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Mechanical Resonance Spectra in Human Cancellous Bone

Abstract. *The dynamic mechanical response of fresh human cancellous bone at low audio frequencies contains two resonance spectra. The spectral frequencies in each series have the ratios 1 : 4 : 9 : 16 . . .* n^2. *The frequencies are in quantitative agreement with the concept of momentum wave modes of calcium and phosphorus atoms in the lamellae, with no variable parameters.*

The dynamic mechanical properties of mammalian bone have received relatively little attention, with the exception of fracture and impact-related trauma. However, measurements on intact human long bones (in vivo and in vitro) have shown resonances at low audio frequencies (*1*). Since the elastic compliance of cancellous bone is about an order of magnitude larger than that of cortical bone, it is likely that the dynamic mechanical properties of the former will be more important; for example, in the absorption of shock and in general dynamic response.

We have investigated the complex compressional (uniaxial) elastic modulus of human cancellous bone with a simple viscoelastometer, consisting of an electromagnetic force generator, a piezoelectric accelerometer, and a piezoelectric force transducer. The dynamic mechanical response of disks of human cancellous bone (1 cm in diameter, 5 mm thick) from the distal femur was measured under longitudinal sinusoidal compression. In essence, we measured the mechanical impedance of the disk and converted our data to the complex elastic modulus. Such techniques have been used extensively on engineering polymers for more than a decade (*2*). Ten samples were obtained at autopsy from four cadavers (all male, 43 to 53 years old at death) and machined carefully under water coolant. Measurements on the wet samples were made at room temperature and within 48 hours of death. The signals from the pickups were conditioned by charge amplifiers and fed into an oscilloscope to produce a Lissajous figure. Amplitudes and phase relationships were used to calculate the elastic (E') and viscous (E'') components of the stiffness (*2*). The viscoelastometer was calibrated with standard specimens and with an accurate vibration standard. Typical stresses were of the order of 1 pound per square inch (psi) (1 psi ≈ 52 torr; strains were 0.001 percent). Subsequent microscopic examination attested to the nondestructive nature of these measurements, and indicated the volume fraction of hard tissue to be 0.42 to 0.45. The phase angle, δ, was measurable to 3 degrees.

All ten samples of cancellous bone exhibited sharp resonances of the type shown in Fig. 1. The viscous component E'' was typically equal to E' at resonance, and was relatively insignificant at frequencies away from resonance. By changing the specimen dimensions and using a variety of materials (such as aluminum and various plastics and rubbers) we have determined that the resonances are intrinsic to the cancellous bone itself, and not due to our apparatus.

Audio frequency resonances have been found in a variety of engineering materials (mostly polymeric) (*3*) and also in canine intervertebral disks (*4*); the types of apparatus used all differed markedly from ours. The resonances were characterized by their sharpness compared to other types of resonance based on material properties, and by the fact that the resonant frequencies can be characterized by the ratios 1 : 1, 4, 9 . . . n^2, where n is an integer. However, the resonances previously found were not reproducible, in the sense that they could usually be eliminated by changing the length of the specimen (*5*). Thus, the origin and nature of the resonances have been controversial (*3*). Our data were reproduced in ten separate specimens with thicknesses ranging from 4 to 6 mm, and within the precision of our apparatus (a few percent) the peaks always occurred at the same frequencies.

The equation that best fits our data

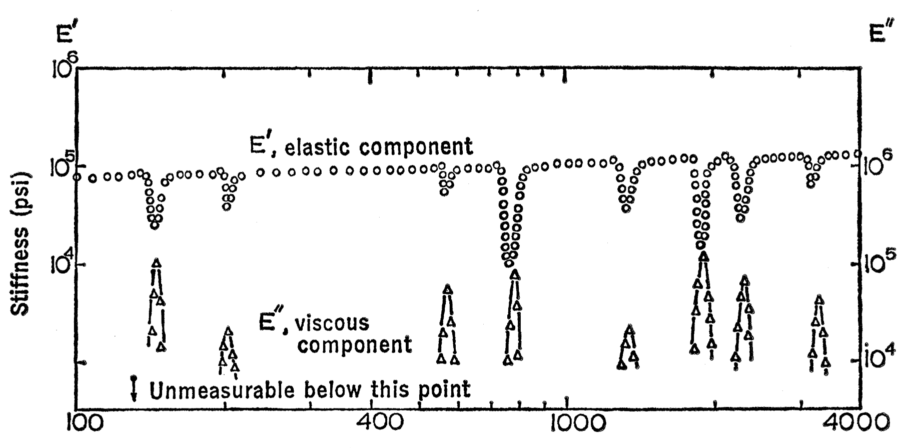

Fig. 1. Typical data for the elastic and viscous components of the complex longitudinal stiffness of fresh human cancellous bone for frequencies between 100 and 4000 hertz.

