Introduction

The TMJ, a structurally and functionally complex unit, is enclosed in an articular capsule, which extends from the articular eminence and mandibular fossa superiorly to the neck of the mandibular condyle inferiorly. The condyle is covered and protected by the TMJ disc as the disc slides between the mandibular fossa and articular eminence with joint movement. The presence of the TMJ disc reduces the shape and size incongruence between the condyle and the articular eminence because the disc's biconcave surfaces conform to the shapes of these articulating structures. Furthermore, the TMJ disc separates the articular capsule into superior and inferior joint compartments. The disc is held in place by the disc attachments to the mandibular condyle and the superior belly of the lateral pterygoid muscle. These anatomical structures facilitate a seamless articulation in the biomechanically demanding TMJ.

The fibrocartilage of the TMJ disc and the mandibular condyle and the ligamentous tissues of the disc attachments vary in structural properties according to their functions. Structural properties of the TMJ include the geometry and the architecture of the TMJ tissues as well as the biochemical properties of the extracellular matrix (ECM). The biochemical properties are further broken down into the quantity, distribution, and arrangement of the ECM molecules. These macro- and micro-scale structural properties are closely related to the functions of the TMJ tissues. These functions include resisting and distributing compressive and tensile loads, and lubricating the joint. For example, tissue collagen is responsible for the TMJ disc's tensile and compressive properties. To understand the structure-function relationships in the TMJ tissues, the biochemical constituents and structures as well as the tissue mechanical properties are studied. In this chapter and the following chapter, concepts in biomechanics are first described to lay the foundation, and then the biochemical contents, mechanical properties, and the structure-function relationships are discussed for the TMJ disc, the disc attachments, and the condyle.

A Primer on Biomechanics

As a ginglymoarthrodial (hinge and gliding) joint with complex anatomical structures, the biomechanics of the TMJ are concomitantly elaborate. The TMJ moves in both rotation and translation. When the jaw opens partially, the condyle only rotates and the disc is located superior to the condyle. When the jaw opens fully, both the condyle and the disc translate forward, and the disc positions anteriorly to the condyle. These movements create compressive, tensile, and shear stresses in the articulating tissues. The stresses can be dynamic, from mastication and speech, or static, associated with bruxism or clenching. The soft tissues in the healthy TMJ are able to withstand repeated and high-magnitude stresses, owing to the biochemical composition and fibrous structures in the tissue.

Similar to most biological tissues, the TMJ contains a large amount of water in its soft tissues, resulting in both elastic solid-like and viscous fluid-like properties. The latter gives the tissues time-dependent physical properties. When mechanical forces such as compression or tension are applied to the tissue, the tissue's response to the applied stress changes with time but eventually reaches an equilibrium. The viscous component of the tissue also causes the tissue mechanical properties to be strain-rate dependent. To closely represent

and understand the tissue behavior, mathematical models and equations are often used; one of the most common models used to describe the soft tissues of the TMJ is based on the theory of viscoelasticity. In this theory, the viscous fluid component of the tissue is represented by one or more dampers or dashpots, and the solid elastic component of the tissue is represented by one or more springs. Harnessing the simplicity of these mechanical devices to represent a much more complex tissue behavior, the mathematical modeling of viscoelastic tissues is powerful for understanding the tissue mechanical properties and for predicting tissue behavior.

The TMJ tissues function primarily in tension or compression, and, thus, it is important to characterize the tissue properties under these two forms of stress. The data can then be fitted to a model to obtain quantifiable parameters describing the mechanical properties. Tissues are characterized using viscoelastic mechanical tests, such as creep or stress relaxation. In a creep test, a constant stress is applied to the tissue while the tissue is allowed to deform or "creep" to an equilibrium strain, and the changing strain is recorded. Immediately after the stress is applied, the tissue experiences rapid deformation followed by progressively slower deformation until an equilibrium strain is reached. When the applied stress is removed, tissues return to their original shape and thickness as long as they are not damaged. In contrast to a creep test, a stress relaxation test controls the strain rather than the stress. In this test, a specimen is compressed or stretched to a specific strain while the changing stress is recorded over time. Immediately after the strain is applied to the tissue, the tissue exerts a high amount of stress in response to the applied load, and then the stress gradually decreases over time due to fluid egress through the collagen network until an equilibrium stress is achieved. Instantaneous (or peak) and relaxation moduli as well as the coefficient of viscosity are then obtained. The elastic modulus, also known as Young's modulus, can be extracted from a uniaxial tensile test. Elastic modulus indicates tissue stiffness or how much force is required to deform the tissue. Moreover, ultimate tensile strength (UTS) is often reported since this important parameter is determined as the maximum stress required to fracture the tissue.

