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Short communication

Electrical conductivity and ion diffusion in porcine meniscus: effects of strain, anisotropy, and tissue region

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ABSTRACT

The purpose of the present study was to investigate the effects of mechanical strain, anisotropy, and tissue region on electrical conductivity and ion diffusivity in meniscus fibrocartilage. A one-dimensional, 4-wire conductivity experiment was employed to measure the electrical conductivity in porcine meniscus tissues from two tissue regions (horn and central), for two tissue orientations (axial and circumferential), and for three levels of compressive strain (0%, 10%, and 20%). Conductivity values were then used to estimate the relative ion diffusivity in meniscus. The water volume fraction of tissue specimens was determined using a buoyancy method. A total of 135 meniscus samples were measured; electrical conductivity values ranged from 2.47 mS/cm to 4.84 mS/cm, while relative ion diffusivity was in the range of 0.235 to 0.409. Results show that electrical conductivity and ion diffusion are significantly anisotropic ($p < 0.001$), both being higher in the circumferential direction than in the axial direction. Additionally, the findings show that compression significantly affects the electrical conductivity with decreasing conductivity levels corresponding to increased compressive strain ($p < 0.001$). Furthermore, there was no statistically significant effect of tissue region when comparing axial conductivity in the central and horn regions of the tissue ($p = 0.999$). There was a positive correlation between tissue water volume fraction and both electrical conductivity and relative ion diffusivity for all groups investigated. This study provides important insight into the electromechanical and transport properties in meniscus fibrocartilage, which is essential in developing new strategies to treat and/or prevent tissue degeneration.

1. Introduction

The fibrocartilaginous meniscus is a charged, hydrated soft tissue important for load distribution, maintaining congruency, and aiding in lubrication in the knee (Makris et al., 2011). The tissue has a composition more similar to temporomandibular joint (TMJ) cartilage than hyaline cartilage, with high water content (~70%), and the remaining comprising mostly collagen (~75% dry weight, primarily type I) with small quantities (2–3% dry weight) of proteoglycans (PGs) (Almarza and Athanasiou, 2004). PGs are large, negatively charged molecules formed by glycosaminoglycans (GAGs) linked to a core protein; the negatively charged anions attached to GAG molecules attract positive cations in the surrounding fluid thus creating the Donnan osmotic pressure. This contributes to tissue hydration and related compressive properties, as well as allowing for the mechano-electrochemical responses in the tissue (Fithian et al., 1990; Hardingham and Fosang, 1992; Mow et al., 1999; Sweigart and Athanasiou, 2001).

Electrical conductivity is an important material property of biological tissues that depends on ion diffusivities and concentrations within the tissues, which are related to tissue composition and structure (Frank et al., 1990; Maroudas, 1968). The electrical conductivity of several cartilaginous tissues has been investigated, see Table 1. These studies have found that conductivity is directly correlated to tissue water content (Gu and Justiz, 2002; Gu et al., 2002; Gu et al., 2004; Jackson et al., 2009; Kuo et al., 2011; Wright et al., 2013), and is strain-dependent (Jackson et al., 2009; Kuo et al., 2011; Wright et al., 2013). Better understanding of electromechanical properties of tissues, including conductivity and ion transport, and their relationship to tissue composition and relevant loading conditions, can provide essential information about endogenous electrical signals, which play a key role in directing resident cellular activity.

Electrical conductivity can be used to estimate the relative ion diffusivity in a tissue (Gu et al., 2004; Jackson et al., 2006; Kuo et al., 2011; Wright et al., 2013). Elucidating transport properties in meniscus is important given that much of the adult meniscus is

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Table 1
Comparison of electrical conductivity and tissue water volume fraction in uncompressed tissues between porcine meniscus and other cartilaginous tissues from the literature. Results were found at 0% compressive strain and are shown as mean ± standard deviation.

Tissue	Conductivity (mS/cm)	Relative diffusivity	Water volume fraction	References
Porcine meniscus	3.66 ± 0.41	0.34 ± 0.03	0.69 ± 0.04	Present study
Human TMJ disc	5.49 ± 0.97	~0.44–0.49	0.77 ± 0.01	Wright et al., 2013
Porcine TMJ disc	3.10 ± 0.68	0.27 ± 0.06	0.73 ± 0.02	Kuo et al., 2011
Human articular cartilage	6.5–8.5	~0.40	–	Maroudas 1968
Porcine annulus fibrosis	5.60 ± 0.89	–	0.74 ± 0.03	Gu et al., 2002
Human annulus fibrosis	7.50 ± 0.80	–	0.80 ± 0.02	Jackson et al., 2009