Table 1. Resonant frequencies and frequency ratios for fresh human cancellous bone. The atomic mass ratio m_P/m_{Ca} is 0.773.

Frequency or ratio	^{40}Ca Calculated	^{40}Ca Observed	^{31}P Calculated	^{31}P Observed	ν^{Ca}/ν^{P} Observed
		Frequencies (hertz)			
ν_1	145	145	203	203	
ν_2	580	570	812	708	
ν_3	1305	1350	1827	1900	
ν_4	2320	2310	3248	3230	
		Frequency ratios			
ν_2/ν_1		3.93		3.49	
ν_3/ν_1		9.31		9.36	
ν_4/ν_1		15.9		15.9	
ν_1/ν_1					0.714
ν_2/ν_2					0.805
ν_3/ν_3					0.711
ν_4/ν_4					0.715

(in fact, the only equation that fits our data at all) is that of Fitzgerald (*6*),

$$\nu_n = (h/8mS^2)n^2 \qquad (1)$$

where n is an integer, h is Planck's constant, m is the mass of the atom responsible for the resonances, and S is the geometric segment length, which can be any repetitive structural feature with a characteristic wavelength of the order of 10^{-4} cm. Fitzgerald's theory was developed to describe (among other things) nonelastic deformation of crystalline solids by wavelike motions of individual atoms—for example, C and H in a natural rubber partially crystallized (by stretching). If the theory is to be applied to our results, the atoms involved must be those in the mineral constituent, which is probably hydroxyapatite (*7*) with a chemical formula of $Ca_{10}(PO_4)_6(OH)_2$, or in the collagen matrix itself. In fact, the observed resonant frequencies broke down into two sets, one corresponding to calcium and the other to phosphorus. We present the first four frequencies of each set in Table 1; the "calculated" values are simply the lowest frequencies multiplied by 4, 9, and 16. With the possible exception of the 708-hertz resonance, every calculated value was well within the spread of the observed peak. All specimens yielded these frequencies, within 2 or 3 percent (which was the limit of precision of our apparatus). The ratios of the corresponding frequencies fall between 0.711 and 0.805, and the atomic mass ratio of P to Ca is 0.773, as shown in Table 1. If the resonance are due to Ca and P, one expects from Eq. 1 that

$$\nu_n^{Ca} : \nu_n^{P} = m_P : m_{Ca} \qquad (2)$$

where ν_n^{Ca} refers to the nth peak in the Ca spectral series and ν_n^{P} to the nth peak in the P series, and m_P and m_{Ca} are the atomic masses.

Also, by use of Eq. 1 the characteristic length S can be calculated directly, since all the other quantities are known. For Ca this length is about 2.93 μm, and for P it is about 2.82 μm; these numbers correspond closely to the lamellar thickness we see in our cancellous bone specimens, approximately 3 μm.

Thus, our data are fit quite well in almost all respects by a theory based on the hypothesis that momentum wave modes for calcium and phosphorus atoms are set up in the lamellae of trabecular bone. In the context of the theory, the crystallographic coherence of the lamellae corresponds to the orientation of collagen, which is reasonably well defined within a lamella (*7*). Adjacent lamellae have, in general, different collagen orientations (*8*).

We have not been able to find any other physical picture, involving either elastic or anelastic modes or resonances due to the apparatus, which fits our data at all. The idea of the transfer of individual atoms—for example, P rather than PO_4^{3-}—is remarkable in a biological system (but commonplace in a crystalline system). It is possible that other phenomena could give rise to Eqs. 1 and 2. For instance, it has been predicted that diffusive and autocatalytic reactions can involve spatially periodic chemical structures (*9*); these structures have been found (*10*) and in general they have wavelengths of the order of a few centimeters, much less than that of low audio frequency sound. Whether such structures can exist in bone and combine with the structural (and electrical) periodicities in bone is at present a matter of speculation.

Since the compact cortical bone that comprises the shafts of the long bones is organized in concentric lamellae (for example, about Haversian canals), a similar spectrum of resonances should be exhibited. In fact, measurements by Black and Korostoff (*11*) on cortical bone at frequencies between 35.4 and 353.6 hertz show "an anomalous reduction in modulus . . . in the neighborhood of 200 Hz" which greatly resembles our data for E' near that frequency. It is also noteworthy (but probably fortuitous) that the skeletal forces due to heel-strike in human gait (*12*) have principal frequency components quite close to the resonances we report here.

If the physical basis for the resonances (and Eqs. 1 and 2) involves mass transport (the momentum wave description certainly does), a central role may be played by such phenomena in the remodeling of bone. Consequently, more extensive exploration of such resonances and their basic physical nature would seem desirable.

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