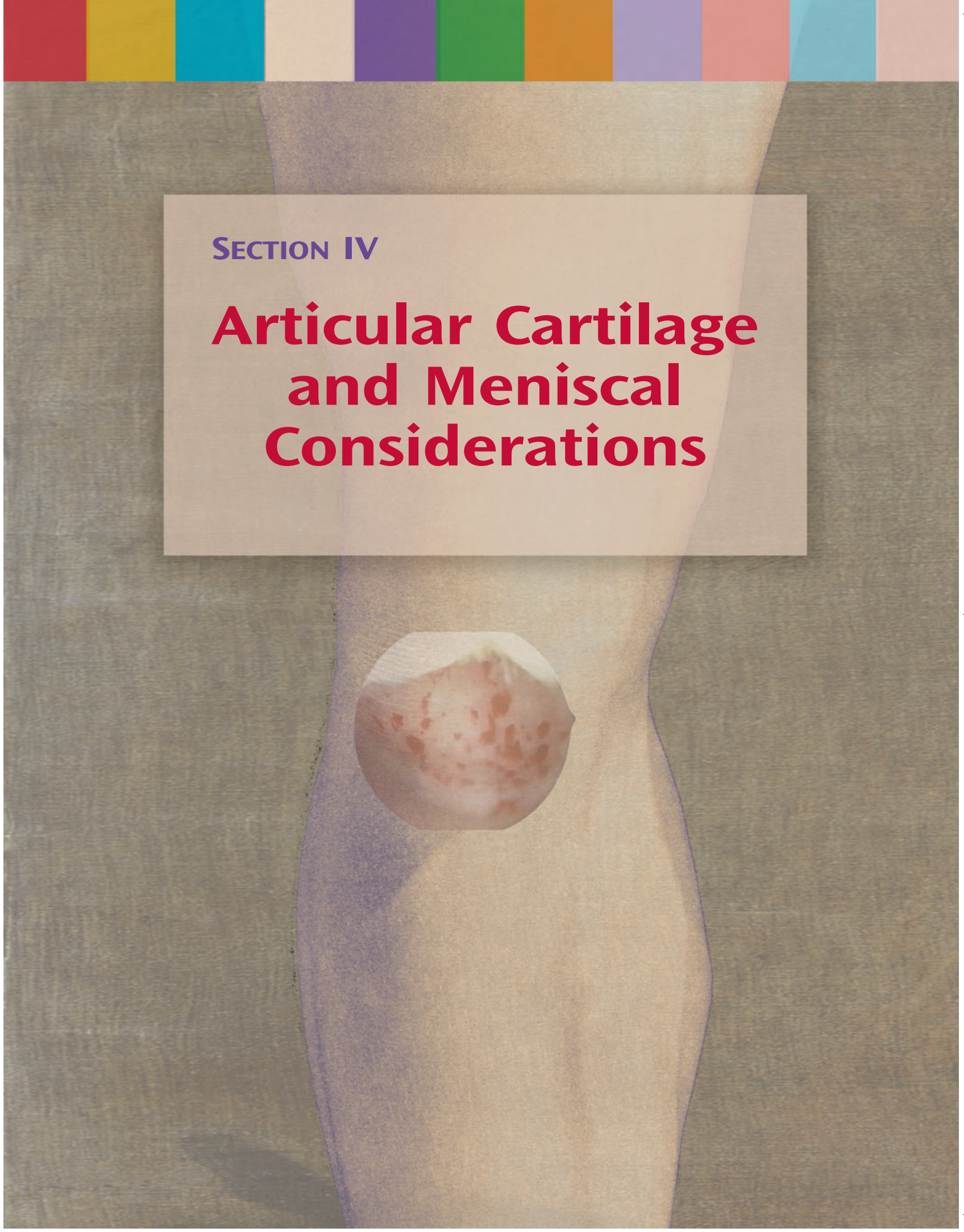
SECTION IV

Articular Cartilage and Meniscal Considerations



CHAPTER 16

Articular Cartilage and Meniscus: Biology, Biomechanics, and Healing Response

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Articular cartilage and the menisci have very important and specialized biomechanical functions.[46] Articular cartilage provides a lubricated bearing surface and is a deformable shock absorber.[46] The meniscus is a primary knee stabilizer.[17] It has very important load-bearing, shock-absorbing, and load-transmitting functions.[17,23]

Articular cartilage lacks a blood or lymphatic supply. In addition, it has no neurological elements and is sheltered from the immune system. Consequently, there is limited healing potential of articular cartilage because of its poor regenerative capacity.[24,34,38] The inner two-thirds of the meniscus is also avascular and does not heal well, and thus only the periphery of the meniscus has the potential to heal. In fact, the location of a meniscal tear is the most important factor related to the healing response.[37] The major issue with regard to these tissues is whether these problems can be overcome and whether we can enable articular cartilage and the meniscus to heal.

The options for treatment of afflictions involving articular cartilage and the meniscus can be summed up in the four r's: restore, replace, relieve, and resect.[34] Treatment in the past has largely centered on the last modality: resection. Loss of the meniscal load-bearing capacity predictably results in arthrosis.[33] Recent advances in articular cartilage[34] and meniscal transplantation,[33] as well as exciting developments in gene therapy,[24,34,38] suggest that this problem of a lack of healing response will be overcome.[12]

To solve the problems of articular cartilage and meniscal repair, basic science must be integrated into clinical practice.[12] Understanding the basic science of articular cartilage and menisci, including the anatomy, biology, biomechanical function, and healing response, is the basis for developing effective treatment of injuries and afflictions of these tissues.