These quantifiable material properties are highly valuable for comparing the tissues of various sources. For example, values for pathological TMJ disc can be compared to those of healthy TMJ disc to understand how alterations in the disc's mechanical properties contribute to degeneration and loss of function. Moreover, tissue mechanical values can also be correlated to tissue biochemical content to determine how changes in biochemical content may alter tissue function. Additionally, the mechanical properties of tissue reflect the function of the tissue as the tissue adapts and remodels to its functional demands. Therefore, comparing the mechanical properties of various regions and anatomies of the tissue is informative for understanding how the tissue functions in vivo. Thus, for each of the major tissues described below, the mechanical properties comprise an important aspect of how they function in concert.

Mandibular Condyle

The mandibular condyle forms a convex surface that articulates with the TMJ disc and indirectly with the articular eminence and glenoid fossa of the temporal bone. The mandibular condyle consists of trabecular and compact subchondral bone covered with unique articular cartilage. The

composition and architecture of the tissues of the mandibular condyle are essential for withstanding the complex forces to which the condyle is subjected during normal functions, such as mastication and speech.

Mandibular Condylar Cartilage (MCC)

The cartilage covering the mandibular condyle is different from the cartilage of most diarthrodial joints. The articular cartilage of other diarthrodial joints consists of hyaline cartilage, whereas the mandibular condyle is covered by fibrocartilage. The different type of cartilage covering the mandibular condyle is likely due to differences between the development of condylar cartilage and the development of hyaline cartilage covering long bones of the appendicular skeleton. Like the hyaline cartilage found in other joints, the major role of the condylar fibrocartilage is to allow nearly frictionless movement of the mandibular condyle relative to the TMJ disc, glenoid fossa, and articular eminence during jaw movement. The specific organization and composition of the condylar fibrocartilage has important implications for normal function of the condyle.

The fibrocartilage of the mandibular condyle is organized into four layers or zones. From superior to inferior, these are the fibrous, proliferative, mature, and hypertrophic zones. There are characteristic differences in the cells, ECM, and architecture making up each zone. The fibrous zone contains fibroblasts as the primary cell type and an ECM of dense, organized, type I collagen. The proliferative zone contains mesenchymal cells and a relatively large proportion of type I collagen. The proliferative zone serves as a cell reservoir and as a transition between the superficial fibrous zone and the deeper mature and hypertrophic zones. The mature and hypertrophic zones of the condylar fibrocartilage have characteristics that resemble the hyaline cartilage found in other joints. Chondrocytes are the primary cell type in these zones and randomly organized type II collagen predominates, similar to the middle zone of hyaline articular cartilage. The content and type of proteoglycans also differ between the zones of the condylar cartilage. The four zones of the condylar fibrocartilage help to create a resilient tissue that tolerates complex forces during joint movement.

Composition and Structure

Cartilage consists of 70-80% water, a macromolecular ECM, and a small proportion of cells and other molecules. The ECM of hyaline cartilage primarily consists of collagen and proteoglycans. Collagen comprises 50-75% of the ECM and proteoglycans make up 15-30% of the ECM. In contrast, fibrocartilage of the human knee disc has a similar proportion of collagen (~ 78%), but much less proteoglycan (~ 3%) than hyaline cartilage. Both hyaline cartilage and fibrocartilage exhibit depth-dependent or regional variations in their ECM composition and organization.

