

Chapter A2

Cancellous Bone

Christopher J. Hernandez

A2.1 Microstructure

Cancellous bone (also referred to as trabecular bone or spongy bone) is a porous cellular solid consisting of platelike and rodlike struts called trabeculae. The size and arrangement of trabeculae vary among species and within regions of the skeleton and change with age. Average trabecular thickness can be as great as 300 μm but, in elderly human tissue, ranges from 100 to 200 μm [1]. The orientation of trabeculae within cancellous bone varies, resulting in considerable specimen-to-specimen heterogeneity. At the continuum level (specimens 3–5 mm in smallest dimension) the density of cancellous bone is measured as the mass of the specimen (wet after removing the marrow) divided by specimen volume and is referred to as the “apparent density.” The apparent density of human cancellous bone typically ranges from 0.05 to 1.1 g/cm^3 . The apparent density of cancellous bone is not to be confused with the “tissue density” which expresses the density of individual trabeculae. The volume fraction of human cancellous bone (expressed in the bone literature as BV/TV) ranges from 5 % to 60 %. The surface-to-volume ratio of human cancellous bone (BS/TV) is related to bone volume fraction in the following manner [2]:

$$\frac{\text{BS}}{\text{TV}} = 8.84 \left(\frac{\text{BV}}{\text{TV}} \right)^{0.70}$$

C.J. Hernandez (✉)

Sibley School of Mechanical and Aerospace Engineering, Cornell University,
219 Upson Hall, Ithaca, NY 14853, USA

Meinig School of Biomedical Engineering, Cornell University, 219 Upson Hall,
Ithaca, NY 14853, USA

e-mail: cjh275@cornell.edu

A2.2 Tissue Composition and Ultrastructure

At the tissue level cancellous bone is a ceramic polymer composite with composition similar to that of cortical bone. By mass, bone tissue is 65 % mineral (primarily an impure hydroxyapatite), 25 % organic (primarily type I collagen but also including non-collagenous proteins), and 10 % water. By volume bone tissue is 36 % mineral, 55 % organic, and 9 % water [3]. These proportions vary with age of the individual as well as length of time the tissue has been present in the body (the “tissue age”) and differ among species. In general tissue density is highly conserved and shows a small range within a species (1.6–2.0 g/cm³ in humans) [3, 4]. Heterogeneity within bone tissue is present, however, and is caused primarily by bone remodeling. Bone remodeling is a process in which bone cells remove and replace bone tissue at discrete locations on bone surfaces. Structures known as cement lines mark the boundaries of previous remodeling activity within trabeculae and divide more recently remodeled (younger) tissue from non-remodeled (older) regions of the tissue that are typically stiffer and more mineralized. The large surface-to-volume ratio of cancellous bone (as compared to cortical bone) enables greater turnover of bone tissue during remodeling, reducing the proportion of older tissue, possibly explaining why cancellous bone has been reported to have 10–14 % lower tissue density than cortical bone [5].

A2.3 Mechanical Properties

The mechanical properties of cancellous bone at the continuum scale (specimens 3–5 mm in smallest dimension) are reported here. Mechanical properties of cancellous bone can vary among species and among anatomical sites within individuals. Mechanical properties can also be altered with aging and in the presence of disease states.

A2.3.1 *Elastic Modulus and Strength*

The stiffness and strength of cancellous bone are determined primarily by apparent density [6, 7]. When loaded in uniaxial compression or tension cancellous bone displays a slightly nonlinear stress-strain curve [8] and yield is commonly determined using the 0.2 % offset criteria. Cancellous bone is anisotropic due to both microstructure and tissue anisotropy.

The Young’s modulus and shear modulus of cancellous bone are determined primarily by tissue apparent density (Table A2.1) and can vary over tenfold among regions of the skeleton within the same individual. Hence, there is no one value for an elastic modulus of cancellous bone and cancellous bone mechanical properties must therefore be estimated from apparent density. Empirically derived power law

Table A2.1 Mechanical properties of cancellous bone are strongly influenced by density. Regression models relating cancellous bone mechanical properties to apparent density (wet) are provided. Mechanical properties are reported on axis (in the direction of primary trabecular orientation). Results are provided as mean \pm SD and (95 % CI) when available. Regression equations were achieved using linear regression on log-transformed data