The purpose of this chapter is to present the basic science of articular cartilage and the menisci, including the biology, biomechanics, and healing response.

ARTICULAR CARTILAGE: INTRODUCTION

Articular cartilage gives synovial joints the ability to provide low-friction, pain-free motion. It varies in thickness, cell density, matrix composition, and mechanical properties within the same joint and among joints. Yet in all synovial joints it consists of the same components, has the same general structure, and performs the same functions. Only a few millimeters thick, it has surprising stiffness to compression, resilience, and an exceptional ability to distribute loads, thereby minimizing peak stress on subchondral bone. Perhaps most impressive, it has great durability—in many people it provides normal joint function for 80 years and more.

Biology

Grossly and microscopically, adult articular cartilage appears to be a simple inert tissue. Opening a synovial joint exposes the smooth, slick, firm articular cartilage surfaces that when probed resist deformation. It consists primarily of extracellular matrix with a sparse population of cells, and it lacks blood vessels, lymphatic vessels, and nerves.[10] Despite its unimpressive appearance, articular cartilage has an elaborate, highly ordered structure.

CHONDROCYTES

Only one type of cell exists within normal articular cartilage: the highly specialized chondrocyte.[14] Chondrocytes from different cartilage zones differ in size, shape, and probably metabolic activity, but all these cells contain the organelles necessary for matrix synthesis, including endoplasmic reticulum and Golgi membranes. Chondrocytes surround themselves with their extracellular matrix and do not form cell-to-cell contact. A spheroidal shape, synthesis of type II collagen, large aggregating proteoglycans, and specific noncollagenous proteins distinguish mature chondrocytes from other cells. To produce a tissue that can provide normal synovial joint function, chondrocytes first synthesize appropriate types and amounts of macromolecules and then assemble and organize them into a highly ordered macromolecular framework. Maintenance of the articular surface requires turnover of the matrix macromolecules, that is, continual replacement of degraded matrix components.[14,15] To accomplish these activities, the cells must sense changes in matrix composition caused by degradation of macromolecules and the mechanical demands placed on the articular surface and respond by synthesizing appropriate types and amounts of macromolecules.

EXTRACELLULAR MATRIX

The articular cartilage matrix consists of two components: tissue fluid and the framework of structural macromolecules that gives the tissue its form and stability.[10,14] Interaction of the tissue fluid and the macromolecular framework gives the tissue its mechanical properties of stiffness and resilience.

TISSUE FLUID

Water contributes up to 80% of the wet weight of articular cartilage, and the interaction of water with the matrix macromolecules significantly influences the mechanical properties of the tissue. This tissue fluid contains gases, small proteins, metabolites, and a high concentration of cations to balance the negatively charged proteoglycans. At least some of the water can move freely in and out of the tissue. Its volume, concentration, and behavior within the tissue depend primarily on its interaction with the structural macromolecules, in particular, the large aggregating proteoglycans that help maintain the fluid within the matrix and the fluid electrolyte concentrations.

STRUCTURAL MACROMOLECULES

The cartilage structural macromolecules—collagens, proteoglycans, and noncollagenous proteins—contribute 20% to 40% of the wet weight of the tissue. The three classes of macromolecules differ in their concentrations within the tissue and in their contributions to tissue properties. Collagens contribute about 60% of the dry weight of cartilage, proteoglycans contribute 25% to 35%, and the noncollagenous proteins and glycoproteins contribute 15% to 20%. Collagens are distributed relatively uniformly throughout the depth of the cartilage, except for the collagen-rich superficial zone. The collagen fibrillar meshwork gives cartilage its form and tensile strength. Proteoglycans and noncollagenous proteins bind to the collagenous meshwork or become mechanically entrapped within it, and water fills this molecular framework. Some noncollagenous proteins help organize and stabilize the matrix macromolecular framework, whereas others help chondrocytes bind to the macromolecules of the matrix.

Collagens

Articular cartilage, like most tissues, contains multiple, genetically distinct collagen types, specifically, collagen types II, VI, IX, X, and XI. Collagen types II, IX, and XI form the cross-banded fibrils seen by electron microscopy. The organization of these fibrils into a tight meshwork that extends throughout the tissue provides the tensile stiffness and strength of articular cartilage and mechanically entraps the large proteoglycans. The principal articular cartilage collagen, type II, accounts for 90% to 95% of the cartilage collagen and forms the primary component of the cross-banded fibrils. The functions of type IX and type XI collagen remain uncertain, but presumably they help form and stabilize the collagen fibrils assembled primarily from type II collagen. The projecting portions of type IX collagen molecules may also help bind the collagen fibril meshwork together and connect the collagen meshwork with proteoglycans. Type VI collagen appears to form an important part of the matrix immediately surrounding chondrocytes and helps chondrocytes attach to the matrix. The presence of type X collagen only near the cells of the calcified cartilage zone of articular cartilage and the hypertrophic zone of the growth plate (where the longitudinal cartilage septa begin to mineralize) suggests that it has a role in cartilage mineralization.

Proteoglycans

Proteoglycans consist of a protein core and one or more glycosaminoglycan chains (long unbranched polysaccharide chains consisting of repeating disaccharides that contain an amino sugar). Each disaccharide unit has at least one negatively charged carboxylate or sulfate group, so the glycosaminoglycans form long strings of negative charges that repel other negatively charged molecules and attract cations. Glycosaminoglycans found in cartilage include hyaluronic acid, chondroitin sulfate, keratan sulfate, and dermatan sulfate. The concentration of these molecules varies among sites within articular cartilage and also with age, cartilage injury, and disease.