Although the composition of mandibular condylar fibrocartilage has not been quantitatively characterized, the four zones of the condylar fibrocartilage contain different proportions and types of ECM macromolecules. The composition of each layer of fibrocartilage reflects the different forces to which each zone is subjected and the contribution each zone makes to the overall function of the mandibular condyle.

Collagen

Collagen is the most abundant molecule in the ECM of both hyaline cartilage and fibrocartilage. Whereas hyaline cartilage contains almost entirely type II collagen, fibrocartilage contains a mix of type I and type II collagens. The functional difference between type I and type II collagen is not well understood. Other types of collagen, such as type III or type X collagen, are found in much smaller amounts in condylar fibrocartilage. The distribution of type I and type II collagen differs among the zones of the condylar cartilage. Type I collagen predominates in the fibrous and proliferative zones of the condylar cartilage where it is responsible for resisting tensile and shear forces near the surface of the condyle. The mature and hypertrophic zones are hyaline-like in their composition and possess mostly type II collagen. Type II collagen in these deeper zones of the condylar fibrocartilage likely contributes tensile stiffness as well as helps resist the osmotic swelling pressure created by proteoglycans. Interestingly, type I collagen is found localized at the posterior aspect of the mature and hypertrophic zones. It has been suggested that this location experiences greater tensile forces than elsewhere in the deeper zones of the condylar cartilage. The organization of the collagen network also differs among the zones of the condylar fibrocartilage. Collagen fibers in the fibrous zone tend to be organized in sheets aligned with the articular surface. Varying degrees of fiber alignment have been observed within these collagen sheets in the fibrous zone. Multiple studies have reported isotropic collagen architecture within these sheets whereas at least two studies found alignment in the anteroposterior (AP) direction. The differing results may be associated with different model species &/or with different means of analysis. In the mature and hypertrophic zones of the condylar cartilage, collagen fibers are oriented randomly in all three planes, creating a fully isotropic collagen network. The fiber orientation and their degree of alignment are important for resistance to tensile and shear forces.

Proteoglycans

Versican is a large, chondroitin sulfate-rich proteoglycan similar to aggrecan that is found in a number of tissues including fibrocartilage. Versican is found in the fibrous and proliferative zones of condylar fibrocartilage of rats and pigs. Both versican and aggrecan increase their expression in the condylar cartilage due to increased compressive forces in the rat TMJ. This suggests that versican contributes to compressive stiffness of the condylar fibrocartilage. It is noteworthy that chondroitin sulfate was not detected in the fibrous zones of the condylar fibrocartilage in nonhuman primates. The varying distribution of chondroitin sulfate and versican suggests that the fibrous and proliferative zones contribute different mechanical properties to the condylar cartilage of different species. **Decorin** is a small proteoglycan with a different role from aggrecan or versican in the condylar cartilage. Decorin consists of a single glycosaminoglycan (GAG) moiety, chondroitin or dermatan sulfate, bound to its protein core. Within the condylar fibrocartilage, decorin is found mostly within the fibrous layer. It is believed to enhance the tensile properties of tissues by influencing collagen fibril synthesis and increasing collagen fiber diameter.

Mechanical Properties

The mandibular condylar cartilage is subject to forces consisting of compression, tension, and shear during normal function. The forces experienced by the condylar cartilage vary depending on location as well as the rate and frequency of loading. The mechanical properties of the condylar fibrocartilage cartilage are both heterogeneous and

anisotropic, reflecting the complex forces to which it is subjected in the demanding environment of the TMJ.

The surface of the mandibular condyle experiences the greatest tensile and shear forces along its AP axis. The collagen content and fiber alignment along the AP direction in the fibrous zone results in anisotropic tensile stiffness. The condylar cartilage exhibits tensile stiffness that is 1.5-2x greater in the AP direction than in the mediolateral (ML) direction. The shear stiffness is also anisotropic with a greater shear modulus in the AP direction.

