The methodology called Face Recognition Vendor Test (FRVT) as used for assessment of face recognition technologies, was here applied for evaluation of the recognition system performance [15]. When an image is correctly recognized as belonging to the group with certain R factor, the performance measure for this case is the True Acceptance Rate (TAR). The second case is when the image is wrongly recognized as belonging to the certain R group (False Acceptance Rate - FAR). Next case is when the image from Rx group is wrongly classified as belonging to Ry (False Rejection Rate - FRR) and the last possibility - when the image is correctly rejected (True Rejection Rate - TRR).

In our work, the Equal Acceptance Rate (EAR) was a measure of system general performance (EAR is the rate at which the TAR is exactly equal to the TRR). The higher is EAR, the better is the recognition, meaning the higher number of similar coatings was detected. After statistical analysis we stated that the quality sol-gel biocoatings on optical fibers depends on the R ratio. The higher is R, the smaller number of images were recognized as belonging to the proper R group. It means that the differences between sol-gel coatings surface images were bigger. In our experiment we stated that for R=20, the EAR is 93%, for R=32 it is 89%, and for R=40, EAR is the lowest one and equals 83%.

Conclusions

The obtained results show that if the hydroxilize contains more solvent (Ethyl alcohol in our case), the drying procedure (even not forced) caused that the sol-gel coatings were not so homogenous (it was more difficult to achieve the repeatability of production process). We have demonstrated that it is possible to produce homogeneous sol-gel biocoatings with high repeatability, providing that the proper properties between solvents and precursor are ensured.

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References


PHYSIOLOGICAL ROLE OF BONE PIEZOELECTRICITY: RETROSPECT AND PROSPECT

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Introduction

It is about five decades now since Iwao Yasuda, a Japanese orthopaedic surgeon, reported a link between the physiology of bone growth and an electrical stimulus [1]. Eiichi Fukuda and Iwao Yasuda [2] then related the empirical evidence of electrical potential to piezoelectric property in 1957, since a piezoelectric material, under stress, possesses the ability to produce electric charge at its surface. Ideal examples of piezoelectric materials are quartz crystal and Pb-based ceramics. In the converse effect, a piezo-
electric material will produce strain under the influence of an electrical field. Fukada and Yasuda [2] demonstrated that application of a shearing stress along the long axis of bone caused a voltage to appear on bone surfaces parallel to the axis. Later on, in 1962, Bassett and Becker [3] independently found that bone produces electrical signal under the application of a mechanical stress, but they relate this observation to a semiconductor behaviour [4]. Based on the Becker’s previous works on electrical regeneration phenomenon, Bassett and Becker conjectured that electrical potentials might be linked with the clinically observed adaptive response that occurs in children with healed malaligned fractures. Later, Shamos and Lavine [5] have reaffirmed that the observed bioelectric effects in bone is of a piezoelectric origin and they explained the importance of physiological functions of such electrical potentials in bone remodelling.

Bone can be considered a ‘living biominersals’ since it contains living cells. The dynamic process of bone formation and destruction accounts for growth during the development stages of the body and enables its regeneration in case of fracture. Although bone piezoelectricity is considered one of the driving mechanisms of bone growth, its origin is attributed to its organic constituent, namely collagen fibre, which has also been found to be piezoelectric. Collagen fibre and nanocrystals of carbonated hydroxyapatite make up the hierarchical structure of bone. The role of apatite in bone piezoelectricity is not however established. Bone apatite is not generally thought as piezoelectric [6], but there are conflicting results in the literature [7, 8]. A link between piezoelectricity and adaptive response of bone cells has been suggested [9] but the question concerning the proximate origin of piezoelectricity from bone still remains open. Here we review some key experimental and theoretical works performed on bone piezoelectricity and its physiological significance. Several authors have reviewed piezoelectric behaviour of bone [10-15] but the question of the origin of bone piezoelectricity did not receive due attention. Since piezoelectricity is fundamentally related to the crystal structure, order and polarisation as a result of mechanical stress, we emphasise on these aspects of bone. The role the major bone constituents play in determining its piezoelectric potential and the concomitant physiological behaviour will also be discussed.

**FIG. 1. Basic structure of compact bone** [ref. 14 and 16].

**Bone architecture**

The hierarchical structure of bone is composed of nanocrystalline-carbonated hydroxyapatite, collagen fibres (a triple helix polypeptide based protein) and mucopolysaccharides. Bone is highly vascular and has cells called osteocytes, which has the ability to differentiate into new bone forming cells (osteoblasts) and bone resorbing cells (osteoclasts). Osteocytes occupy a small cavity- lacuna, and the fine tunnels (canaliculi) that radiate from lacunae serve as sites for cytoplasmic activities. These canaliculi also give rise to a very densely populated interconnected canal system, which gives bone its characteristic porous and permeable structure [14, 16].

