Osteoporosis and Age-Related Changes in Bone

BME 7210

Bone Pathologies

- Diseases can affect:
  - Bone mineralization
    - Over or under mineralization will reduce strength
  - Collagen organization
    - Unorganized collagen matrix will reduce strength
  - Bone mass and structure
- Most common is osteoporosis

Osteoporosis

- Reduction in bone mass that results in increased risk of fracture
  - Loss of bone -- osteopenia
- All individuals lose bone after approximately 35 years of age
  - What makes one individual more susceptible to fracture?

Osteoporosis

- Generally thought to be due to a mismatch in osteoclast (resorption) and osteoblast (formation) activity
  - More bone is removed than is replaced

Osteoporosis

- The ultimate question:
  - What changes in the bone make it more susceptible to fracture?

Whole Bone Strength

- The ability of a whole bone to withstand a given load without fracturing is a function of:
  - Bone material properties
    - Strength
    - Energy absorption
    - Ultimate strain
  - Bone geometry
    - Thickness of cortical bone
    - Distribution of bone
    - Cross-sectional area and shape

Bone Material

- For this discussion, bone material means:
  - Trabecular tissue -- including effect of porosity and microarchitecture
  - Cortical tissue -- including effect of porosity, collagen orientation, and osteonal type and arrangement

Bone Material Strength

- What material property changes will result in a reduction in material strength?

Whole Bone Strength

- Bone material properties will depend on microstructure
  - Porosity (cortical or trabecular)
  - Trabecular architecture
    - Thickness
    - Separation
    - Number (density)

Whole Bone Strength and Age

- Bone strength generally increases with age up to age 30
  - Increase in bone geometry and mineralization

Whole Bone Strength and Age

- Lumbar vertebral body load bearing capacity
  - Young: 1000 kg (9.8 kN)
  - Elderly: 80 - 150 kg (784 - 1470 N)
- How do properties that affect bone strength change with age and the additional affect of osteoporosis?
  - Combination of changing parameters results in probablility of fracture

Bone Material Strength and Age

- Strength and (elastic region) stiffness of trabecular and cortical material decreases with age
- Bone becomes more brittle
  - Less able to absorb energy
- Stiffness during plastic deformation phase increases

Bone Mass

- Peak bone mass
  - About 20 - 30% higher in men
  - Due to differences in overall bone geometry, not inherent material properties
- If individuals lose bone at the same rate, those with higher initial bone mass will have less risk of fracture

Bone Mass

- Reduction in bone strength with age is greater than can be explained through the loss of bone mass alone
- Evaluation of fracture risk as a function of bone mass (clinical measures of bone density) produces overlap between fracture and non-fracture groups
  - Not good for predicting an individual's risk

Mineral Content

- Overall mineral content is tightly regulated in healthy individuals
  - Higher mineralization results in stiffer, more brittle bones
- Remodeling results in local variations in mineral content
  - More remodeling results in lower overall density
  - Children have high remodeling, giving them more compliant and ductile bones

Trabecular Structure

- Thickness and number of horizontal trabeculae decreases steadily with age in the mid-section of a vertebrae (Mosekilde Fig. 5)
- Trabecular structure of the femoral neck and head varies in a predictable manner
  - Tensile and compressive bands of trabeculae are lost in a repeatable fashion
  - Used to stage osteoporosis

Trabecular Structure

- Normal age-related loss of trabecular bone reduces the number of beams or struts, but has minimal effect on the thickness of the remaining trabeculae
- In many regions, trabecular bone becomes more anisotropic with age
  - More pronounced in women

Trabecular Structure

- Thickness:
  - Young
    - Vertical: 200 - 220 µm
    - Horizontal: 180 µm
  - Elderly
    - Vertical: 200 µm
    - Horizontal: 90 µm

Trabecular Structure

- Once a trabeculum is fully perforated through resorption, it is no longer load bearing
  - Removed by osteoclasts
- Normal remodeling of trabeculae tends to gradually increase porosity
  - Trabeculae thin slightly with each remodeling event
  - Process appears to be less evident in those trabeculae that are more heavily loaded
  - Which trabeculae in vertebrae? What is effect?

Trabecular Structure

- Kleerekoper (1985) -- iliac bone
  - Age and density matched individuals with and without fracture (w/ = osteoporotic)
  - Fracture cases had
    - Lower numbers of trabeculae (plate density - 19%)
    - Higher plate thickness (19%)
    - Greater separation (21%)

Trabecular Structure

- Bergot (1988) - vertebral bone
  - Reduction in mean trabecular width
  - Fragmentation and complete loss of struts
  - No evidence of trabecular thickening
    - 110 - 180 µm
- How can this be reconciled with study of Kleerekoper?

Trabecular Structure and Gender

- Original structural parameters similar for men and women
- Changes in trabecular structure more evident in women than men

Trabecular Structure

- The same amount of bone mass provides higher mechanical integrity if:
  - 1. Trabeculae are greater in number
  - 2. Trabeculae are more fully connected within the structure
  - 3. Trabeculae have less separation

Cortical Structure

- Porosity due to presence of Haversian canals
- Remodeling produces a new osteon, a new vascular canal, therefore increased porosity
  - Until new osteons more completely overlap old ones, so no new net gain in canals

Cortical Structure

- Remodeling processes appear to cause differences in canal size in different regions of a bone
  - Areas less stressed during bending tend to have larger canal sizes following remodeling
- Cortical remodeling also produces the weaker, less stiff secondary osteons

Cortical Geometry

- Vertebral body -- thin cortical shell
  - Young: 400 - 500 µm thick
  - Elderly: 200 - 300 µm thick
- Vertebral cortical shell carries varying amounts of load as we age:
  - Small portion of load (<40%) in young, healthy individuals
  - As trabecular bone is lost, carries up to 90% of load

Bone Geometry

- Bone mass may be redistributed with age to best resist loads
  - Main loads in bending and torsion
  - To increase rigidity, distribute mass away from center of bone
- Only 30% of bone mass lost at endosteum needs to be replaced at periosteum in order to maintain torsional or bending strength

Bone Cross-Section

- Radii of femoral and tibial diaphysis increases in men
  - 3.2% increase in polar moment of inertia of tibia per decade with no change in cortical area
  - In women, cortical area decreases 6.7% without a change in PMI

Bone Cross-Section

- Cross-sectional area of vertebral body increases about 20 - 30% with age in men (20 - 80 years)
  - Similar change not seen in women

Microcrack Accumulation and Remodeling

- Assumed that the biological cost of remodeling (with reduction in bone mineralization and increased porosity) is less than that of fatigue damage accumulation

Theories of Osteoporosis

- Two populations
  - Low turnover - fatigue cracks accumulate through lack of remodeling
  - High turnover - fracture occurs due to higher remodeling rates that result in faster bone loss

Elastic Models of a Viscoelastic Tissue

- What are the discrepancies?
- How might we account for these while still using an elastic model?