Articular cartilage contains two major classes of proteoglycans: large aggregating molecules, or aggrecans, and smaller proteoglycans, including decorin, biglycan, and fibromodulin. Aggrecans have large numbers of chondroitin sulfate and keratan sulfate chains attached to a protein core filament. Decorin has one dermatan sulfate chain, biglycan has two dermatan sulfate chains, and fibromodulin has several keratan sulfate chains. Aggrecan molecules fill most of the interfibrillar space of the cartilage matrix. They contribute about 90% of the total cartilage matrix proteoglycan mass, whereas large nonaggregating proteoglycans contribute 10% or less and small nonaggregating proteoglycans contribute about 3%. Although the small proteoglycans contribute relatively little to the total mass of proteoglycans when compared with the aggrecans, because of their small size, they may be present in equal or higher molar amounts.

In the articular cartilage matrix, most aggrecans noncovalently associate with hyaluronic acid (hyaluronan) and link proteins, small noncollagenous proteins, to form proteoglycan aggregates. These large molecules have a central hyaluronan backbone that can vary in length from several hundred to more than ten thousand nanometers. Large aggregates may have more than 300 associated aggrecan molecules. Link proteins stabilize the association between monomers and hyaluronic acid and appear to have a role in directing the assembly of aggregates. Aggregate formation helps anchor proteoglycans within the matrix, thereby preventing their displacement during deformation of the tissue, and helps organize and stabilize the relationship between proteoglycans and the collagen meshwork.

The small nonaggregating proteoglycans have shorter protein cores than the aggrecan molecules do, and unlike

aggrecans, they do not fill a large volume of the tissue or contribute directly to the mechanical behavior of the tissue. Instead, they bind to other macromolecules and probably influence cell function.

Noncollagenous Proteins and Glycoproteins

A wide variety of noncollagenous proteins and glycoproteins exist within articular cartilage. In general, they consist primarily of protein and a few attached monosaccharides and oligosaccharides. Fibronectin and tenascin, noncollagenous matrix proteins that are found in a variety of tissues, have also been identified within cartilage. Their functions in articular cartilage remain poorly understood, but they may have roles in matrix organization, cell matrix interactions, and responses of the tissue in inflammatory arthritis and osteoarthritis.

STRUCTURE

To form articular cartilage, chondrocytes organize the collagens, proteoglycans, and noncollagenous proteins into a unique, highly ordered structure. The composition, organization, and mechanical properties of the matrix, cell morphology, and probably cell function vary with the depth from the articular surface. Matrix composition, organization, and function also vary with the distance from the cell.

ZONES

The morphological changes in chondrocytes and matrix from the articular surface to subchondral bone make it possible to identify four zones, or layers: the superficial zone, the transitional zone, the radial zone, and the zone of calcified cartilage. The relative size and appearance of these zones vary among joints, and although each zone has different morphological features, the boundaries between zones cannot be sharply defined.

Superficial Zone

The unique structure and composition of the thinnest articular cartilage zone, the superficial zone, give it specialized mechanical and possibly biological properties. It typically consists of two layers. A sheet of fine fibrils with little polysaccharide and no cells covers the joint surface. This portion of the superficial zone presumably corresponds to the clear film, often identified as the "lamina splendens," that can be stripped from the articular surface in some regions. Deep to this acellular sheet of fine fibrils, flattened ellipsoid-shaped chondrocytes arrange themselves so that their major axes are parallel to the articular surface. They synthesize a matrix that has a high collagen concentration and a low proteoglycan concentration relative to the other cartilage zones, and studies of superficial zone cells in culture show that they degrade proteoglycans more rapidly and synthesize less collagen and proteoglycans than do cells from the deeper zones. Fibronectin and water concentrations are also highest in this zone.

Transitional Zone

As the name "transitional zone" implies, the morphology and matrix composition of the transitional zone is intermediate between that of the superficial zone and the radial zone. It usually has several times the volume of the superficial zone. The cells have a higher concentration of synthetic organelles, endoplasmic reticulum, and Golgi membranes than superficial zone cells do. Transitional zone cells assume a spheroidal shape and synthesize a matrix that has larger-diameter collagen fibrils, a higher proteoglycan concentration, but lower concentrations of water and collagen than present in the superficial zone matrix.

Middle (Radial or Deep) Zone

The chondrocytes in the middle zone are spheroidal in shape, and they tend to align themselves in columns perpendicular to the joint surface. This zone contains the largest-diameter collagen fibrils, the highest concentration of proteoglycans, and the lowest concentration of water. The collagen fibers of this zone pass into the "tidemark," a thin basophilic line seen on light microscopic sections of decalcified articular cartilage that roughly corresponds to the boundary between calcified and uncalcified cartilage.

Calcified Cartilage Zone

A thin zone of calcified cartilage separates the radial zone (uncalcified cartilage) and subchondral bone. The cells of the calcified cartilage zone have a smaller volume than do cells of the radial zone and contain only small amounts of endoplasmic reticulum and Golgi membranes.

MATRIX REGIONS

Variations in the matrix within zones distinguish three regions or compartments: the pericellular region, the territorial region, and the interterritorial region. The pericellular and territorial regions appear to serve the needs of chondrocytes, that is, binding the cell membranes to the matrix macromolecules and protecting the cells from damage during loading and deformation of the tissue. They may also help transmit mechanical signals to the chondrocytes when the matrix deforms during joint loading. The primary function of the interterritorial matrix is to provide the mechanical properties of the tissue.