Microscopically, a compact bone consists of osteons and interstitial lamellae. Osteon is an irregular-shaped hollow cylinder and consist mainly of finely interleaved collagen fibres and nanocrystalline HA [17]. Osteons also consist voids, which host blood vessels and capillaries along with osteocytes[14]. The osteons are usually oriented parallel to long axis of bone shaft and the walls have a definite lamellar structure. Within each lamella of the osteons, collagen fibres have one predominant direction, while this direction can vary from osteon to osteon.

**Bone piezoelectricity and theoretical modelling**

Piezoelectricity has been experimentally observed both in dry and wet state. The methods used include inter alia static, quasi static and low frequency dynamic methods using direct piezoelectric effect. Converse piezoelectric effect was also observed. Samples from different origins: human, bovine and horse have been tested. Most of these samples were obtained from femur, for the compactness of sample and convenience in handling. A list of numerical values obtained from these experiments is summarised in ref. 14. It will be useful to discuss some of the fundamentals of piezoelectricity before we start looking into bone piezoelectricity.

Piezoelectricity is a property of crystal that originates from the absence of a centre of symmetry in the crystalline structure. Among the total 32 crystal classes, there are 21 crys-
tual classes that do not possess a centre of symmetry and are piezoelectric[18]. However, the above mentioned point groups are not sufficient for discussing symmetry of physical properties, especially for polycrystalline samples and highly oriented polymers, and consideration of Curie’s limiting group with infinite rotation symmetry is required [18]. Mathematically, piezoelectricity is described within a material’s constitutive equation, which defines how the piezoelectric material’s stress (T), strain (S), charge-density displacement (D), and electric field (E) interact: $S = \varepsilon T + dE$ and $D = e + eE$, where, $s_{ik}$ means the compliance measured under a constant or zero applied electric field, $e$ represents the permittivity measured at constant, or zero applied stress, and $d$ represents a third order tensor and known as piezoelectric strain coefficients. The SI unit for $d$ is pC N$^{-1}$, which is a direct measure of generated charge (measured in Coulomb, C) as a function of applied force (measured in Newton, N). The value of piezoelectric polarisation can be directly found from the piezoelectric stress coefficient $e$, which is related to the strain coefficient through the materials stiffness $c$ (a fourth-rank tensor as: $e = d_{ij} c_{ij}$ (Eq.1) and measured by the amount of charge generated over a given area (C m$^{-2}$). The stiffness, $c$ is related to the compliance, $s$ by the Kronecker delta as $c_{ij} s_{ij} = d_{ij}$ (Eq.1).

As a third rank tensor $d$ or $e$ coefficients have 18 elements. In the matrix notation it is described as:

$$
\begin{bmatrix}
  d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\
  d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\
  d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \\
  d_{41} & d_{42} & d_{43} & d_{44} & d_{45} & d_{46} \\
  d_{51} & d_{52} & d_{53} & d_{54} & d_{55} & d_{56} \\
  d_{61} & d_{62} & d_{63} & d_{64} & d_{65} & d_{66}
\end{bmatrix}
$$

(Eq. 2),

where 1, 2, 3, 4, 5 and 6 directions are defined as shown in FIG. 3. These 18 coefficients are reduced to a simpler form by considering their symmetry. The original hexagonal hollow-symmetric ($A_2$ or $D_3$) symmetry for bone proposed by Fukada [2] had only the $d_3$ coefficients to measure. This symmetry, which was later found wrong, suggested that bone should not exhibit pyroelectricity. Collagen fibre belongs to point group 3, which has a three-fold rotational axis (FIG.3.b [19]) as its single element of symmetry [20] and thus it should be pyroelectric. Lang [21] proved that bone and tendon (predominantly made of collagen fibres with no apatite) both showed pyroelectricity and belonged to a hexagonal polar class with cylindrical symmetry ($A_2$ or $C_3$) as below:

$$
\begin{bmatrix}
  0 & 0 & 0 & d_{14} & d_{15} & 0 \\
  0 & 0 & 0 & d_{24} & -d_{25} & 0 \\
  0 & 0 & 0 & d_{34} & d_{35} & 0 \\
  \end{bmatrix}
$$

(Eq. 3).

This matrix is appropriate for a material with a linear texture and spontaneous polarisation along that axis, as was approximately the case for tendon and, to a lesser degree for bone. Considerable effort was invested to prove this symmetry experimentally, but instead of only 4 independent piezoelectric coefficients as suggested in Eq. 3, finite values were measured for all the 18 piezoelectric coefficients in the matrix shown in Eq. 2. A slight misorientation of the collagen fibre from the fibre axis was held responsible to such lowering of symmetry, with the belief that bone piezoelectricity resulted from its collagenous crystal only [22]. Recent results on bone morphology suggests a more random orientation than that was usually thought and a biaxial orientation of bone apatite.

