Electromechanical properties of dried tendon and isoelectrically focused collagen hydrogels

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1. Introduction

Collagenous tissues comprise a major constituent of the extracellular matrix, providing structural support for cells, and performing important developmental and physiological functions [1]. The tissue-specific orientations of collagen fibrils give rise to different functional and mechanical properties [2]. Piezoelectricity is a functional property of collagen, and thus collagen will generate charge under strain (direct piezoelectric effect), and, conversely, undergo deformation in an applied electric field. The direct effect has been linked with the ability of bone to grow and remodel in response to directionally dependent applied stress [3]. Studies of macroscopic electro-mechanical coupling have shown that collagenous tissues such as bone, tendon, dentin, and skin [3–6] all exhibit piezoelectricity. Fibril-forming collagens are composed of collagen molecules, which are hydrogen bond stabilized triple-helical molecules consisting of three polypeptide chains [7]. Collagen molecules have a polar orientation directed from the amino (N)-terminus towards the carboxyl (C)-terminus. Type I collagen molecules self-assemble under appropriate conditions to form fibrils, which maintain the unipolar (N to C) orientation of the monomers at the fibril ends [2]. The staggered stacking of collagen molecules in a fibril gives rise to the characteristic 67 nm D-periodicity, which corresponds to the gap and overlap regions of the molecules, while the cross-sectional hexagonal packing of collagen molecules has been suggested to be the origin of collagen piezoelectricity [5].

Previous studies have demonstrated the potential of collagenous scaffolds [8] and hydrogels [9] for tissue engineering applications [10]. The ability to assemble collagenous scaffolds in vitro with the same structure and properties as natural collagenous tissues would be of significance for studying cell–matrix interactions, as well as for developing compatible engineered tissues. In addition, comparing the electro-mechanical properties between natural collagenous tissues and engineered collagenous constructs could help understand the biological significance of piezoelectricity in collagen. Numerous approaches to assemble fibrillar collagen structures have been implemented, including hydrodynamic flow in the presence of potassium [11,12], magnetic field alignment [13], dip-pen lithography [14], chemical nanopatterning [15], microfluidics [16], and atomic force microscopy (AFM) manipulation [17]. Recent attempts to align collagen by electrochemical processes have demonstrated successful alignment of anisotropically oriented collagen molecules [9,18].