

## The TMJ Disc

The TMJ disc is a fibrocartilage tissue, biconcave and elliptical in shape. The disc provides low friction articulation surfaces in the joint. Moreover, its biconcave profile allows a smooth articulation between two incongruent surfaces of the mandibular condyle and the articular eminence. Without the TMJ disc, the incongruent surfaces would have a small area of contact, creating concentrated stresses in the tissues that can lead to tissue damage. The TMJ disc increases the contact area between opposing articulating surfaces and, thus, distributes lower magnitude stresses to a larger surface area in the joint.

On average, the TMJ disc in an adult human is 19 mm long and 13 mm wide. The disc is longer in the mediolateral (ML) direction than the anteroposterior (AP) direction and, thus, is anatomically compatible with the articulating mandibular condylar surface. The inferior surface of the disc is also closely adapted to the shape of the condylar surface such that the rotational and translational movements occur in a near frictionless manner. In a sagittal view, the disc is divided into three regions: The anterior band, the intermediate zone, and the posterior band. The posterior band is the thickest, measuring approximately 3-4 mm in thickness, and the intermediate zone is the thinnest, measuring approximately 1 mm. The variations in thickness and the contour of the disc create distinguishable regions in the disc, providing varied functions and mechanical properties. The thin intermediate zone allows flexibility, enables smooth articulation, and protects the superior and inferior articulating surfaces. The thick bands fill the space created by the convex surface of the mandibular condyle and also provide structural integrity to the disc. In a coronal view, the disc can be divided into medial, lateral, and central regions. All around its periphery, the disc is attached to the joint capsule via its attachments; medially and laterally, the disc is also attached to the mandibular condyle. Due to these arrangements, the center of the TMJ disc is suspended by the peripheral bands and attachments. Thus, the disc can be conceptualized as a structure similar to a trampoline, where the central region is compressed or stretched and the outer region supports the movements of the central region.

### Composition and Structure

The TMJ disc contains 66-80% water, and the solid constituent is made of collagen, elastin, glycosaminoglycans (GAG), proteoglycans, and cells. Cells are of fibrocytic, fibroblastic, fibrochondrocytic, and chondrocytic phenotypes. The distribution of cells and extracellular matrix (ECM) components vary among the different zones of the TMJ disc according to their contribution to the overall function of the disc.

### Collagen

The predominant ECM component of the TMJ disc is fibrillar collagen type I. Other types of collagen, including types II, III, VI, IX, and XII, are also present in small quantities. The network of collagen in the TMJ disc is extremely dense, and it makes up approximately 30% of the tissue wet weight or 83-96% of the tissue dry weight. The concentration of collagen varies by location in the disc. A higher concentration of collagen is present in the intermediate zone compared to the bands. Collagen is also more concentrated in the medial region than the lateral region of the disc. The collagen network of the TMJ disc is important for resisting tensile forces; the varying

collagen densities throughout the disc lend different tensile properties to each of the zones of the disc.

Collagen fibers are found to have undulations or crimping patterns. When visualized under differential interference contrast microscopy, crimps appear in the collagen fibers at a periodicity of 15  $\mu\text{m}$  on average. Collagen crimping contributes to the mechanical properties of the tissue, when the tissue is subjected to tensile stress. At small tensile strains, the collagen crimps get straightened and then, at large strains, the fibers are stretched and bear load. On the resulting stress vs. strain curve, the toe region of the curve corresponds to the crimps straightening, and the linear region corresponds to the collagen fibers stretching and eventually reaching the breaking point. The presence of crimps allows the tissue to withstand higher strains than it could otherwise.

Collagen distribution in the TMJ disc is anisotropic, meaning that the collagen fibers have a directional alignment rather than random orientation. Such alignment generates high tensile properties in the direction of alignment. When visualized under polarized light microscopy, the collagen fibers in human TMJ discs are observed as thick and compact bundles. Macroscopically, collagen fibers in the intermediate zone align parallel to the disc surface in the AP direction. In the bands, the fibers run circumferentially along the periphery, enclosing the intermediate zone and forming a ring-like structure. These orientations of collagen fibers in the intermediate zone and the bands reinforce the concept that the TMJ disc acts as a trampoline-like structure. The fiber arrangements enable the TMJ disc to withstand radial stresses in the intermediate zone and circumferential stresses in the bands, similar to the stresses borne in the center and the periphery of a trampoline. When the intermediate zone transitions to the bands, the collagen fibers run continuously with those in the bands; however, they become branched and disorganized. In the bands, although collagen fibers still align parallel at the surface of the disc, some fibers below the surface align in the perpendicular or oblique angles in relation to the surface of the disc. These various orientations of collagen fibers weaving through one another form a complex network. Thus, collagen anisotropy is a crucial characteristic in the structure-function relationships and the mechanical properties of the TMJ tissues and is one example of how tissue structure meets functional requirements.

