, B1, B2, B3, B6, and B12 are also needed for optimal bone health

Non-dairy sources of calcium

- Whole grain products
- Green vegetables: broccoli, kale, cabbage, bok choy
- Dark leafy greens: collards, spinach, beet greens
- Rhubarb
- Canned fish (with bones)
- Beans, legumes
- Okra
- Nuts
- Seeds
- Mineral water

Kale seeds

nuts beans

Bone building exercises
(weight bearing exercises)

- walking
- tennis
- running
- volleyball
- hiking
- ice hockey
- field hockey
- dancing
- skiing
- soccer
- skateboarding
- gymnastics
- in-line skating
- basketball
- weight lifting
- jumping rope
- aerobics

Behaviors bad for bones

- Prolonged inactivity or immobility
- Inadequate nutrition (especially deficient in calcium, vitamin D, vitamin K, magnesium)
- Tobacco smoking
- Alcohol abuse

Bad foods

- Too much protein
- Caffeine
- Salt
- Carbonated drinks (phosphoric acid)

Bone loss in space

Astronauts loose (per month):

- 2% of bone mass
- 5% of bone strength

Two major causes of bone loss:

- microgravity
- radiation

Durations of space trips:

- 12 month stay on space station
- 6 month trip to moon
- 30 month trip to mars

Bone loss in space

Astronauts exercise 2 hours a day in space to slow down bone loss

Dual Energy X ray Absorptiometry - Bone Mineral Densitometry

- DXA, or formerly DEXA
- Technique used to measure bone mineral density (BMD)
- Preferred regions for BMD measurement:
  - lumbar spine
  - proximal femur
  - whole body.

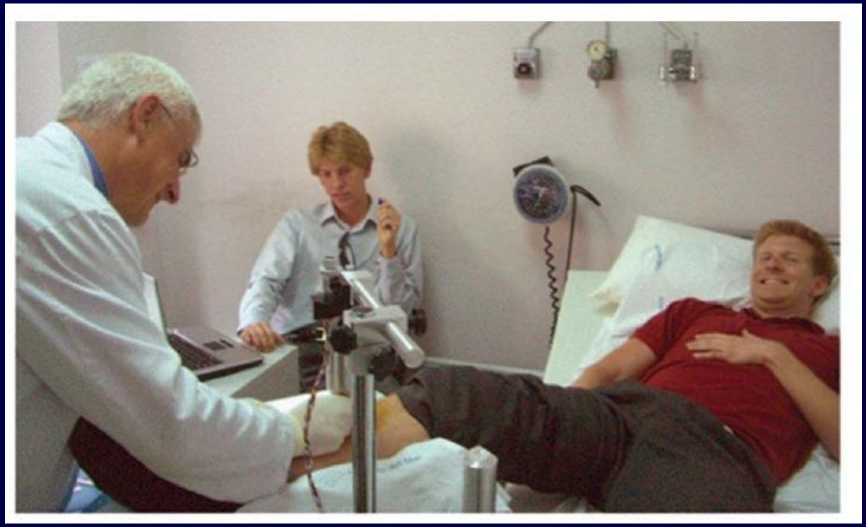
DXA scanner

Severe osteoporosis:
T-score less than -2.5
1+ osteoporotic fractures

Proximal femur

Reference Point Indentation (RPI)

- RPI is a novel microindentation technique which can provide insights into material properties of bone
- It can potentially be used *in vivo* to assess bone properties of living patients
- Currently research is conducted to understand the outputs of this technique.



http://www.activelifescientific.com/

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Materials Research Laboratory

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