Piezoelectric Effect and Growth Control in Bone

THE adaptability of bone under impressed mechanical forces has been known since the time of Wolff[1]. A possible control mechanism for the process became apparent with the discovery of the piezoelectric effect in bone[2]. In theory this effect could translate an environmental stimulus into a biologically recognizable signal controlling growth or resorptive processes. It has been recognized that the action of the piezoelectric signal may be to alter the chemistry of pertinent macromolecules such as collagen, or to influence cellular activity directly[3]. Of the two possibilities, evidence tends to rule out the importance of the former and we consider here only the latter[4].

For ordinary piezoelectric materials and for small isolated bone samples, the magnitude and sign of the charges that will appear on application of a load can be predicted. Such calculations, however, are not possible for larger bone samples, including whole bones, because of the variable architecture present. (The direction of the symmetry axis of the piezoelectric tensor becomes a function of position.) This means we have no way of knowing what constitutes a normal or abnormal charge distribution for a given bone, and therefore no basis for comparison with observed growth patterns. Alternative considerations for relating the piezoelectric effect and bone adaptability are the signal produced and the expected physical effects at the cellular level. On loading, bone will generate a bound surface charge distribution $\rho(\bar{x},t)$. In a process typically occurring in seconds, $\rho(\bar{x},t)$ is nulled by ion current in the permeating interstitial fluid. When the process is monitored macroscopically by measuring a voltage, a symmetric biphasic pulse is seen[5,6]. The symmetry of such a pulse, however, is not characteristic of the underlying process. Consider a Gedanken experiment in which ;here is an observer at every bone cell. In general, no two observers will record the occurrence of the same local barge distribution on loading. Similarly, they will not agree on the charge neutralization kinetics that occur

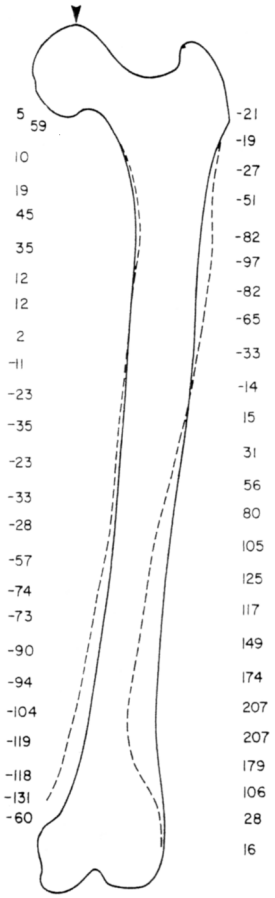
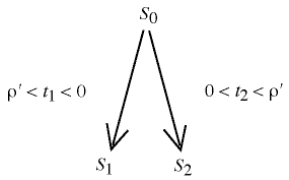


Fig. 1. Solid human femoral outline and charge distribution in pC/cm² as given by McElhaney. The medial surface is displaced at each charge location (left for growth, right for resorption) by an amount proportional to that charge. The lateral surface is similarly displaced (except left for resorption, right for growth). The dotted femoral outline is the result.

because neutralization will depend on a host of locally varying factors such as membrane shielding of the bone surface, fluid viscosity and the concentration and mobility of diffusible ions. Thus, each observer will see two processes, the creation of a $\rho(x,t)$ and its subsequent neutralization. Either process can theoretically represent a biological control signal because each possesses two of the necessary properties, variability and unidirectionality. By variability we mean that the parameters for each process will vary with cell location. For instance, for the first process some observers will note the appearance of negative regions on the adjacent bone surface, while others will see positive areas. If the former represents the biological control signal for growth, then the latter may correspond to resorption. By unidirectionality we mean that neither process generates a biphasic signal which sums to zero.

Young- postulated that the three major types of bone cells are interchangeable, the change of specialization occurring because of changes in the microenvironment which selectively activate and repress genes. We propose that either physical process described above may be responsible for switching bone cells from one kind of specialization state to another. In this case, normal bone in normal loading conditions would produce a normal $\rho(x,t)$ controlling its own remodelling, and abnormal hone (such as a healed angulated fracture) in normal loading conditions would produce an altered $\rho(x,t)$ which increases bone deposition in some areas and decreases it in others (modelling). Normal bone in conditions of no load would produce no $\rho(x,t)$ and, in the absence of this directing influence, atrophy would result.

Next we must find a relationship between one of the processes and bone cell states. We choose the process of creation of $\rho(x,t)$. On the basis of previous work[9], polarity correlations with growth are assigned as follows



Bone cell state	Function
S_0	Resting
S_1	Building bone
S_2	Resorbing bone

where ρ' is an average over some suitable time, t_1 and t_2 are thresholds, and the rate of cellular activity in S_1 and S_2 is assumed to be proportional to the magnitude of ρ'. This scheme has been applied to the results of McElhaney[10], who subjected a whole human femur to a periodic load and measured $\rho(x,t)$. The dotted femoral outline in Fig. 1 results from connecting points plotted from the original femoral surface with a direction and magnitude proportional to each surface charge. Modelling is produced in response to and the integrity of the femur is preserved. If the measured $\rho(x,t)$ was unrelated to bone adaptability, we would expect a random pattern to occur. Modelling rather than remodelling is expected here because, while the femur is anatomically normal, the loading is abnormal, for muscular effects were not included.

Further tests of these propositions require more measurements of $\rho(x,t)$ and *in vitro* studies of the interaction of charged surfaces and cells. It is clear that further study of a link between the piezoelectric effect and bone adaptability is necessary.

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ANDREW A. MARINO
ROBERT O. BECKER

Veterans Administration Hospital, and
Department of Orthopedic Surgery,
Upstate Medical Center, Syracuse, New York.

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