Pericellular Matrix

Chondrocyte cell membranes appear to attach to the thin rim of the pericellular matrix that covers the cell surface.

This matrix region is rich in proteoglycans and also contains noncollagenous matrix proteins. It has little or no fibrillar collagen.

Territorial Matrix

An envelope of territorial matrix surrounds the pericellular matrix of individual chondrocytes and, in some locations, pairs or clusters of chondrocytes and their pericellular matrices. In the radial zone, a territorial matrix surrounds each chondrocyte column. The thin collagen fibrils of the territorial matrix nearest to the cell appear to adhere to the pericellular matrix. At a distance from the cell they decussate and intersect at various angles to form a fibrillar basket around the cells. An increase in collagen fibril diameter and a transition from the basket-like orientation of the collagen fibrils to a more parallel arrangement mark the boundary between the territorial and interterritorial matrices. However, many collagen fibrils connect the two regions, thus making it difficult to precisely identify the boundary between these regions.

Interterritorial Matrix

The interterritorial matrix makes up most of the volume of mature articular cartilage. It contains the largest-diameter collagen fibrils. Unlike the collagen fibrils of the territorial matrix, these fibrils are not organized to surround the chondrocytes, and they change their orientation relative to the joint surface 90 degrees from the superficial zone to the deep zone. In the superficial zone, the fibril diameters are relatively small and the fibrils generally lie parallel to the articular surface. In the transitional zone, interterritorial matrix collagen fibrils assume more oblique angles relative to the articular surface, and in the radial zone, they usually lie perpendicular (or radial) to the joint surface.

MENISCUS: INTRODUCTION

Injury to the meniscus from both athletic events and activities of daily living is common. As a result, arthroscopic treatment of meniscal injuries has become one of the most common orthopedic surgical procedures, and arthroscopic partial meniscectomy is one of the top 10 orthopedic surgical procedures performed in this country.[2,25] Occurring in isolation or in association with ligamentous injury, meniscal tears can result in abnormal knee joint function, abnormal loading, and subsequent osteoarthritis of the joint.

There has been substantial progress in the management of meniscal tears and deficiency with appreciation of the biomechanical importance of these structures to joint stability and articular preservation. In 1887, Bland-Sutton described the meniscus as "the functionless remains of a leg muscle."[9] Not until 1948 did Fairbank[21] appreciate that "meniscectomy is not wholly innocuous" in his classic report of postmeniscectomy radiographic changes.

In terms of meniscal repair and healing, in November 1883, Thomas Annandale[4] was the first to suture a medial meniscus. Half a century later, in 1936, King[28] showed that degenerative changes would appear in the canine stifle after meniscectomy. He showed that a peripheral meniscal tear has the potential to heal. In the 1950s and 1960s, the menisci were discarded as an unnecessary appendage that can easily be removed. Total meniscectomy was performed for almost any meniscal tear suspected on clinical examination. It took almost a century from Annandale's report until a conservative approach to the management of meniscal tears was applied clinically. In the last 2 decades, understanding of meniscal importance and the development of arthroscopic techniques have improved meniscal preservation and the healing response.

Anatomy

GROSS FEATURES

Various authors have extensively studied meniscal anatomy. In terms of gross anatomy, the menisci are C-shaped or semicircular fibrocartilaginous structures with bony attachments at the anterior and posterior aspects of the tibial plateau (Fig. 16–1). The medial meniscus is C shaped, with the posterior horn larger than the anterior horn in the anteroposterior dimension. The anterior horn attachment of the medial meniscus is variable, an important consideration, particularly for meniscal transplantation. In an anatomic study, Berlet and Fowler[8]

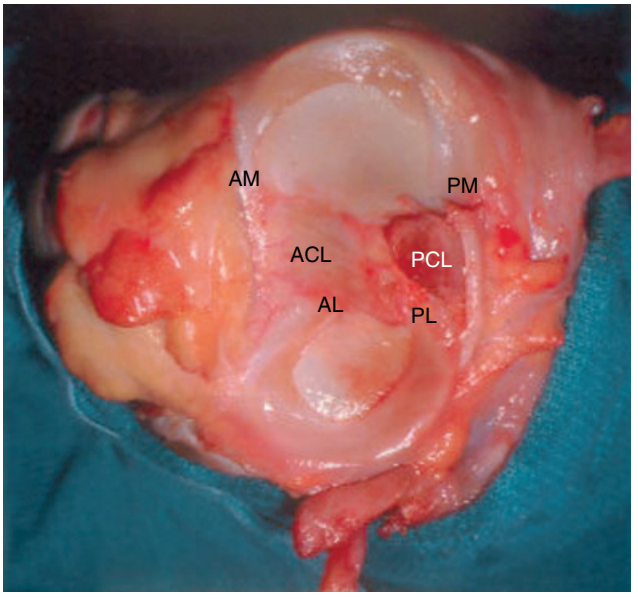

Figure 16–1. Anatomy of the menisci viewed from above. Note the differences in position and shape of the medial and lateral menisci. Meniscus horn insertion sites viewed from above. Note the proximity to the anterior cruciate ligament (ACL). AL, anterior horn lateral meniscus; AM, anterior horn medial meniscus; PCL, posterior cruciate ligament; PL, posterior horn lateral meniscus; PM, posterior horn medial meniscus.

