

PIEZOELECTRICITY IN CEMENTUM, DENTINE AND BONE

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Summary—Unlike the dental hard tissues, bone remodels when subjected to orthodontic forces. Bone is also piezoelectric (generates a surface electrical charge upon application of force). In dentine and cementum from sperm whale teeth (which gave samples of sufficient size), the existence and magnitude of piezoelectricity were examined and compared with human bone. Both dental tissues were found to be piezoelectric with coefficients of *0.027* and 0.028 PC/N, respectively; the coefficient of human bone was eight times greater *(0.22 PC N). Thus* the strength of the piezoelectric effect was correlated with the known capacities of the tissues to undergo adaptive remodelling. This result is consistent with the theory that piezoelectricity mediates orthodontically induced alveolar remodelling.

INTRODUCTION

Bone undergoes morphological change in response to mechanical forces; an example is the alveolar adaptation that accompanies the application of orthodontic appliances. In normal circumstances, only the bone responds by growth and resorption (Sicher, 1966), thereby illustrating both the adaptability of bone and the absence of this in the dental hard tissues, which are similar to bone in chemical composition.

Bone is piezoelectric and therefore capable of transforming mechanical forces into an electrical signal (Fukada and Yasuda, 1957). Dental enamel is not piezoelectric (Braden *et al*., 1966). Dentine is piezoelectric, but the strength of the effect in comparison to bone has not been measured (Braden *et al*., 1966; Shamos and Lavine, 1967). There are no reports concerning the piezoelectric property of cementum. Our specific purpose was to determine the existence and magnitude of piezoelectricity in cementum and dentine in comparison to that of bone. More generally, the question of interest to us was: Can the differential response of bone and dental hard tissues be correlated with a difference in their piezoelectric properties?

MATERIALS AND METHODS

Adult human tibias and whale teeth were used because these gave samples of suitable size. The bones had been degreased in acetone for 24 h and stored in air (21°C, 30-50% relative humidity) for several years prior to use. Similarly treated sperm whale teeth *(Phvseter catodon)* were obtained commercially. The teeth were composed of a central core of dentine encapsulated by a 6-mm thick layer of cementum; adult sperm whale teeth lack enamel (Slijper, 1962). The bones and teeth contained 4-8% water, as determined by heating to constant weight at 100°C. Samples of bone, dentine and cementum approx. 15 x 10 x 5 mm^3 (oriented to produce the maximum piezoelectric response) were cut by hand. The piezoelectric coefficient relating a compression along the sample long axis to an electrical polarization on the 15 x 10 mm^2 surfaces was measured (Fukada and Yasuda, 1957). The sample was clamped with inorganic crystals (quartz, and a piezoelectric ceramic) having known piezoelectric properties. A voltage applied to the sample (V_s) resulted in a strain that was transmitted to the ceramic where it produced a corresponding voltage, V_0. The voltage applied to the quartz (V_q) that also resulted in V_0 across the ceramic was then determined, and the piezoelectric coefficient of the sample (d) was calculated as: $d = d_q(V_q/V_s)(2c/a)$, where d_q is the piezoelectric coefficient of quartz, and c and a are the sample thickness and height, respectively. The measurements were made at the resonant frequency of the clamped system (2-3 kHz). After the piezoelectric coefficient was determined, the sample's organic components were removed by refluxing with ethylenediamine (Williams and Irvine, 1954), and a second piezoelectric measurement was made.

The % organic component of each tissue was determined by ashing specimens in a muffle furnace at 550°C for 4-24 h.

RESULTS

Piezoelectricity was observed in both cementum and dentine, and their piezoelectric constants were essentially equal (Table 1). The significantly greater piezoelectric coefficient measured in bone (Table 1) was similar to that reported by Fukada (1981). Figure 1 shows the surface charge density, P, on each tissue as a function of applied stress. The curves

Table I. Piezoelectric constant and organic composition of mammalian hard tissues (N = number of samples; the variations are SD)

Material %	N	d (pC/N)	Matrix
Cementum	6	0.027 ± 0.018	32.1 ± 0.3
Dentine	6	0.028 ± 0.015	28.2 + 0.4
Bone	7	0.22 ± 0.036	31.2 ± 2.1