### Elastin

Elastin makes up 3-7% by dry weight of the TMJ disc. While elastin is present throughout the disc, its distribution varies by region. It is distributed 26, 10, 2, and 61% by volume in the anterior band, posterior band, intermediate zone, and posterior bilaminar attachments, respectively. Elastin is speculated to contribute to tissue recovery after deformation to retain shape. Thus, the bilaminar attachment tissues may be more responsible for keeping the disc in place than the disc itself.

### Glycosaminoglycans

Glycosaminoglycans (GAG) make up a much smaller fraction of the ECM, compared to collagen. The GAG content is reported to be approximately 5% of dry weight, ranging from 1-10%. Dermatan sulfate and chondroitin sulfate are the major GAG in the disc. Similar to other ECM components, GAG content varies by region. The intermediate zone and anterior band contain more GAG than the posterior band. Moreover, the medial side contains more GAG than the lateral side. The

negative charges on the GAG chains increase the resistance to fluid flow, keeping the fluid in the tissue for a longer duration under compression, thus contributing to compressive properties.

## Mechanical Properties

The TMJ disc displays viscoelastic material properties that are related to its ECM components described above. Remarkably, the TMJ disc is observed to be 100-1000 times stiffer under tension than compression.

## Compression

The compressive properties reported in the literature for the TMJ disc are inconsistent due to the studies using different sample preparation and mechanical testing methods. However, it is commonly observed that the disc's compressive properties vary by region. Using a stress relaxation method, the instantaneous moduli of the human TMJ disc ranged from 0.2-3.0 megapascals (MPa), depending on the region. The posterior band showed the highest instantaneous modulus value, 1.5 times higher than the anterior band and 3-4 times higher than the intermediate zone. The compressive relaxation moduli follow a similar trend in these disc regions. It is possible that the thick bands surrounding the intermediate zone distribute and reduce stresses better than the thin intermediate zone and, thus, have higher compressive moduli. The compressive properties of the disc may be contributed by both GAG and collagen. It is speculated that when the tissue is compressed, collagen fibers become more condensed and obstructive to fluid flow, and, thus, the density of collagen also plays a role in the compressive properties of the disc.

## Tension

The disc frequently experiences tensile forces during normal joint movements. When the disc is stretched to a small strain, it is more compliant than when it is stretched to a large strain. This effect is due to the presence of periodic crimps in the collagen fibers as described earlier in this chapter. At strains of 0-2%, the instantaneous elastic modulus of the healthy TMJ disc is 44 MPa, compared to 53 MPa for internally deranged tissue. The greater stiffness of the pathologic tissue may be due to remodeling of the tissue associated with the increased mechanical stress and overloading of the tissue. However, the relaxed elastic moduli were not different between healthy and deranged tissues. In a different study, which examined the tensile properties in various regions and directions of the disc, the highest peak and relaxed elastic moduli were observed in the AP direction of the intermediate zone, with values approximately 52 MPa and 35 MPa, respectively. As mentioned earlier in this chapter, this zone also has the greatest degree of collagen fiber alignment, supporting the hypothesis that collagen structure and orientation are essential for robust tensile properties. It also confirms that the primary loading direction of the disc is in the AP direction during joint movement. In contrast, the intermediate zone in the ML direction possesses much lower tensile properties, approximately 10 MPa in peak modulus and 7 MPa in relaxed modulus, as the collagen alignment lacks in this direction. Further, the medial side of the intermediate zone in the AP direction is observed to have the second highest tensile properties, approximately 38 MPa in peak modulus and 31 MPa in relaxed modulus. The tensile properties in both the anterior and posterior bands tested in the ML direction are slightly lower than those in the intermediate zone in the AP direction, with the peak modulus approximately 32 MPa and

the relaxed modulus approximately 23 MPa. As expected from these tensile data, the collagen fibers in the band region are observed to be less organized than the intermediate zone since there are more transversely and obliquely oriented fibers.