described four types of anterior horn medial meniscus attachments. The type IV variant has no firm bony attachment and is attached to the intermeniscal ligament or the soft tissues at the base of the anterior cruciate ligament (ACL). This variability makes standard bony reattachment difficult, either with replantation or reattachment of an avulsed anterior horn. Nelson and LaPrade[32] found a similar type of attachment in 14% of 47 specimens. In the majority of specimens, however, a firm anterior bony attachment was observed. The posterior root attaches anterior to the insertion of the posterior cruciate ligament and behind the medial tibial eminence. Johnson et al[26] mapped the bony insertion sites of the meniscus in an effort to identify appropriate landmarks for meniscus transplantation. They noted the location of each insertion site (Fig. 16–2) and the insertion site surface area. The anterior horn of the medial meniscus has the largest insertion site surface area (61.4 mm^2), and the posterior horn of the lateral meniscus has the smallest (28.5 mm^2). The remainder of the medial meniscus is firmly attached to the joint capsule and the deep surface of the deep medial capsular ligament. The capsular attachment of the medial meniscus on the tibial side is referred to as the coronary ligament. A thickening of the capsular attachment in the midportion spans from the tibia to the femur and is referred to as the deep medial collateral ligament. The lateral meniscus has an almost semicircular configuration. It covers a larger portion of the tibial articular surface than the medial meniscus does (see Fig. 16–1). Discoid lateral menisci have been reported with a prevalence of 3.5% to 5%, most being the incomplete type.[42] The anterior and posterior horns attach much closer to each other than do those of the medial meniscus, thus making this anatomic area very consistent with a relationship easy to maintain during meniscal transplantation. The anterior horn inserts adjacent to the ACL and can often be used as a landmark for the drill guide and ACL graft placement. The posterior root is posterior to the lateral tibial eminence. The attachment includes the Wrisberg variation of the discoid lateral meniscus, in which the posterior horn bony attachment is absent and the posterior meniscofemoral ligament of Wrisberg is the only stabilizing structure. This variation can allow excessive motion and result in posterior horn instability, although a hypermobile meniscus may occur without any variant. The anterior meniscofemoral ligament of Humphrey runs from the posterior horn of the lateral meniscus anterior to the posterior cruciate ligament and inserts on the femur. Posterior and lateral to the posterior bony insertion of the lateral meniscus lies the popliteus tendon. The popliteal hiatus identifies the lateral meniscus, and there is no firm peripheral attachment to the femur or tibia in this location, which contributes to the less likely healing of lateral meniscal tears involving this area. Simonian et al[40] have investigated the role that the popliteomeniscal fasciculi play in lateral meniscus stability. Disruption of both these fascicular attachments may increase meniscal motion at the hiatus and be important in causing hypermobility of the posterior horn of the lateral meniscus. In addition, the lateral meniscus is more mobile than the medial meniscus through the knee range of motion, as shown by Thompson et al[41] with three-dimensional magnetic resonance imaging. They demonstrated 11.2 mm of posterior excursion of the lateral meniscus and 5.2 mm of the medial meniscus during knee flexion. The anatomic attachment of the lateral meniscus allows for mobility by less rigorous capsular attachment.

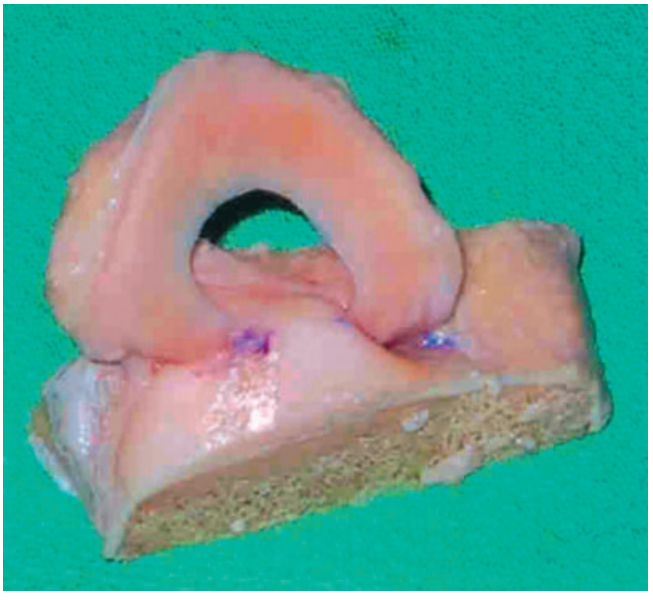

Figure 16–2. Lateral meniscus. Note the proximity of the anterior and posterior horns on either side of the tibial eminence.

MICROSCOPIC ANATOMY

The fibrocartilaginous structure of the meniscus has been well described and is made of coarse collagen bundles. The orientation of collagen fibers is mainly circumferential, with some radial fibers at the surface and within the midsubstance.[6] This orientation allows compressive loads to be dispersed by the circumferential fibers, whereas the radial fibers act as tie fibers to resist longitudinal tearing (Fig. 16–3). The surface fiber orientation is more of a mesh network or random configuration, which is thought to be important in the distribution of shear stress. The majority of collagen (90%) is type I, and the remainder consists of types II, III, V, and VI. Elastin accounts for approximately 0.6% of the dry weight of the meniscus, and noncollagenous proteins, for 8% to 13%.[30]

The cells of the meniscus have been called fibrochondrocytes because of their appearance and the fact that they synthesize a fibrocartilaginous matrix. The fibrochondrocytes appear to be of two types, with the more superficial cells being oval or fusiform and the deeper cells more rounded. Both types contain abundant endoplasmic reticula and Golgi complexes and few mitochondria.

