Uncoupled poroelastic and intrinsic viscoelastic dissipation in cartilage

Guebum Han[a], Cole Hess[a], Melih Eriten[a], Corinne R. Henak[a,b,*]

[a] *Department of Mechanical Engineering, University of Wisconsin-Madison, 1513 University Ave, Madison, WI 53706, USA*
[b] *Department of Biomedical Engineering, University of Wisconsin-Madison, 1550 University Ave, Madison, WI 53706, USA*

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ABSTRACT

This paper studies uncoupled poroelastic (flow-dependent) and intrinsic viscoelastic (flow-independent) energy dissipation mechanisms via their dependence on characteristic lengths to understand the root of cartilage's broadband dissipation behavior. Phase shift and dynamic modulus were measured from dynamic micro-indentation tests conducted on hydrated cartilage at different contact radii, as well as on dehydrated cartilage. Cartilage weight and thickness were recorded during dehydration. Phase shifts revealed poroelastic- and viscoelastic-dominant dissipation regimes in hydrated cartilage. Specifically, phase shift at a relatively small radius was governed by poroviscoelasticity, while phase shift at a relatively large radius was dominantly governed by intrinsic viscoelasticity. The uncoupled dissipation mechanisms demonstrated that intrinsic viscoelastic dissipation provided sustained broadband dissipation for all length scales, and additional poroelastic dissipation increased total dissipation at small length scales. Dehydration decreased intrinsic viscoelastic dissipation of cartilage. The findings demonstrated a possibility to measure poroelastic and intrinsic viscoelastic properties of cartilage at similar microscale lengths. Also they encouraged development of broadband cartilage like-dampers and provided important design parameters to maximize their performance.

1. Introduction

Articular cartilage is a connective tissue that functions as a load-bearing and dissipative material over a broadband spectrum of loading frequency. Cartilage has a heterogeneous structure composed of the dense solid matrix (e.g., collagen fibrils and proteoglycans) and fluid (Mow et al., 1992). Fluid is the largest constituent (about 60 – 85% of wet weight), and it plays an important role in swelling interfibrilar space (about 30% of total water) and extrafibrilar space (Maroudas et al., 1991; Mow et al., 1992; Torzilli, 1985). Cartilage dehydrate and rehydrate due to pressure-induced exudation of fluid through the solid matrix under normal loading conditions in vivo. Time-dependent properties of cartilage are from coupled mechanisms of the solid matrix and fluid flow. The mechanisms have been characterized as poroelasticity and intrinsic viscoelasticity, resulting in efficient and sustained broadband dissipative properties (Nia et al., 2011, 2013; Fulcher et al., 2009; Lawless et al., 2017).

Previous studies have provided evidence on poroelasticity and intrinsic viscoelasticity of cartilage, but the relative contributions of the two are unclear. Poroelasticity-driven dissipation and response originates from solid-fluid frictional (viscous drag) interaction, and therefore is flow-dependent (Nia et al., 2011, 2015). Previous studies showed that poroelasticity-driven dissipation was dominant at relatively small

length scales (about 5–6 μm) under oscillatory loading (Nia et al., 2011, 2013). Intrinsic viscoelasticity-driven dissipation is associated with delay due to molecular friction and rearrangement of a solid matrix (Nia et al., 2011, 2015), and therefore is flow-independent (June et al., 2009; Lai and Hu, 2017; Mak, 1986). Previous work measured intrinsic viscoelasticity of cartilage by employing macroscale compression tests (Fulcher et al., 2009; June et al., 2009; Lawless et al., 2017; Mak, 1986) and small magnitude shear loading (Henak et al., 2016). Although a few studies have individually measured poroelasticity (Nia et al., 2011, 2013) and intrinsic viscoelasticity of cartilage (Fulcher et al., 2009; Lawless et al., 2017) over a wide spectrum of frequency, their relative contributions have not been uncoupled from each other. Also, it is difficult to utilize previously reported results to uncouple the mechanisms because test length scales (about 5–6 μm for poroelasticity (local) versus about 5 mm for intrinsic viscoelasticity (full-thickness)) are polarized, and therefore depth-dependent heterogeneous structure (e.g., collagen direction and diameter) of cartilage cannot be compared precisely.

Poroelasticity-driven dissipation is length-dependent, while intrinsic viscoelasticity-driven dissipation is not. This difference provides a means to distinguish the contributions of the two. Poroelastic dissipation is flow-dependent, and therefore is associated with characteristic poroelastic diffusion time. The diffusion time is proportional to the
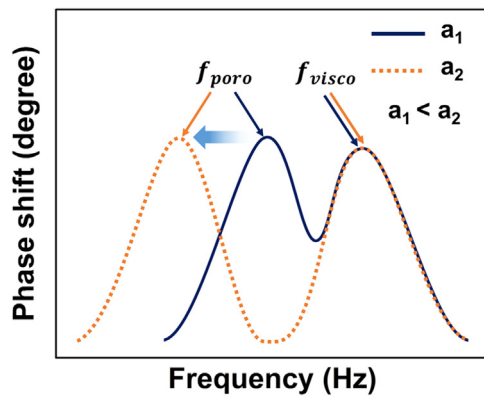

Fig. 1. Schematic diagram of dependence of poroelastic and intrinsic viscoelastic energy dissipation on contact radii. The poroelastic peak frequency, f_{poro}, is inversely proportional to the square of the contact radius, a (Eq. (5)). Therefore, the effects of the two mechanisms can be uncoupled by performing dynamic testing at different contact radii.

squared of a characteristic length (e.g., contact radius) (Lai and Hu, 2017; Nia et al., 2011). Consequently, a characteristic length can govern poroelasticity-driven dissipation. A poroelasticity-driven dissipation spectrum moves toward a low frequency range as a characteristic length increases, and its peak frequency, f_{poro}, can be estimated with poroelastic diffusion time (Fig. 1) (Lai and Hu, 2017; Nia et al., 2011). In contrast, intrinsic viscoelastic dissipation is flow-independent (June et al., 2009; Lai and Hu, 2017; Mak, 1986). Accordingly, an intrinsic viscoelasticity-driven dissipation spectrum and its peak frequency, f_{visco}, are independent of a characteristic length (Fig. 1). Consequently, the two dissipation mechanisms can be distinguished over a broad frequency range by carefully selecting characteristic lengths.