The proposition that bone piezoelectricity originates from collagen fibre found experimental evidence when Marino and Becker [6] measured piezoelectricity in deminerallised bone, but could not find piezoelectricity in de-collagenated bone. However, piezoelectricity could still be found in bones that have been boiled for 2 hours, boiled and dried at 120°C (collagen denatures at ~60°C) for 5 hours, freshly excised bones and bones that have been just dried [2,23]. These treatments should effect the mechanical properties of organic materials and consequently, piezoelectricity should have been substantially compromised if collagen were solely responsible for bone piezoelectricity. Interestingly, even after using practically similar method to that as used by Marino and Becker [6] for obtaining de-collagenation, bone apatite was found piezoelectric in dynamic measurements [7,24].

The effect of hydration, however, showed considerable effect on collagen as practically no piezoelectricity was found in tendon at 100% relative humidity. It has been suggested that the bound water in the material may change the symmetry to the point where no piezoelectricity can be observed [25, 26]. To the contrary, wet bone exhibited higher piezoelectric coefficients and some of the coefficients (such as the $d_3$ coefficients) were over 50 times higher than those of dry bone [26]. The nature of electricity in bone is a steady-state potential measured as dc-potentials on the surface of living tissue and therefore relates to mechanically induced charge separation (i.e. piezoelectric polarisation) or to a concentration gradient between cations and anions at a surface giving
rise to a surface potential called zeta (z-) potential [27]. Under an electric field across the bone/body fluid interface, electrokinetic phenomenon (streaming potential) results when one phase moves with respect to the other. Recent theories [28,29] suggest that, when considered in non-classical sense, both piezoelectric polarisation and electrokinetic potential can be responsible for the electromechanical response of bone. No role for apatite was however suggested.

Physiological significance

Many authors have reported a correlation between bone piezoelectricity and its physiological significance [1, 3, 4, 9, 11, 14, 15, 27, 30]. As bone is pyroelectric, it has permanent dipoles. Ateshianstadi [31] has demonstrated electric polarisation pattern in the lower extremity of an infant (FIG.4) and explained the role of polarisation in ossification process. When a human reaches a certain age, radial polarisation disappears but longitudinal polarisation remains. So, if one creates an artificial radial polarisation vector in an area in the proximity of bone, then bone growth and regeneration can be induced locally in the radial direction [30,31], thus theorising experimentally observed electrical stimulation of osteogenesis. Based on piezoelectric polarisation in shear, Gurelsu calculated that, in wet bone, time required for deposition of an apatite layer having the same thickness (~10mm) as that of an osteon was about 12 days [30]. Bone can adjust its densities and orientations according to their functions. This response of bone to its functionality is known to occur in accordance with Wolff’s law. In bone remodelling, this works as a feedback mechanism. While polarisation (piezoelectric or electrokinetic) in bone has been considered as responsible for such feedback mechanism, no quantitative insight is available for the ossification process under streaming potential.

To some extent, bone remodelling is a continuous process. A constant source of charge generation is required to sustain the process. Both piezoelectric and electrokinetic phenomena qualify as being the source in vivo. Whether they are competing or completing phenomenon is a matter of debate. However, it is interesting to note that in bone piezoelectric polarisation (~1.89 mC/m²) exceeds electret polarisation (~0.1 mC/m²). In contrast, electret polarisation in collagen (~1 mC/m²) is almost two orders higher than its piezoelectric polarisation. It is therefore reasonable to assume that collagen piezoelectricity on its own should not exhibit osteogenesis capability. Indeed, decalcified bone (essentially fully of collagen) had failed to cause bone growth despite that its chemical and piezoelectric property was unchanged [27]. To compare, the maximum electret polarisation in pure hydroxyapatite has been reported is ~150 mC/m² [32], which is less than a quarter of what has been predicted theoretically for piezoelectric hydroxyapatite [33]. Apatite in bone is a carbonated form of hydroxyapatite, which as a single crystal, may or may not be piezoelectric, nevertheless, as has been argued by Shamos and Lavine [5], the ordered assemblage of small hydroxyapatite crystals within the bone structure may show this property. In other words this will mean that, in addition to providing mechanical stiffness to compact bone and working as a Ca-storage bank, there is also a physiological role for bone apatite.

Conclusions

Key experimental and theoretical works performed on bone piezoelectricity over the last five decades were critically reviewed here. It has been found that, despite numerous efforts, the origin of bone piezoelectricity is not well understood. The physiological significance of polarisation in bone was well studied but there are controversies as related to what causes this polarisation in vivo. Most of the studies reviewed here considered collagen fibre as the origin of bone piezoelectricity and its physiological significance. A quantitative insight into the polarisation in bone, however, puts question to such assumption. Finally the study suggested that, bone apatite, similar to collagen can be piezoelectric too. Whether this is the case or not will remain a matter of further research.

Reference