VASCULARITY

At birth, the entire meniscus is vascular; by 9 months of age, the inner third has become avascular. This decrease

in vascularity continues to the age of 10 years, when the meniscus closely resembles the adult meniscus. Arnoczky and Warren[5] studied the adult blood supply and demonstrated that only the outer 10% to 25% of the lateral meniscus and 10% to 30% of the medial meniscus are vascular (Fig. 16–4). This vascularity arises from the superior and inferior branches of the medial and lateral genicular arteries, which form a perimeniscal capillary plexus. A synovial fringe extends a short distance over both the femoral and tibial surfaces of the menisci but does not contribute to the meniscal blood supply. At the popliteal hiatus, the meniscus is relatively avascular, which probably contributes to poorer healing and a higher incidence of retears of the lateral meniscus. Because of the avascular nature of the inner two-thirds of the meniscus, cell nutrition is believed to occur mainly through diffusion of synovial fluid.[31] The neuroanatomy of the meniscus is not totally clear, but the distribution of neural elements has been demonstrated to be in essentially the same anatomic distribution as the vascular supply. The anterior and posterior horns are the most richly innervated, and the body innervation follows the pattern along the periphery. Though not entirely clear, these nerve endings are believed to play a role in sensory feedback and proprioception. It seems that the greatest feedback occurs at the extremes of flexion and extension, when the meniscal horns are compressed and neural elements are stimulated.

Dye et al,[19] who performed neurosensory mapping of the internal structures of the knee, confirmed that probing peripheral tissues is more painful than probing central ones. This finding can be confirmed when performing meniscectomy under local anesthesia only. The innervation of the knee may be important for proprioceptive feedback during motion.

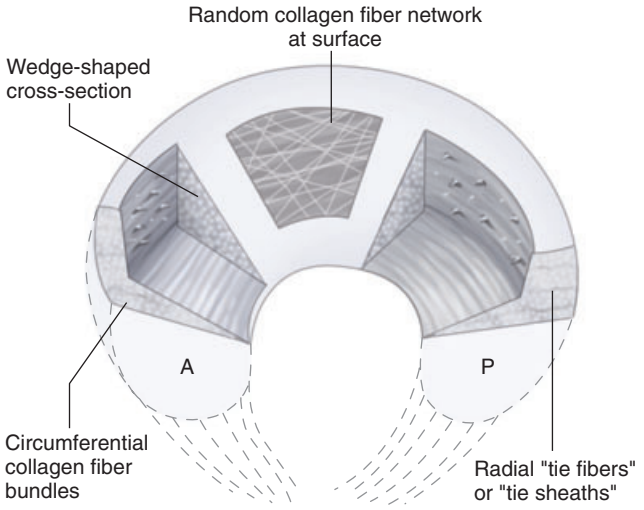

Figure 16–3. Schematic of collagen bundles and their orientation within the meniscus. (Reproduced with permission and copyright © of the British Editorial Society of Bone and Joint Surgery, from Bullough PG, Munuera L, Murphy J, Weinstein AM: The strength of the menisci of the knee as it relates to their fine structure. J Bone Joint Surg Br 52:564-567, 1970.)

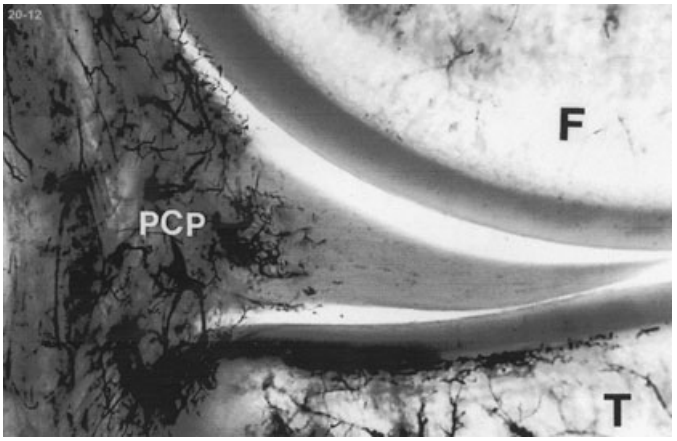

Figure 16–4. The microvasculature of the meniscus. (From Arnockzy SP, Warren RS: Microvasculature of the human meniscus. Am J Sports Med 10:90-95, 1982. Reprinted with permission of Sage Publications, Inc.) F, femur; T, tibia; PCP, perimeniscal capsular periphery.

ARTICULAR CARTILAGE: BIOMECHANICS

Articular cartilage is subjected to a wide range of static and dynamic mechanical loads. The ability of cartilage to withstand physiological compressive, tensile, and shear forces depends on the composition and structural integrity of its extracellular matrix. In turn, maintenance of a functionally intact matrix requires chondrocyte-mediated synthesis, assembly, and degradation of proteoglycans, collagens, noncollagenous proteins and glycoproteins, and other matrix molecules. The collagen fibrils effectively resist tensile and shear deformation forces, whereas the highly charged glycosaminoglycan constituents of aggrecan molecules resist compression and fluid flow within the tissue. Joint loading induces a range of responses in cartilage. Dynamic compression of cartilage results in deformation of cells and extracellular matrix, hydrostatic pressurization of tissue fluid, pressure gradients and the accompanying flow of fluid within the tissue, and streaming potentials and currents induced by tissue fluid flow. The local changes in tissue volume caused by static compression also lead to physiochemical changes within the matrix, including alterations in matrix water content, fixed charge density, mobile ion concentrations, and osmotic pressure. Any of these mechanical, chemical, or electrical phenomena in the environment of the chondrocyte may affect cellular metabolism. Static loading within the physiological range can reversibly inhibit the synthesis of critical components of the cartilage matrix. Such static compressive forces can downregulate the gene expression and production of type II collagen, aggrecan core protein, and link protein, whereas cyclically applied hydrostatic pressure and compressive strain stimulate aggrecan core protein and protein synthesis. Immobilization or reduced loading can decrease the synthesis of proteoglycans and lead to softening of the tissue.

