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The region-dependent biphasic viscoelastic properties of human temporomandibular joint discs under confined compression

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ABSTRACT

The objective of this study was to determine the biphasic viscoelastic properties of human temporomandibular joint (TMJ) discs, correlate these properties with disc biochemical composition, and examine the relationship between these properties and disc dynamic behavior in confined compression. The equilibrium aggregate modulus (H_A), hydraulic permeability (k), and dynamic modulus were examined between five disc regions. Biochemical assays were conducted to quantify the amount of water, collagen, and glycosaminoglycan (GAG) content in each region. The creep tests showed that the average equilibrium moduli of the intermediate, lateral, and medial regions were significantly higher than for the anterior and posterior regions (69.75 ± 11.47 kPa compared to 22.0 ± 5.15 kPa). Permeability showed the inverse trend with the largest values in the anterior and posterior regions ($8.51 \pm 1.36 \times 10^{-15}$ m^4/Ns compared with $3.75 \pm 0.72 \times 10^{-15}$ m^4/Ns). Discs were 74.5% water by wet weight, 62% collagen, and 3.2% GAG by dry weight. Regional variations were only observed for water content which likely results in the regional variation in biphasic mechanical properties. The dynamic modulus of samples during confined compression is related to the aggregate modulus and hydraulic permeability of the tissue. The anterior and posterior regions displayed lower complex moduli over all frequencies (0.01–3 Hz) with average moduli of 171.8–609.3 kPa compared with 454.6–1613.0 kPa for the 3 central regions. The region of the TMJ disc with higher aggregate modulus and lower permeability had higher dynamic modulus. Our results suggested that fluid pressurization plays a significant role in the load support of the TMJ disc under dynamic loading conditions.

0. Introduction

The temporomandibular joint (TMJ) is a load bearing joint with unique articular structure and function (Werner et al., 1991). The TMJ disc, a fibrocartilaginous tissue, is a major component of jaw function by providing stress distribution and lubrication in the joint (Nickel and McLachlan, 1994a, 1994b). The TMJ disc pathophysiology, such as disc derangement, is central to many TMJ disorders (Stegenga et al., 1989), which affects more than 10 million Americans. It is generally believed that pathological mechanical loading, such as sustained mechanical loading during jaw clenching, is the leading cause of TMJ disc derangement (Milam, 2005). Although the exact mechanism has not been established, the understanding of the biomechanical behavior of the TMJ disc is the first step to elucidate the pathophysiology of TMJ disorders.

The TMJ disc has a unique matrix composition and cell phenotype when compared to hyaline cartilage and other fibrocartilaginous tissues (e.g., the intervertebral disc (IVD) or knee meniscus). The human TMJ disc is comprised mostly of water with a significant amount of collagen (mainly type I) and a very small amount of proteoglycans (Berkovitz and Robertshaw, 1993; Nakano and Scott, 1989). Differences in biochemical composition and structure distinguish the disc into three regions: the anterior band, intermediate zone, and posterior band (Rees, 1954). Most recently, finite element models based on the well-known biphasic (poroelastic) theory (Mow et al., 1980) have been developed to examine the viscoelastic mechanical behavior and loading support mechanism of the human TMJ disc (Beek et al., 2003; Donzelli et al., 2004). In these biphasic models, the TMJ disc tissue was considered as a mixture of water phase and solid phase. However, the major limitation of these models is the lack of realistic biphasic mechanical properties for the human TMJ disc. Very few studies have been done to characterize the

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viscoelastic properties of the human TMJ disc (Beek et al., 2001; Tanaka et al., 2000), most likely due to the limited access to human specimens. In all published studies, the TMJ disc was treated as a single-phase viscoelastic solid. To our knowledge, only one study on the porcine TMJ disc has used a biphasic model to fit the indentation data (Kim et al., 2003). The biphasic mechanical properties, such as aggregate modulus and hydraulic permeability, have not been measured for human TMJ disc tissues.

When hydrated soft tissues are subjected to dynamic compression of loading frequencies higher than the characteristic frequency of the tissue, the interstitial fluid pressure will increase significantly and the tissue becomes stiffer due to the fluid pressurization effect (Soltz and Ateshian, 1998). Theoretical and experimental studies in articular cartilage and IVD have shown that the fluid pressurization effect is related to the biphasic mechanical properties of the tissue, such as hydraulic permeability and equilibrium compressive modulus. This effect contributes significantly to the measured dynamic stiffness of the tissue (Soltz and Ateshian, 2000; Yao et al., 2002).

It has been hypothesized that the compressive mechanical load on the human TMJ disc is mainly supported by fluid through the fluid pressurization effect (Tanaka and van Eijden, 2003). A biphasic finite element model of the porcine TMJ disc showed that more than 90% of the load during plowing experiments was supported by the fluid phase (Spilker et al., 2009). However, it is not clear how the biphasic mechanical properties affect the dynamic behavior of human TMJ disc tissue during compression. Therefore, the objective of this study was to determine the regional biphasic viscoelastic properties, as well as dynamic properties, of human TMJ discs in confined compression. Confined compression allows for well controlled 1-D strain state experiments, and compared to indentation and unconfined compression, fewer parameters are needed to be determined by the curve fit in order to obtain more reliable results (Mow et al., 1980). The biochemical composition of the disc was also determined to correlate with the biphasic mechanical properties. The effect of the aggregate modulus and permeability on the dynamic properties was examined to further delineate the load supporting mechanisms in the TMJ disc under compression.

