Harvard-MIT Division of Health Sciences and Technology
HST.523J: Cell-Matrix Mechanics
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BONE

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Several slides have been removed from this presentation for copyright reasons.

Sources: (1) American Academy of Orthopaedic Surgeons (AAOS). "Orthopaedic Basic Science Slide Set," CD-ROM, 2nd ed., 1999. Slides on bone structure, types of bone, Haversian System, osteoblasts and osteocytes, bone chemistry and mechanical properties.

(2) Frank Netter illustrations, Ciba.

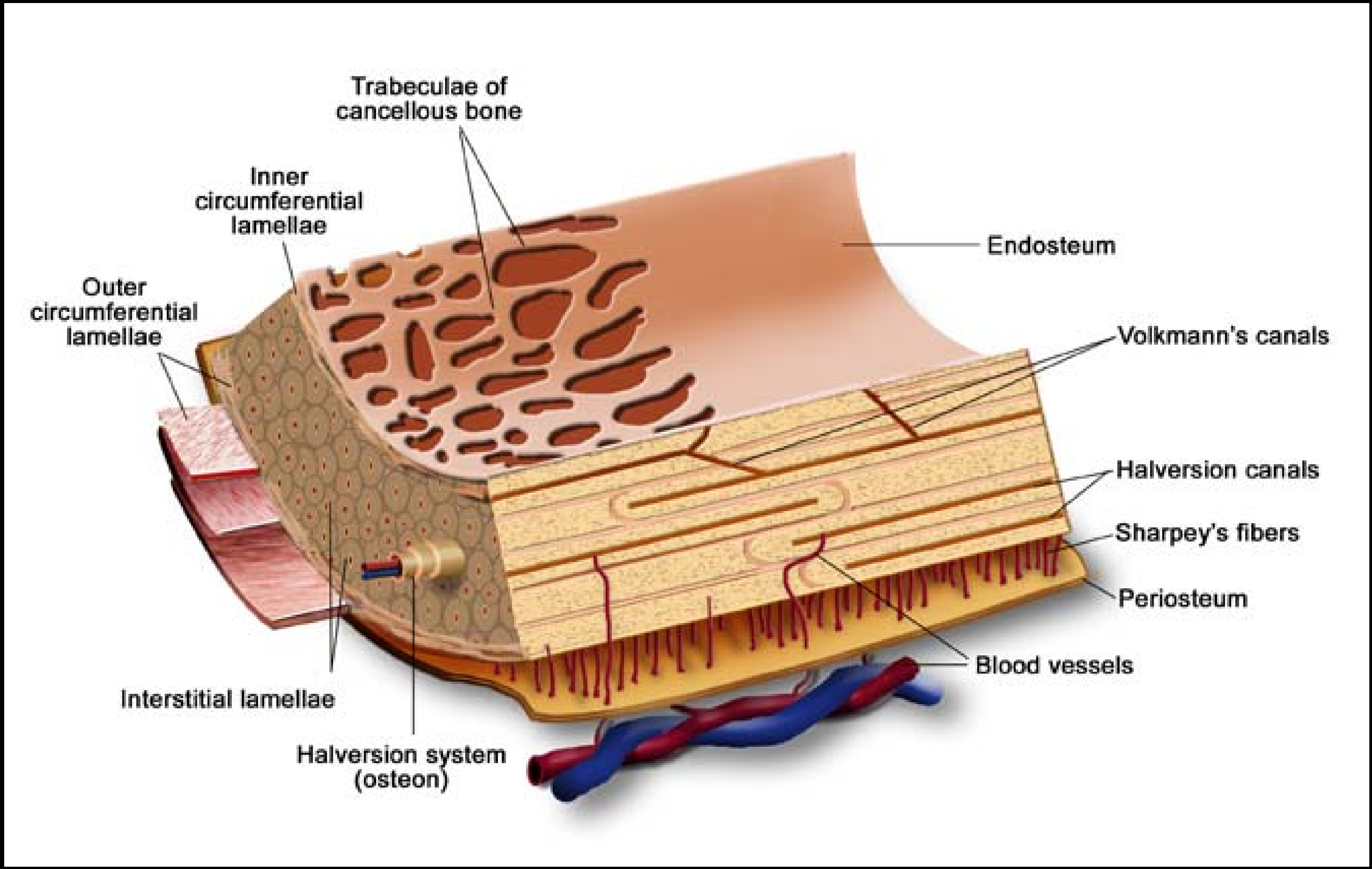

Figure by MIT OCW.