MENISCUS: BIOMECHANICS

The menisci are important in many aspects of knee function, including load sharing, shock absorption, reduction in joint contact stress, passive stabilization, increase in congruity and contact area, limitation of extremes of flexion and extension, and proprioception. Many of these functions are achieved through the ability of the menisci to transmit and distribute load over the tibial plateau. The findings of joint space narrowing, osteophyte formation, and squaring of the femoral condyles after total meniscectomy suggested that the meniscus is important in joint protection and led to investigations of the role of the meniscus in joint function. The medial and lateral menisci transmit at least 50% to 70% or more at times of the load when the knee is in extension; it increases to 85% with 90 degrees of knee flexion.[1]

Radin et al[35] demonstrated that these loads were well distributed when the menisci were intact. Removal of the medial meniscus results in a 50% to 70% reduction in femoral condyle contact area and a 100% increase in contact stress.[22,27,44] Total lateral meniscectomy causes a 40% to 50% decrease in contact area and increases contact stress in the lateral compartment to 200% to 300% of normal. In addition, partial removal of the meniscus alters load characteristics, particularly when two-thirds of the posterior horn is removed.[43] With the decrease in contact area within the joint, stress is increased and unevenly distributed. This change results in increased compression and shear across the joint. Along with the biomechanical changes that can occur with meniscectomy, the results of some studies[31] suggest that the biochemical activity of cartilage is also affected. The improved joint congruity, which occurs through meniscus contact, is thought to play a role in joint lubrication and cell nutrition. The meniscus also plays a role in shock absorption. Compression studies using bovine menisci have demonstrated that meniscal tissue is approximately half as stiff as articular cartilage. In one study,[43] the shock absorption capacity of the normal knee was reduced by 20% after meniscectomy. The menisci also play a key role in enhancing joint stability.[29] Medial meniscectomy in an ACL-intact knee has little effect on anteroposterior motion, but in an ACL-deficient knee, it results in an increase in anterior tibial translation of up to 58% at 90 degrees of flexion. Shoemaker and Markolf[39] demonstrated that the posterior horn of the medial meniscus is the most important structure in resisting an applied anterior tibial force in an ACL-deficient knee. Allen et al[2] showed that the resultant force in the medial meniscus of an ACL-deficient knee increases by 52% in full extension and by 197% at 60 degrees of flexion under a 134-N load. Although the inner two-thirds of the meniscus is important in maximizing joint contact area and increasing shock absorption, integrity of the peripheral third is essential for both load transmission and stability.

HEALING RESPONSES: ARTICULAR CARTILAGE

Based on the type of tissue damage, articular surface injuries caused by mechanical forces can be classified into three types (Table 16–1): (1) damage to the cells and matrices of articular cartilage and subchondral bone that is not associated with visible disruption of the joint surface; (2) visible mechanical disruption of articular cartilage limited to articular cartilage that takes the form of chondral fissures, flap tears, or chondral defects; and (3) visible mechanical disruption of articular cartilage and

Table 16–1. Chondral and Osteochondral Injuries

INJURY	EVALUATION	REPAIR RESPONSE	POTENTIAL FOR HEALING
Damage to chondral matrix and/or cells without visible disruption of the articular surface	Inspection of the articular surface and current clinical imaging methods for articular cartilage cannot detect this type of injury MRI of subchondral bone may show edema	Synthesis of new matrix macromolecules Cell proliferation?	If the basic matrix structure is intact and enough viable cells remain, the cells can restore the normal tissue composition If the matrix and/or cell population sustains significant damage or if the tissue sustains further damage, the lesion may progress to cartilage degeneration
Cartilage disruption (chondral fractures or rupture)	CT and MRI imaging can demonstrate these injuries	No fibrin clot formation or inflammation Synthesis of new matrix macromolecules and cell proliferation, but new tissue does not fill the cartilage defect	Depending on the location and size of the lesion and the structural integrity, stability, and alignment of the joint, the lesion may or may not progress to cartilage degeneration
Cartilage and bone disruption (osteochondral fractures)	CT imaging can demonstrate these injuries	Formation of a fibrin clot, inflammation, invasion of new cells, and production of new chondral and osseous tissue	Depending on the location and size of the lesion and the structural integrity, stability, and alignment of the joint, the repair tissue may remodel and serve as a functional joint surface, or it may degenerate

CT, computed tomography; MRI, magnetic resonance imaging.

bone, that is, intra-articular fractures. Each type of tissue damage stimulates a different repair response.[11,13,15,16]

Cell and Matrix Damage

Articular cartilage damage that leaves the overlying articular surface intact occurs with almost every joint injury. The intensity and type of joint loading that can cause chondral and subchondral damage without visible articular surface disruption has not been well defined. Physiological levels of joint loading do not cause this type of joint injury, but impact loading above that generated by normal activities such as walking or lifting light objects but less than that necessary to produce visible cartilage disruption can disrupt the cartilage matrix macromolecular framework, damage or kill chondrocytes, decrease proteoglycan concentration and synthesis, and increase matrix water concentration and permeability.