## Attachments

The TMJ discal attachments are fibrous connective tissues that surround the disc all around the periphery, connecting the sides of the disc with the TMJ capsule. The posterior region of the disc is continuous with the posterior disc attachment called the bilaminar zone (retrodiscal tissue), which splits into a superior attachment that connects with the posterior wall of the glenoid fossa and an inferior attachment that connects with the base of the condyle at the posterior condylar neck. The anterior disc attachment links the disc to the articular eminence of the temporal bone and the anterior horn of the condyle via the pterygoid fovea. The medial, lateral and anterolateral disc attachments connect the disc to the capsule which in turn attaches to the medial and lateral sides of the condylar neck. The disc and the attachments together separate the joint capsule into superior and inferior joint spaces. Translational motions are associated with the superior joint space, whereas the rotation motions are associated with the inferior joint space. The attachments are crucial for the movement of the disc in the joint as well as for the restoration to the resting position. During condylar movements from TMJ motions, the attachments transmit tensile forces to the disc.

## Composition and Structure

The TMJ disc attachments and the TMJ disc exhibit similarities; however, a few important distinctions differentiate their structural and functional properties. Similar to the disc, the disc attachments are viscoelastic tissues made of 70-80% water and a dry fraction mainly composed of collagen and elastin. However, unlike the disc, the attachments are not fibrocartilage and contain negligible amounts of GAG and type II collagen.

## Collagen

The major type of collagen found in the TMJ attachments is type I. Studies have been performed to quantify the amount of collagen in different attachments. In humans, the amounts of collagen found in the posterior attachments and the lateral attachment are similar, 37.67% and 37.16% of the tissue wet weight, respectively. These amounts are higher than that of the disc, which contains 30% collagen by wet weight. Additionally, in pigs, the collagen contents of various disc attachments are 67-72% collagen by dry weight and there is no statistical difference in collagen content among the different disc attachments.

The collagen fibers in the attachments are thinner compared to those in the disc, but they are observed to have a highly anisotropic alignment similar to the disc. The structure and organization of these fibers are mainly responsible for the tensile properties of the attachments. To understand the structure-function relationships of the attachments, the morphology and the mechanical properties of the disc attachments have been evaluated using the porcine animal model. The images from polarized light microscopy and scanning electron microscopy show that the fibers in the posterior inferior attachment and the medial and lateral attachments align in the AP direction. On the other hand, the

fibers in the posterior superior and anterior superior attachments align in the ML direction. These directional alignments of the disc attachments form a ring-like fibrous structure around the TMJ disc, in continuation with the ring-like structures formed by the TMJ disc bands. This structure leads to the hypothesis that the disc attachments aid in load transmission by the circumferential tensile strains.

## Elastin

Elastin fibers are important for retaining the shape of the attachments. The orientation of the fibers are observed to be parallel to the collagen fibers. The elastin fibers are thicker and more abundant in the disc attachments compared to the disc. A quantitative analysis of elastic fiber density shows that the fibers are significantly denser in the upper bilaminar zone than the lower bilaminar zone, but they are both significantly higher than the density in the TMJ disc. A high density of elastic fibers in the upper bilaminar zone is explained by the fact that it is essential for providing an elastic withdrawing force to pull the TMJ disc from the anterior position to the resting position on top of the condyle during the mandible opening and closing.

## Mechanical Properties

The TMJ disc attachments mainly function to facilitate disc movement and to hold the disc in place relative to the condyle and the articular eminence. The attachments, particularly in the bilaminar zone, are primarily loaded in tension with the jaw opening; however, a small amount of compressive and shear stresses are also produced in this tissue.

The mechanical characterization of disc attachments has not been performed in human tissues; however, studies have been performed using the porcine model due to anatomical and morphological similarities. The tensile properties of the superior attachments are comparable to those of the disc, and, thus, these attachments function and transmit loads in continuation with the disc. The posterior attachments demonstrate tensile properties twice as high as those of the anterior attachments, and, thus, the posterior attachments may experience more substantial tensile stresses than the anterior attachments during normal joint movement. Additionally, the attachments show anisotropy in stiffness. The medial and lateral attachments are stronger in the AP direction, whereas the anterior superior attachment is stronger in the ML direction. These results correspond with the directions of collagen fiber alignment as described above. From these data, it is suggested that the medial and lateral attachments are primarily loaded in vivo in the AP direction and the anterior superior attachment in the ML direction. Overall, the disc is held in place by a combination of both the inferior and the lateral and medial attachments, while the posterior and lateral attachments may be more involved in transmitting load. Therefore, a defect in these attachments can lead to disc displacement.

The posterior attachments in the bilaminar zone tissues, which fill the posterior joint spaces, is likely loaded in compression when the jaw is closed. The bovine bilaminar tissue is highly effective in energy dissipation as it reduces 90% of the instantaneous compressive stress. Therefore, the role of bilaminar zone may be to dissipate energy under normal joint movement, unless the disc becomes displaced. It may experience compressive stresses by the condyle when the TMJ disc is displaced anteriorly and the attachment becomes the articulation surface. However, Tanaka et al reported that

the compressive properties of the bilaminar zone are lower than those of the TMJ disc, thus the posterior attachment can potentially become perforated when compressed repeatedly.