The main aim of this study is to understand the origin of cartilage's broadband dissipation behavior by uncoupling the poroelastic and intrinsic viscoelastic dissipation mechanisms through their dependence on characteristic lengths. Phase shifts, a measure of dissipation, were measured at three different contact radii (characteristic lengths). Results of phase shifts were compared to uncouple the dissipation mechanisms. Dynamic moduli were also measured to examine dynamic response of cartilage based on the uncoupled dissipation mechanisms. In addition, phase shift and dynamic modulus of dehydrated cartilage were measured to further investigate the effect of fluid loss on broadband dissipative and mechanical properties.

2. Methods

2.1. Sample preparation

Full-thickness cartilage samples were harvested from patellae of porcine joints (12 animals, 5–6 months old, gender unknown and assumed random). Cylindrical samples with a diameter of 6 mm were obtained using a biopsy punch and a scalpel. Subchondral bone was trimmed using a microtome to create a level articular surface for indentation testing. The deep zone of each sample was adhered to the center of a glass petri dish (Loctite 495, Henkel, Germany). Dulbecco's phosphate-buffered saline (DPBS) was used to keep samples hydrated during preparation.

2.2. Dehydration curve of cartilage

Dehydration of cartilage was evaluated to determine how long to dehydrate cartilage for testing. Samples were dehydrated at room temperature of 20.9 °C and relative humidity of 25%. The weight of cartilage was measured every 10 min for 3 h using an analytical
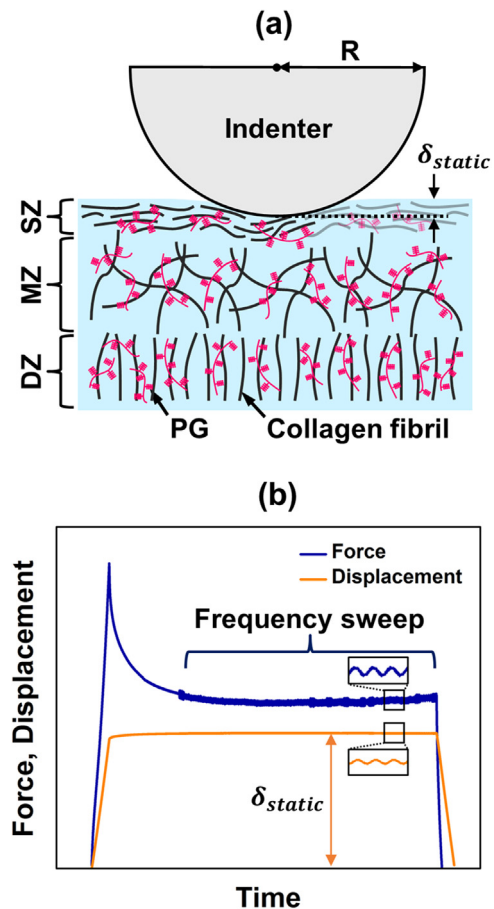

Fig. 2. (a) Schematic diagram of contact between impermeable indenter and cartilage and (b) representatives of force-time and displacement-time curves from hydrated cartilage. R and δ_{static} are the tip radius and the static displacement, respectively. SZ, MZ, and DZ are superficial zone, middle zone, and deep zone, respectively. Since δ_{static} (about 1–3 μm) was shallow, the measured values were from SZ (10–20% of total thickness (Mow et al., 1992) = about 300 μm).

electronic balance (MS104TS, Mettler Toledo, OH). After 3 h, the weight of cartilage was measured every 20 min until 4 h of dehydration, and then the weight was measured at 5 h. The thickness of cartilage was also measured every 45 min using a digital caliper before 2 h of dehydration. After 2 h, the thickness was measured every hour until 5 h of dehydration. The measured weight and thickness of cartilage during dehydration were normalized with the initial weight and thickness. A total of three samples were tested, they were from one patella.

2.3. Broadband dynamic indentation tests

Dynamic microindentation tests were conducted to measure phase shift and dynamic modulus, in order to uncouple poroelastic and viscoelastic effects. Tests were conducted on a Hysitron TI950 TriboIndenter (Bruker Inc, Minneapolis, MN) using a diamond spheroconical indenter with a tip radius of 50 μm and cone semi-angle of 45°, and a sapphire spherical indenter with a tip radius of 1 mm. For each test, a static displacement was applied and held until equilibrium, then a small amplitude (0.5–2 nm) frequency sweep was applied. Open-loop control setting was used, resulting in curves similar to force-relaxation curves for hydrated cartilage (Fig. 2b) and curves similar to creep curves for dehydrated cartilage. A slight drift in force measurement was observed, likely from thermal drift (Lai and Hu, 2017). A reference frequency technique was employed to minimize the effect of the drift by correcting contact area based on measured stiffness at a reference