Mechanical property	<i>n</i>	Age	Apparent density (g/cm ³)	$Y=A \times X^B$		
				A	B	<i>r</i> ²
Young's modulus (MPa) ^a	142	67 \pm 15 (61–68)	0.27 (0.09–0.75)	8920 (7540–10,550)	1.83 (1.72–1.94)	0.88
Shear modulus (MPa) ^b	42	Bovine	NR ^b	2.09	1.90	0.84
σ_y (MPa, tension) ^a	52	65 \pm 14 (61–68)	0.29 (0.25–0.34)	31.35 (23.81–41.29)	1.67 (1.58–1.77)	0.86
σ_s (MPa, compression) ^a	68	65 \pm 14 (61–68)	0.27 \pm 0.17 (0.24–0.32)	51.15 (41.53–62.99)	1.85 (1.72–1.99)	0.91
σ_{ult} (MPa tension) ^c	22	54 \pm 11 (27–82)	0.19 \pm 0.04 (0.09–0.29)	13.3	1.07	0.47
σ_{ult} (MPa compression) ^c	22	54 \pm 11 (27–82)	0.17 \pm 0.04 (0.07–0.27)	33.2	1.53	0.68
τ_{ult} (MPa) ^b	15	Bovine	NR ^b	72.74	1.86	0.64
K_Q (MPa/m ^{1/2} , crack oriented ⊥ to trabeculae) ^d	166	82 \pm 6.8 (65–99)	Range: 0.25–1.10 g/cm ³	0.67	1.58	0.62
K_Q (MPa/m ^{1/2} , crack oriented to trabecular orientation) ^d	169	82 \pm 6.8 (65–99)	Range: 0.25–1.10 g/cm ³	0.54	1.60	0.56

NR not reported

^aRegression models include cancellous bone from vertebrae, proximal tibia, and proximal femur. More predictive regression models for each anatomical region are available [9, 10]

^bDetermined in the bovine proximal tibia through torsion testing [11]

^cVertebral trabecular bone [12]

^dSpecimens from human femoral head and equine vertebrae were pooled. Measures of K_{IC} were not achieved due to elastic-plastic behavior associated with trabecular bending/torsion [13]

models are useful for general prediction of specimen Young's modulus and shear modulus, although linear regressions are appropriate when the range in apparent density is small (for example, if only one region of the skeleton is considered). The Poisson's ratio of cancellous bone is difficult to measure and poorly understood and is typically estimated (common estimates range from 0.1 to 0.3). Cancellous bone strength is strongly correlated with Young's modulus. The ultimate strength of cancellous bone is strongly correlated with yield strength (in vertebral cancellous bone ultimate strength is 20 % greater than yield strength [14]). Yield strain and ultimate strain are not correlated with apparent density. Yield strain of cancellous bone within a region of the skeleton shows little interindividual variability, but differences among skeletal sites have been noted. Compressive yield strains of human cancellous bone have been reported to range from 0.70 to 0.85 (across different regions of the skeleton). Yield strains in tension are always lower than those in compression (reported to range from 0.60 to 0.70). Ultimate strain is more variable for unknown reasons.

Trabecular alignment and microstructure have been shown to influence mechanical properties of cancellous bone. Trabecular alignment is the primary cause of cancellous bone anisotropy. When loading is applied at 90° to the primary trabecular orientation, cancellous bone Young's modulus is 40–60 % smaller and the ultimate strength is 30–45 % smaller [15]. Interestingly yield strain in the transverse directions is not different from that on axis. The effects of trabecular alignment on Young's modulus can be described using a fabric tensor and a quadratic Tsai-Wu criteria has been used successfully to describe a multiaxial failure envelope for cancellous bone [16]. More complicated multiaxial failure criteria have been used to address some shortcomings of the Tsai-Wu criteria [17, 18].

Tissue material properties also influence cancellous bone Young's modulus and strength. Compressive Young's modulus and strength of bone (cancellous and cortical bone pooled) is related to bone volume fraction (BV/TV) and the tissue degree of mineralization (α , inorganic mass/bone mass) in the following manner [19]:

$$E(\text{GPa}) = 84 \left(\frac{\text{BV}}{\text{TV}} \right)^{2.58} \alpha^{2.74}$$

$$\sigma_{\text{ult}}(\text{MPa}) = 794 \left(\frac{\text{BV}}{\text{TV}} \right)^{1.92} \alpha^{2.79}.$$

The regression exponents applied to tissue degree of mineralization are greater than those on bone volume fraction, demonstrating that bone strength is more sensitive to variation in tissue degree of mineralization than to variation in bone volume fraction.