The compressive properties of condylar fibrocartilage are especially complex. Like hyaline cartilage and the TMJ disc, the condylar fibrocartilage exhibits viscoelastic properties. The viscoelastic nature of the condylar fibrocartilage results in a response to compressive stress that varies with static vs. dynamic loading, magnitude of the applied load, and frequency of loading. Compressive stiffness also varies by location across the condyle. The condylar fibrocartilage exhibits the greatest compressive stiffness at its anterior, medial aspect with decreasing stiffness toward the posterior and lateral aspects of the condyle. Regional variations in compressive stiffness as well as stiffness that varies with loading conditions suggest that healthy condylar cartilage is a highly dynamic tissue capable of responding differently to varying mechanical stimuli.

Osseous Component of Condyle

The bone of the mandibular condyle consists of a thin layer of compact subchondral bone supported by trabeculae oriented perpendicular to the articular surface. The trabecular bone of the mandibular condyle is essentially organized as a series of parallel, sagittally oriented "plates" connected by ML "rods." The organization of trabecular bone creates great mechanical anisotropy of the mandibular condyle. The predicted compressive stiffness of the mandibular condyle is greatest in the superior-inferior direction followed by the AP direction. The condyle is least resistant to compressive stresses oriented in the ML direction. The resistance to shear stress is also expected to be greatest in the sagittal plane and relatively small in either the transverse or frontal planes. Interestingly, the degree of anisotropy is greatest in the inferior part of the condyle with the superior part of the condyle becoming more isotropic. The change in anisotropy is consistent with the inferior part of the condyle being subject primarily to compressive forces in the superior-inferior direction whereas the bone closest to the articular surface is subject to more complex loading conditions.