1. Materials and methods

1.1. Specimen preparation

Human TMJ discs from the left joint of fresh cadavers were extracted in conjunction with the MUSC Gross Anatomy Laboratory under institutional approval. The discs were immediately photographed, morphologically examined, and wrapped in gauze soaked in a normal saline solution with protease inhibitors and stored at $-80\,^{\circ}\mathrm{C}$ until mechanical testing. It has been reported that mechanical properties of porcine discs were retained over five freeze–thaw cycles (Allen and Athanasiou, 2005). Discs exhibiting physical signs of trauma, such as fissures or bruises, were discarded. In total, twelve morphologically healthy TMJ discs from twelve male human heads (mean age=78 years) were sectioned and used for mechanical testing. To limit the heterogeneity of the experiment, only samples from male cadavers were used.

Cylindrical tissue plugs were obtained from the intermediate, posterior, anterior, lateral, and medial regions of the TMJ disc (Fig. 1a), using a 5 mm corneal trephine. The plugs were microtomed to remove the natural concave shape of the tissue with a sledge microtome (Leica SM2400) and allow for a flat surface for the confined compression test. Thin layers from both superior and inferior surfaces were removed to prepare disc shaped samples with an average height of 1.4 mm and a diameter of 5 mm.

1.2. Mechanical testing

All mechanical tests were performed in PBS (pH 7.4) on a Perkin-Elmer 7e Dynamic Mechanical Analyzer (DMA). The testing chamber with the sample was maintained at $37 \pm 0.5\,^{\circ}\mathrm{C}$ by a furnace with circulated cooling water. The precision of the DMA for force was 0.5 mN while the precision for displacement measurements was 0.5 μm. A uniaxial, confined compression test chamber was used for testing (Fig. 1b). The specimen was confined laterally by a ring and compressed axially between a porous platen (20 μm average pore size) on the bottom and the test probe (5 mm nominal diameter) on top (Soltz and Ateshian, 2000; Yao et al., 2002). Fig. 1c shows schematically the mechanical testing protocol which will be described in further detail. Prior to testing, measurements for the wet weight and weight in PBS were taken to be used in calculating the water volume fraction of the specimen.

The testing protocol of confined compression was similar to our previous studies on IVD tissues and hydrogels (Yao et al., 2002; Gu et al., 2003). First, the specimen was subjected to a minute compressive tare load (5 mN) to measure specimen height prior to the addition of PBS and this height served as the initial height for all mechanical tests. The specimen was then compressed to the height corresponding to 10% compressive strain (relative to the initial height). This offset

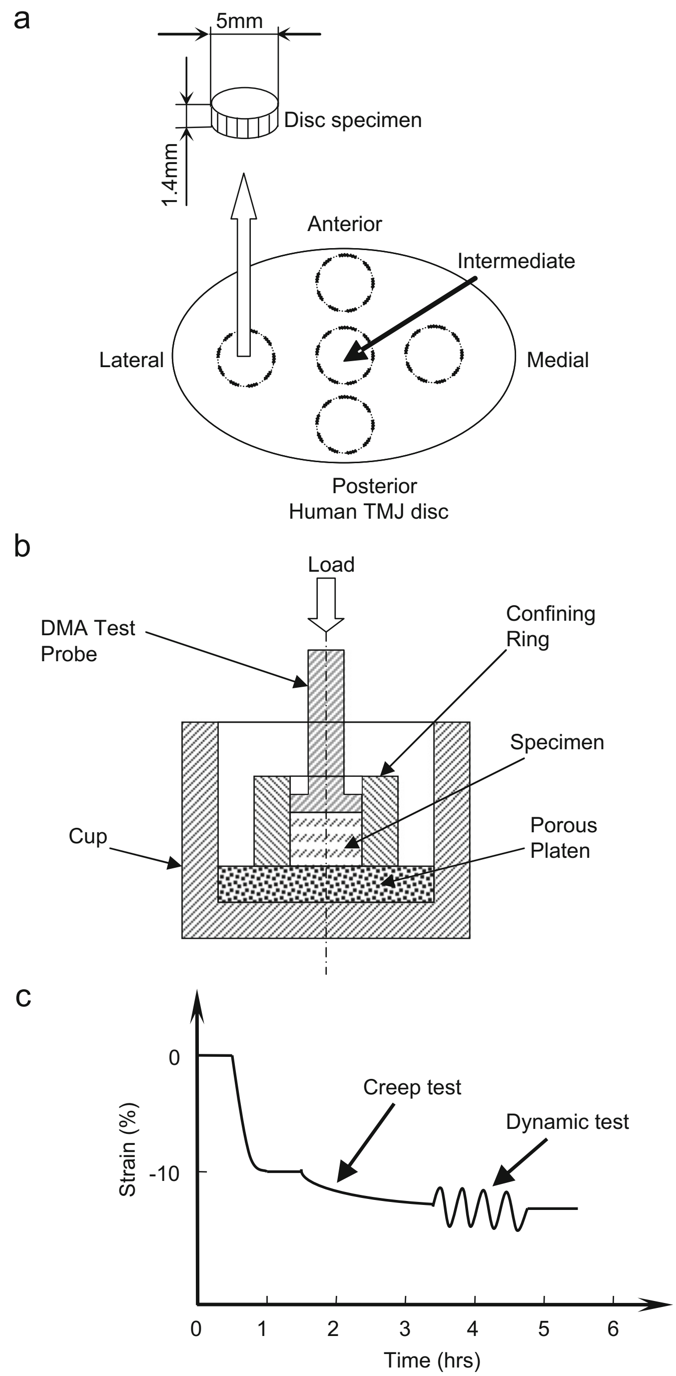

Fig. 1. (a) Schematic of specimen preparation. The region and size of test specimens are shown. (b) Schematic of a uniaxial and confined compression test chamber. (c) Schematic of the mechanical testing protocol.