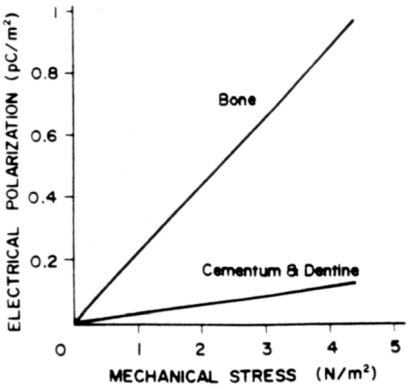

Fig. 1. Strength of the piezoelectric surface charge in cementum, dentine and bone. The curves were calculated using the measured values of the piezoelectric coefficients (Table 1).

were computed from $P = dT$, where d is the pertinent (Table 1) piezoelectric constant, and T is the (assumed) applied stress.

Piezoelectricity was not detected in any specimen in which the organic component had been chemically digested. The sensitivity of our apparatus was such that we would have been able to detect an effect as small as 0.003 pC/N. The % organic composition did not vary significantly among the tissues (Table 1).

DISCUSSION

Our cementum and dentine specimens were capable of producing (on average) only about 12% of the surface charge density produced by cortical bone under similar conditions of mechanical load. It would have been desirable to make the measurements using alveolar bone, but the relatively large sample needed in our technique prevents this. If the response of tibial bone reasonably reflects the piezoelectric strength of alveolar bone, then our results show that the piezoelectric properties of the dental hard tissues are correlated with their differential response to orthodontic force (compared to bone): dentine and Cementum are weak piezoelectrics compared to bone.

The magnitude and sign of the surface charge of a piezoelectric material depend on the type and magnitude of the local stress, and on the crystal structure (or, in the case of bone, microarchitecture). On the application of orthodontic force, complex position-dependent stresses are produced on the bone surface around the periphery of the tooth. These stresses, in concert with those associated with occlusion and disclusion, result in a pattern of positive and negative surface charges that could trigger bone cells to produce and resorb bone, thereby permitting the relative tooth movement. The tooth itself does not exhibit a growth response because its piezoelectric effect is weak (or absent, as in the case of enamel). Based on detailed stress-charge measurements (McElhaney, 1967), a similar hypothesis has been proposed for modelling of the long bones (Marino, 1988). Thus piezoelectricity is a possible mechanism to explain alveolar remodelling.

The dentine and cementum that we studied contained no viable cells, and piezoelectricity was lost when the matrix was removed: thus, the piezoelectric effect arose from the organic matrix. A similar result has been reported for bone (Marino, Soderholm and Becker, 1971). The relatively large piezoelectric constant of bone could have resulted from an organic constituent not present in the dental tissues, but this seems unlikely because the matrix of all three tissues is predominantly collagen. Small chemical differences in the collagens could conceivably account for their differential piezoelectric behaviour, but perhaps the most likely explanation is that it arose from a microarchitectural feature possessed by one tissue and not the other. A strong dependence of the piezoelectric surface charge in bone on microarchitecture has been shown (Martin, Holt and Advani, 1979).

Electromechanical signals have been recorded from mineralized tissue for more than 30 years, and both their origin and physiological role have been the subject of extensive discussion. It is now clear that, in physiologically moist tissue, the measured voltages arise from the motion of ions near the tissue surface—a phenomenon known as streaming potentials (Marino, 1988). Voltages of piezoelectric origin, in contrast, are not normally measured in wet tissue (because the developing piezoelectric polarization is neutralized by the motion of ions in the bulk fluid). It is important to recognize that piezoelectric polarization and concomitant neutralization kinetics actually exist at the cellular level in physiologically moist tissue (and hence can serve as a cell stimulus), even though they are not normally measured over the macroscopic dimensions of wick or metal-foil electrodes. The evidence suggesting a physiological role for piezoelectricity is indirect (Marino, 1988; Marino *et al.*, 1988), and it is generally unimpressive except in comparison to the data supporting the alternative. There is no real evidence that streaming potentials have a physiological role—interest in that phenomenon can be traced primarily to the fact that it is easily measured.

Our result is consistent with the theory that piezoelectricity mediates alveolar remodelling. But the magnitudes of streaming potentials in teeth, bone and cartilage are essentially identical (Cochran, Pawluk and Bassett, 1967; Grodzinsky, Lipshitz and Glimcher, 1978; Otter, Shoenung and Williams, 1985), thereby obviating the possibility that streaming potentials could explain a differential physiological response.

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