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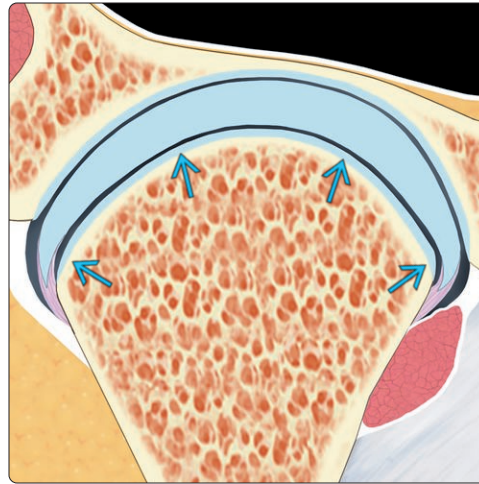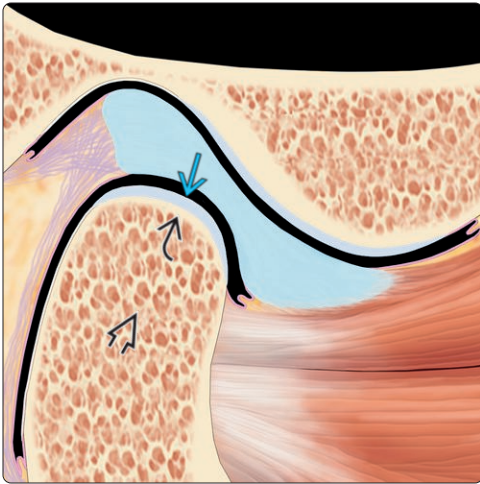
(Left) *Sagittal oblique graphic shows a cross section through the mandibular condyle. The mandibular fibrocartilage ➔ is a thin cap that covers the articular surface of the condyle. The thin subchondral bone ➔ is a product of the growth and maturation of the fibrocartilage. The medullary bone ➔ is porous and houses the marrow.* **(Right)** *Graphic of a coronal oblique cross section shows the mediolateral extent of the mandibular fibrocartilage ➔.*
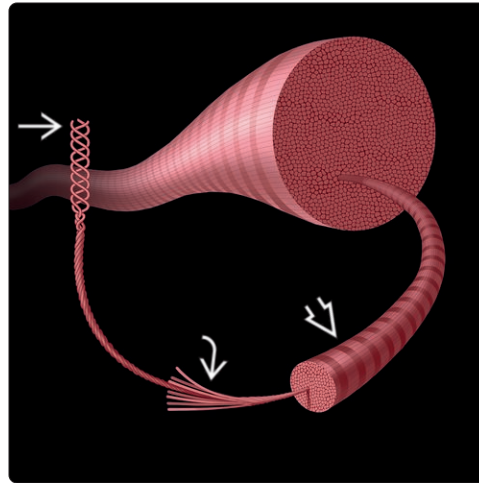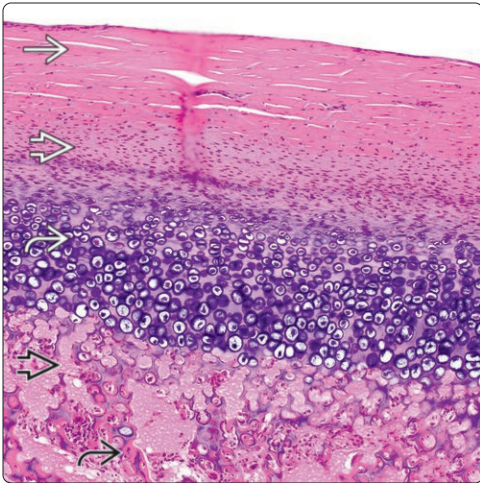
(Left) *Microphotograph of MCC shows the 4 layers of cell types: Fibrous ➔, proliferative ➔, mature fibrocartilage ➔, and hypertropic ➔. Bone formation ➔ is seen beneath the hypertrophic layer. (Courtesy N. Vapniarsky, DVM.)* **(Right)** *Graphic shows the structure of collagen. The smallest unit of collagen is a collagen molecule, which is a triple helix structure ➔. Multiple collagen molecules organize into a collagen fibril ➔. Multiple fibrils in turn associate to form a collagen fiber ➔.*
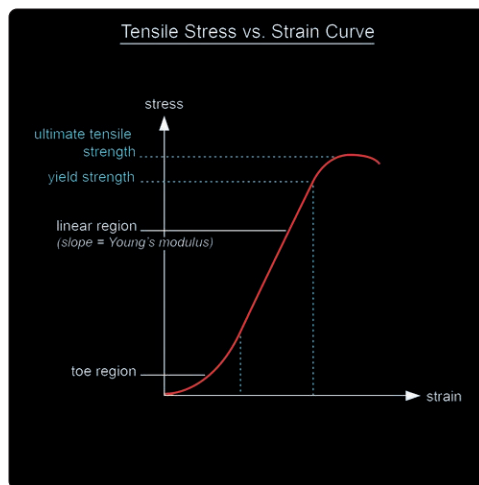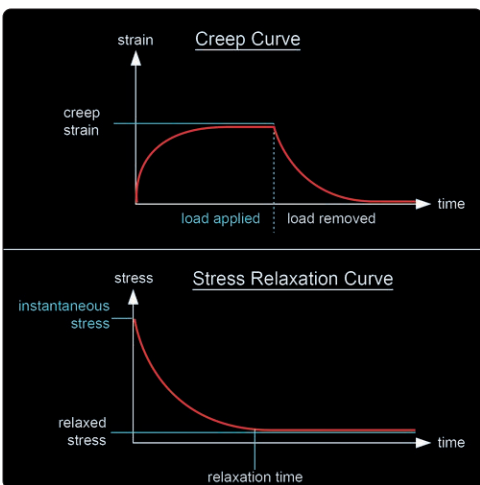
(Left) *Creep and stress relaxation curves of a viscoelastic tissue are shown. In a creep test, tissue deforms rapidly when load is applied, then deforms slowly toward an equilibrium creep strain. The tissue recovers when load is removed. In a stress relaxation test, tissue displays a substantial instantaneous stress, then reaches a lower relaxed stress at equilibrium.* **(Right)** *A typical tensile stress vs. strain curve of a viscoelastic tissue is shown. Slow increase in stress in the toe region is due to presence of crimps in collagen fibers.*