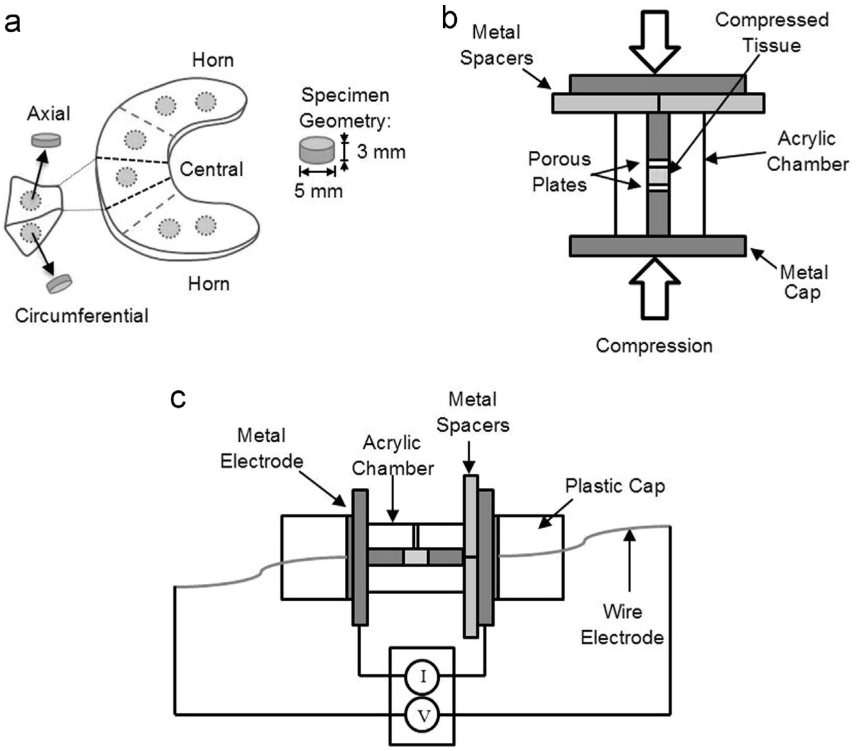

Fig. 1. (a) Schematic showing locations and sizes of test specimens. The meniscus was divided into central and horn regions (demarcated by larger dashed lines). From the central region, both axial and circumferential specimens were prepared; only axial specimens were prepared from the horn region. All specimens were cylindrical with a height of ~3.0 mm and a diameter of 5 mm. Samples from both medial and lateral menisci were pooled. (b) Schematic drawing of the specimen compression chamber. A vise clamp was used to hold the tissue in place and slowly compress the chamber until it was flush with the metal spacers. (c) Schematic of the custom-designed chamber for measuring the electrical conductivity. The metal spacers between the chamber and one of the metal electrodes are used to control the amount of uniaxial confined compression on the specimen; that is, the spacer matches the desired compressed height of the tissue (i.e., for a 3.00 mm thick specimen at 0% strain, the spacer is used to make a 3.00 mm space in the chamber).

avascular (Makris et al., 2011). As a result, essential nutrients are supplied by vasculature in outer tissue regions and surrounding synovial fluid. Solute concentrations in the tissue are related to transport rates through the ECM (i.e., solute diffusivities). Thus, better understanding transport properties in meniscus can provide necessary information regarding the chemical environment in the tissue.

Increased knowledge of electromechanical and transport properties in meniscus is important for fully understanding structure-function relations in the tissue. Such information is valuable in developing novel strategies for meniscus repair and/or regeneration (e.g., tissue engineering or drug delivery approaches) and can be employed in theoretical modeling, used to predict the in vivo environment in the meniscus. To our knowledge, no previous study has investigated the electrical conductivity and/or ion diffusivity in meniscus fibrocartilage. We hypothesized that electrical conductivity and ion diffusivity in porcine meniscus is strain-dependent, anisotropic, and region-dependent. Therefore, our objective was to measure the electrical conductivity of porcine meniscus from two tissue regions, in two directions, and under three levels of compression. This information was then used to estimate relative ion diffusivity in the tissue.

2. Materials and methods

2.1. Specimen preparation

Fifteen menisci were harvested from the knees of 9 pigs (Yorkshire, ~20–25 weeks) obtained from a local abattoir within one hour of death. Cylindrical specimens ($d=5$ mm, $h=3.06 \pm 0.27$ mm) were punched using a corneal trephine and trimmed to the desired height using a microtome with freezing stage. Specimens were harvested from either the central or horn region in either axial or circumferential orientation, see Fig. 1(a). A total of nine groups were investigated, including three orientation/regions [axial central (A–C), axial horn (A–H), circumferential central (C–C)] and three levels of compressive strain (0%, 10%, 20%). In each group, fifteen ($n=15$) samples were measured, for a total of 135 tissue specimens; only one conductivity measurement was taken on each sample.