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Origin of the Piezoelectric Effect in Bone

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The piezoelectric effect was measured in samples of human bone and repeated with the same samples after either demineralization or decollagenation. The results indicate that at least part and possibly all of the piezoelectric effect found in whole bone arises from the organic component. The existence of two alternatives results from the unknown role of the collagen-mineral interface. In either case, bone mineral per se makes no contribution to the piezoelectric effect in bone.

Key words: Bone — Collagen — Piezoelectricity.

L'effet piézoélectrique est mesuré dans des échantillons d'os humain avant et après déminéralisation ou extraction du collagène. Les résultats indiquent qu'une partie et, peut-être, la totalité de l'effet piézoélectrique de l'os intact est produit par le constituant organique. L'existence de deux possibilités est lié au rôle non connu joué par l'interphase collagène-minéral. Dans chaque cas, le minéral osseux ne contribue pas à l'effet piézoélectrique de l'os.

Es wurde der piezoelektrische Effekt an menschlichen Knochenproben gemessen und diese Messung an denselben Proben nach Entkalkung und Entkollagenisierung wiederholt. Die Resultate weisen darauf hin, daß mindestens ein Teil, jedoch vermutlich der gesamte, im intakten Knochen gefundene piezoelektrische Effekt durch die organische Komponente hervorgerufen wird. Das Vorhandensein zweier Alternativen ist auf die unbekannte Rolle der Kontaktfläche zwischen Kollagen und Mineral zurückzuführen. In beiden Fällen trägt das Knochenmineral an sich nicht zum piezoelektrischen Effekt im Knochen bei.

Introduction

The piezoelectric effect (P.E.) has been found in a variety of biological tissues (Fukada and Yasuda, 1957. 1964; Shamos and Lavine, 1967; Fukada, 1968; Anderson and Eriksson, 1970). It is of non-cellular origin and is often closely associated with the structural protein collagen. Interest in the P.E. centers on the possibility that it may be a biological transducer, converting environmental stimuli into biologically-recognizable signals capable of controlling growth or resorptive processes.

In the case of bone, we have proposed a link between the P.E. and the adaptive response of bone cells (Marino and Becker, 1970). An important question which arises in this connection concerns the proximate origin of the P.E. from bone. Is the observed effect due to bone collagen, bone mineral, or does it arise from their anatomical relationship? While it is commonly assumed to arise from the collagen

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moiety (Shamos and Lavine, 1967; Anderson and Eriksson, 1970), we know of no experimental confirmation, with the exception of a brief comment (Fukada and Yasuda, 1957). Similarly, the existence of the P.E. in bone mineral has not been reported, although the possibility of its existence has been suggested (Shamos and Lavine, 1964; Bassett, 1968). The present study deals with the relative contributions to the P.E. in bone made by its major organic and inorganic components.

Materials and Methods

Samples were prepared from normal human cortical bone which had been air-dried but otherwise untreated. The expression governing the electric polarization (P_i) resulting from a stress (S_j) is given by $P_i = d_{ij} S_j$, where the 18 elements (d_{ij}) are referred to as the piezoelectric coefficients. The index j takes values from 1 to 6, corresponding to the six possible stresses on a cube, and the index i takes values of 1, 2 or 3, corresponding to the three Cartesian coordinates. It is generally agreed that the largest coefficient in a collagenous system is d_{14} (Fukada, 1968). The samples were therefore cut and the electrodes attached in a manner which permitted its determination. The piezoelectric measurements employed the converse effect and were made using a modified version of Fukada's method (Fukada and Yasuda, 1957). Eight samples were prepared, each with a different value of θ, the angle between the original bone axis and the direction along which pressure was applied when the sample was mounted in the apparatus. Their average size was $15 \times 10 \times 5$ mm. After the piezoelectric behavior of the bone samples was measured they were divided into two groups. The first group was demineralized by treatment with 5% formic acid for 72 h, the second was made collagen-free by refluxing with ethylenediamine (Williams and Irvine, 1954). A second measurement was then made of the piezoelectric behavior of each sample. The average error for all measurements was about 20%.