Cortical Bone Properties

Property	Human	Bovine
Elastic Modulus Transverse	17.4 GPa	20.4 GPa
Elastic Modulus Long	9.6 GPa	11.7 GPa
Shear Modulus	3.5 GPa	4.1 GPa
Tensile Yield Stress Long	115 M Pa	141 MPa
Tensile Ult Stress Long	133 M Pa	156 MPa
Tensile Ult Stress Trans	51 M Pa	50 MPa
Comp Yield Stress Long	182 M Pa	196 MPa
Comp Yield Stress Trans	121 M Pa	150 MPa
Comp Ult Stress Long	195 M Pa	237 MPa
Comp Ult Stress Trans	133 M Pa	178 MPa
Tensile Ultimate Strain	2.9 - 3.2%	0.67 - 0.72%
Compressive Ult. Strain	2.2 - 4.6%	2.5 - 5.2%

Martin, *et al.* (1998)

Osteon Properties

Ascenzi and Bonucci

Osteon Type*	Mechanical Test	Elastic Modulus(GPa)	Ultimate Stress (MPa)
Longitudinal	Compression	6.3	110
Transverse	Compression	9.3	164
Alternating	Compression	7.4	134
Longitudinal	Tension	11.7	114
Alternating	Tension	5.5	94
Longitudinal	Shear	3.3	46
Transverse	Shear	4.2	57
Alternating	Shear	4.1	55

*Orientation of the collagen fiber bundles with respect to the plane of the osteon section. Collagen fiber bundles oriented with the direction of testing produce a higher normal stiffness while collagen fiber bundles oriented out of the plane of testing produce a lower stiffness but a higher shear stiffness.

Correlation Between Trabecular Bone Compressive Modulus and Density

R^2 for Linear and Power Models

Region	Linear	Power
Proximal Femur	0.50	0.55
Distal Femur	0.65	0.65
Proximal Tibia	0.41	0.40
Proximal Humerus	0.65	0.66
Distal Radius	0.17	0.13

$$E = A + Bv_f \quad \text{Linear Model}$$

$$E = Av_f^B \quad \text{Power Law Model}$$

Ciarelli et al. (1991)

Effects of biomechanical stress on bones in animals

Diagram removed for copyright reasons.

When bone is subjected to bending, fluid is forced through the canalicular channels from regions of greater compression toward regions of lesser compression (or from more concave surfaces to more convex surfaces). This gradient of flow is proportional to the strain gradient across the cortex of the bone. The magnitude of the fluid shear stress on osteocytes lying within the lacunae is proportional to the rate at which fluid is forced through these channels, which in turn is proportional to the strain rate.

DB Burr, *et al.*, *Bone* 30:781 (2002)

See the following two papers - images have been removed for copyright reasons.

(1) Turner, J. and F.M. Pavalko. "Mechanotransduction and functional response of the skeleton to physical stress: the mechanisms and mechanics of bone adaptation." *J Orthop Sci* 3:346 (1998)

(2) Burr, D.B., A.G. Robling and C.H. Turner. "Effects of biomechanical stress on bones in animals." 30:5 (May 2002)781-6

Effects of Spaceflight on Bone

RT Turner, et al., *Proc Soc Exp Biol Med* 180:544 (1985)
RT Turner, et al;. *Physiologist* 24:S-97 (1981)

Photos removed for copyright reasons.

BONE CELLS:
OSTEOBLASTS

- Contraction of osteoblasts
- Expression of α-smooth muscle actin in osteoblasts *in vivo*
- Fracture healing
- Distraction osteogenesis

CONTRACTILE CONNECTIVE TISSUE CELLS

Express SMA *in vivo*

Capable of contracting collagen-GAG matrices *in vitro*

SMA-positive cells retain differentiated phenotype

SMA trait derived from the stem cell

Amount of contraction correlated with the SMA content

SMA and contraction up-regulated by TGF-β1

Roles have yet to be determined, but may be both positive and negative

POSSIBLE ROLES FOR SMA-ENABLED CONTRACTION OF MS CELLS

Healing	**Closure of skin wounds; fx. heal?**
	Tensioning of a healing ligament
	Retraction of the ends of torn ligaments/tendons that do not heal
Disease processes	**Contracture**
Tissue formation and remodeling	**Modeling of ECM architecture (*e.g.*, crimp in ligament/tendon?)**
Tissue engineering	**Contracture of scaffolds**

See the following papers - images have been removed for copyright reasons.

(1) Menard, C.G., S. Mitchell and M. Spector. "Contractile behavior of smooth muscle actin-containing osteoblasts in collagen-GAG matrices in vitro: implant-related cell contraction." *Biomaterials* 21:18 (2000 Sept) 1867-77.

(2) Kinner, B. et al. JOR 2002;20:622-632

(3) Kinner, B. et al. "Expression of smooth muscle actin in connective tissue cells participating in fracture healing in a murine model." *Bone* 30:738 (2002).

(4) B. Kinner, et al., *JOR* 21:20 (2003)

SMA AND CONTRACTION OF MUSCULOSKLETAL CELLS

Many Questions to be Answered

What are the roles of SMA-enabled contraction in normal and pathological processes?

What therapeutic approaches can be taken for its regulation?

How does the SMA-enabled contraction impact musculoskeletal tissue engineering?