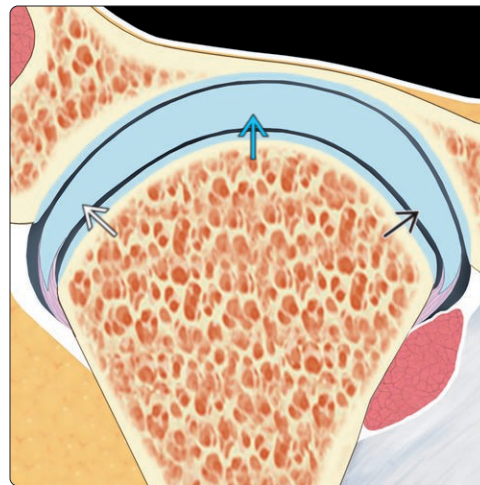
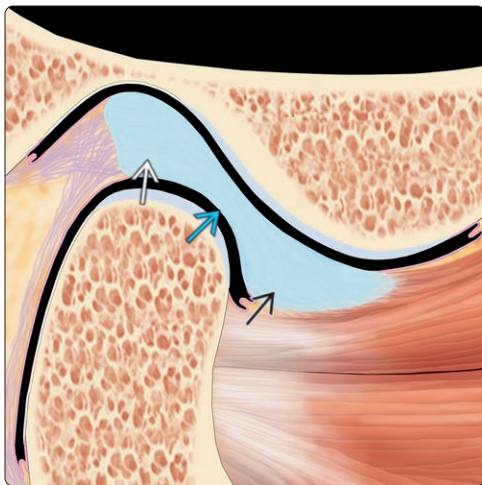
## Summary

Both the macroscopic and microscopic structures of the TMJ joint are intimately related with the overall functions of the joint. The morphological, mechanical, and biochemical analyses of the viscoelastic TMJ components shed light on these structure-function relationships in the TMJ. Macroscopically, the tissue components are shaped and arranged such that the joint can articulate freely and repeatedly. The biconcave shape of the TMJ disc is compatible with the convex shape of the condyle such that the condyle can rotate and translate smoothly against the stationary articular eminence and fossa. Moreover, the formation of ring-like collagen organization in the bands surrounding the intermediate zone is also critical for the disc's role in enduring the radial and circumferential stresses when the joint moves in rotation and translation. Microscopically, the distributions and organization of various biochemical components in the ECM give critical building blocks to a tissue that can withstand substantial forces. Particularly, the density and the degree of organization of collagen are primarily associated with the tensile properties in the TMJ disc, disc attachments, and the condyle. Since this relationship holds true in various TMJ components, it emphasizes the importance of collagen for the structure and function of the joint. As noted above, the structure-function relationship is important in providing a comprehensive view of the disc in both health and disease. Although our understanding of the TMJ has improved owing to tremendous research efforts in recent years, further studies need to be performed to fill our gap of knowledge. For example, although the mechanical properties of the disc attachments are characterized in animal models, the research is still unfulfilled for human tissue specimens. Although it has been found that the role of GAG in hyaline cartilage is to resist compression, its function in the TMJ disc is not as well defined. Therefore, the presence of a small quantity of GAG in TMJ tissues and how it interacts with collagen fibers need to be explored to fully comprehend its contribution to the mechanical properties of the TMJ tissues. Our understanding of the biochemical properties and the structure-function relationships of the TMJ tissue components can help illuminate pathophysiology of TMJ disorders, aid in clinical diagnosis and treatments, and inform the design and development of replacement tissues.