Results

Fig. 1 illustrates the piezoelectric behavior of bone and its constituents. In both bone and bone collagen the effect is maximum at about 45°, the same angle at which the shear forces along the collagen fibers are also a maximum. In the bone mineral samples no piezoelectric behavior was observed. For both bone and bone collagen, d_{14} was calculated from the transformation epuation $d'_{14} = (d_{14}/2) \sin 2\theta$, and averaged for the measured points (Table 1).

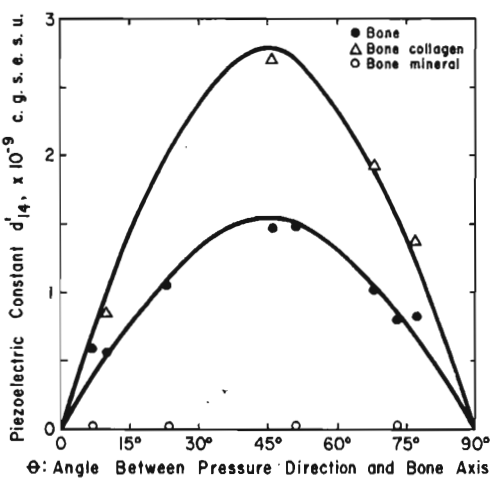

Fig. 1. Piezoelectric effect in bone and its constituents. The solid lines are drawn from the transformation equation given in the text for the values of d_{14} given in Table 1

Table 1. *Piezoelectric Modulus* d_{14}

	d_{14} ($\times 10^{-9}$ c.g.s.e.s.u.)
Human bone	3.1
Human bone Collagen	5.5
Human bone mineral	< 0.3
Human bone	2.9, 3.5[a]
Bovine achilles tendon	80[b]
Horse achilles tendon	57[b]

[a] Fukada (1957). — [b] Fukada (1968).

Discussion

The individual crystallites of bone mineral are believed to belong to a centrosymetric class and would therefore be theoretically incapable of exhibiting piezoelectricity. We have found that the ordered aggregation of these crystallites as they exist in bone is also incapable of the effect. With the apparatus employed we would have been able to measure an effect as small as 0.3×10^{-9} c.g.s.e.s.u., and we would have observed the existence of an effect for smaller values than this.

The existence of the P.E. in bone collagen indicates that at least part of the effect in bone is due to the organic matrix. Bone collagen exhibits a piezoelectric coefficient larger than that of bone basically because it is not a composite material. Anatomically, bone is composed of a low modulus of elasticity piezoelectric (collagen) embedded in a high modulus non-piezoelectric (mineral). When it is subjected to an applied electric field, the princible of combined action acts to equalize the strain in each component. In the absence of the high modulus mineral a greater strain is produced for the same applied electric field. Since the piezoelectric coefficient is a measure of the strain produced per unit of applied field, the result is a higher value for the coefficient in bone collagen.

It can be seen from Table 1 that d_{14} of bone collagen is about one-sixth of the value of tendon collagen. This may be a result of the more orderly parallel arrangement of fibrils in tendon as compared to bone, or alternatively it may be due to a difference between the bonding which exists in each collagen. At present we are unable to distinguish and thus the ultimate origin of the P.E. in the collagens remains unknown.

The data here do not indicate that the P.E. in bone arises solely from the collagen, although of course it may. The possibility exists that d_{14} of bone is a sum of d^A, the contribution from bone collagen, and d^B a contribution arising from the application of shear to the collagen-mineral interface tending to move the mineral crystals along the fibers. In any measurement of the P.E. in bone, the relative contribution of d^A and d^B to the observed polarization would be unknown, and in any measurement of the P.E. in the individual constituents of bone, d^B would not exist.

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