A2.3.2 Viscoelastic and Fatigue Properties

Cancellous bone displays viscoelastic properties. The strain rate has only a small effect on the Young's modulus and strength of cancellous bone under uniaxial loading; Young's modulus and strength are related to strain rate to the power of 0.06 [6]. Hydraulic stiffening of the marrow does not influence Young's modulus and strength

until strain rates exceed 1 s^{-1} [6]. Creep deformation in cancellous bone follows the pattern of a rapid primary phase, slow secondary phase, and rapid tertiary phase [20]. The creep rate of bovine cancellous bone is related to normalized stress (σ/E_0 , where E_0 is the initial Young's modulus) as follows [20]:

$$\frac{d\varepsilon_c}{dt} = 2.21 \times 10^{33} \left(\frac{\sigma}{E_0} \right)^{17.65}.$$

Human vertebral cancellous bone submitted to low-magnitude, compressive creep loading ($\sigma/E_0 = 1500 \mu\epsilon$ or less) has been shown to have nonlinear viscoelastic properties such that residual strains persist up to ten times longer than the period of constant loading [21].

Under fatigue loading cancellous bone displays an S-N curve such that the number of cycles to failure (N_f) is related to normalized stress (σ/E_0) as follows [22]:

$$N_f = 4.57 \times 10^{-18} (\sigma / E_0)^{-8.54}.$$

A2.3.3 *Fracture Toughness*

Relatively little is known regarding resistance to crack growth in cancellous bone. Resistance to crack growth in cancellous bone specimens has been assessed with linear elastic fracture mechanics approaches (Table A2.1), but care must be taken in interpreting the quantitative values because large deformations in trabeculae at the crack tip prevent assessment of K_{IC} (see [13] for a discussion of the utility of linear elastic fracture mechanics in continuum specimens of cancellous bone).

A2.3.4 *Post-Yield and Damage Behavior*

Tissue damage in cancellous bone impairs mechanical performance during subsequent loading. Reductions in Young's modulus have been observed in specimens of cancellous bone submitted to as little as 0.4 % apparent strain (well below yield strain) [23]. Loading in compression causes reductions in Young's modulus [24–26] and strength [24, 25] that are related to the maximum applied strain experienced by the specimen. Tissue damage in the form of microscopic and sub-microscopic cracks is also related to the maximum applied strain and subsequent reductions in Young's modulus and strength. Relatively small amounts of microscopic tissue damage (less than that characterized as “naturally occurring”) have been associated with 50–60 % reductions in strength and the use of over 90 % of cancellous bone fatigue life [24, 26]. Hence, microscopic tissue damage accumulated in cancellous bone in vivo may contribute to bone failure. Microscopic tissue damage is generated more rapidly following changes in loading mode (between compression and shear for example) [27]. Despite the presence of microscopic damage, residual strains

following loading are typically small; upon removal of load cancellous bone recovers as much as 70–94 % of the applied strain [24, 25, 28].

A2.4 Tissue-Level Mechanical Properties

The mechanical properties of cancellous bone tissue (the constituents of individual trabeculae) remain poorly understood. Mechanical testing of individual trabeculae is challenging and requires many assumptions that may limit the accuracy of the results. The Young's modulus of individual trabeculae typically averages 3–6 GPa [29]. In contrast, the Young's modulus of human cancellous bone tissue assessed through nanoindentation is, on average, 10–18 GPa [30–32], and is similar to the range to tissue-level Young's moduli estimated using finite element models of cancellous bone microstructure [33]. Relatively little is known regarding tissue-level anisotropy, tissue-level viscoelasticity, fatigue, and fracture toughness.

Additional Reading

Cowin S. Bone Mechanics Handbook. In. 2 ed. Boca Raton: CRC Press; 2001.

This book provides a complete review of bone mechanical properties and interactions with bone cell biology.

Currey JD. Bones: Structure and Mechanics. Princeton, NJ, USA: Princeton University Press; 2002.

This is a review that includes thorough discussion of non-human bone mechanical properties and function.

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