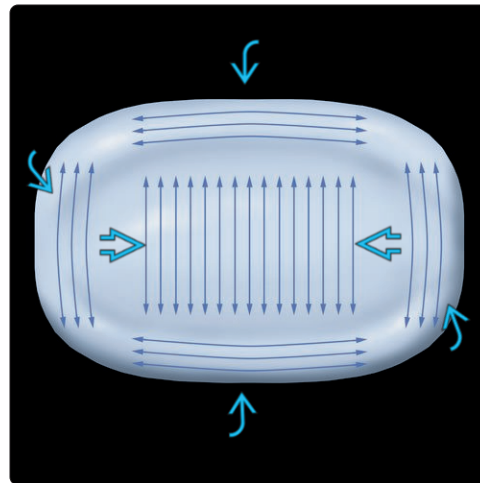
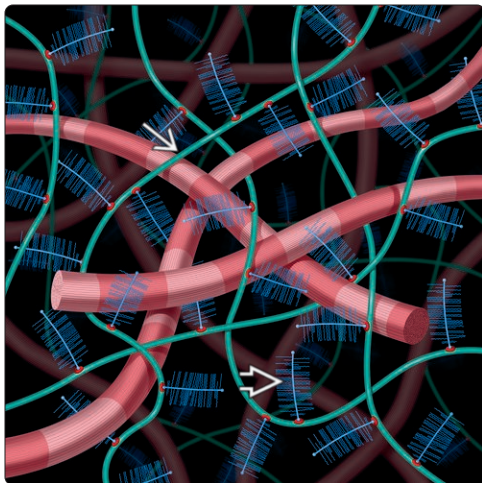
## Selected References

1. Murphy MK et al: Tensile characterization of porcine temporomandibular joint disc attachments. *J Dent Res.* 92(8):753-8, 2013
2. Kalpakci KN et al: An interspecies comparison of the temporomandibular joint disc. *J Dent Res.* 90(2):193-8, 2011
3. Clément C et al: Quantitative analysis of the elastic fibres in the human temporomandibular articular disc and its attachments. *Int J Oral Maxillofac Surg.* 35(12):1120-6, 2006
4. Scapino RP et al: Organization and function of the collagen fiber system in the human temporomandibular joint disk and its attachments. *Cells Tissues Organs.* 182(3-4):201-25, 2006

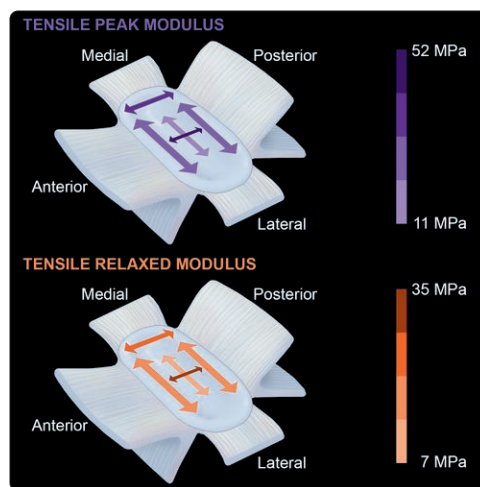
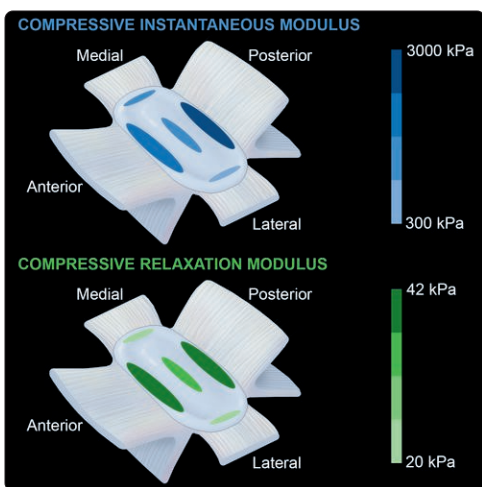
# Structure and Function of the TMJ Disc and Disc Attachments



(Left) The sagittal view of the TMJ is shown. The disc is biconcave and is divided into intermediate zone and anterior and posterior bands. The TMJ disc reduces stress in the mandibular condyle, mandibular fossa, and articular eminence during articulation. (Right) The coronal view of the TMJ is shown. The articular capsule encloses the TMJ disc, disc attachments, and the head of the condyle. The disc is divided into the center, medial, and lateral regions and is attached to the articular capsule and the condyle.



(Left) Graphic representation of collagen and proteoglycans of the TMJ tissues is shown. Glycosaminoglycans (GAGs) are bottle brush-like structures, and they bind to hyaluronic acid backbone to form proteoglycans. (Right) Graphic shows the predominant collagen alignment of the TMJ disc. The fibers of the intermediate zone align in the anteroposterior direction, whereas in the band regions, the fibers align in a ring-like structure.



(Left) Instantaneous & relaxation moduli of various regions of the disc are shown. The intermediate zone has the highest moduli, followed by the anterior band, then the posterior band. (Right) Graphic shows peak & relaxed tensile moduli of various regions & directions in the TMJ disc. The center of the intermediate zone displays the highest moduli in the AP direction, followed by the medial region in the AP direction, then the bands in the ML direction. The center of the intermediate zone in the ML direction shows the lowest moduli.