Experimental evidence suggests that increased degradation or decreased synthesis of aggrecans is the least severe cartilage injury caused by impact loading. However, even this ostensibly minimal injury increases the risk for joint degeneration. Loss of proteoglycans decreases cartilage stiffness and increases its permeability. These alterations may cause greater loading of the remaining macromolecular framework, thus making the tissue more vulnerable to additional damage from loading, including distortion or disruption of the collagen fibril network and collagen-proteoglycan relationships, swelling of the matrix, and chondrocyte injury or death. Impact loading also may cause chondrocyte death directly. Chondrocytes that survive a joint injury may have decreased ability to maintain and repair the tissue as a result of increased mechanical or metabolic stress.

The ability of chondrocytes to sense changes in matrix composition and synthesize new molecules makes it possible for them to repair damage to the macromolecular framework. It is not clear at what point this type of injury becomes irreversible and leads to progressive loss of articular cartilage. Presumably, chondrocytes can restore the matrix if the loss of matrix proteoglycans does not exceed what the cells can produce rapidly, as long as the fibrillar collagen meshwork remains intact and enough chondrocytes remain capable of responding to the matrix damage. When these conditions are not met, the cells cannot restore the matrix, chondrocytes will be exposed to excessive mechanical and metabolic stress, and the tissue will degenerate.

Cartilage Disruption

Chondrocytes respond to injuries that disrupt articular cartilage, but not to those that extend into subchondral bone (see Table 16–1). After this type of injury they proliferate and increase the synthesis of matrix macromolecules near the injury; however, the newly synthesized matrix and proliferating cells do not fill the tissue defect, and soon after injury the increased proliferative and synthetic activity ceases. This leaves a permanent articular surface defect that can alter joint mechanical function and increase the risk for joint degeneration.

Cartilage and Subchondral Bone Disruption (Intra-articular Fractures)

Unlike injuries limited to cartilage, injuries that extend into subchondral bone cause hemorrhage and fibrin clot formation and activate the inflammatory response. As a result, repair and remodeling of intra-articular fractures differ from the events that follow injuries that cause only cell and matrix injury or disruption of the articular surface limited to articular cartilage (see Table 16–1). However, the force required to produce an intra-articular fracture causes cell and matrix damage and chondral disruption. For these reasons, intra-articular fractures include all three types of articular surface injury (see Table 16–1).

The degree of displacement of the fracture and the size of the gaps between fracture fragments influence the extent and outcome of the repair and remodeling responses. Repair of the chondral portions of intra-articular fractures with gaps between the fracture fragments has not been extensively studied, and therefore current understanding of this process is based on studies of osteochondral repair of experimental drill hole defects. These studies show that soon after injury, blood escaping from the damaged bone blood vessels forms a hematoma that temporarily fills the injury site. Fibrin forms within the hematoma and platelets bind to fibrillar collagen. A continuous fibrin clot fills the bone defect and extends for a variable distance into the cartilage defect. Platelets within the clot release vasoactive mediators and growth factors or cytokines (small proteins that influence multiple cell functions, such as migration, proliferation, differentiation, and matrix synthesis), including transforming growth factor β (TGF-β) and platelet-derived growth factor (PDGF). Bone matrix also contains growth factors such as TGF-β, bone morphogenetic proteins (BMPs), PDGF, insulin-like growth factor type I (IGF-I), IGF-II, and possibly others. Release of these growth factors may have an important role in the repair of osteochondral defects. In particular, they probably stimulate vascular invasion and migration of undifferentiated cells into the clot and influence the proliferative and synthetic activities of the cells.

Shortly after entering the tissue defect, the undifferentiated mesenchymal cells proliferate and synthesize a new matrix. Within 2 weeks after injury, some mesenchymal cells assume the rounded form of chondrocytes and begin to synthesize a matrix that contains type II collagen and a relatively high concentration of proteoglycans. These cells produce regions of hyaline-like cartilage in the chondral and bony portions of the defect. Six to 8 weeks after injury, the repair tissue within the chondral region of osteochondral defects contains many chondrocyte-like cells in a matrix consisting of type II collagen, proteoglycans, some type I collagen, and noncollagenous proteins. Unlike the cells in the chondral portion of the defect, the cells in the bony portion of the defect produce immature bone, fibrous tissue, and hyaline-like cartilage. The bony

repair tissue is well vascularized, but blood vessels rarely enter the chondral portion of an osteochondral defect. Six to 8 weeks after injury, the chondral repair tissue typically has a composition and structure intermediate between hyaline cartilage and fibrocartilage; it rarely, if ever replicates the elaborate structure of normal articular cartilage.

Repair tissue that fills osteochondral defects is less stiff and more permeable than normal articular cartilage, and the orientation and organization of the collagen fibrils in even the most hyaline-like chondral repair tissue do not follow the pattern seen in normal articular cartilage. In addition, the repair tissue cells may fail to establish the normal relationships between themselves and the matrix and among matrix macromolecules, in particular, the organization of the pericellular, territorial, and interterritorial matrices. The decreased stiffness and increased permeability of repair cartilage matrix may increase loading of the macromolecular framework during joint use and result in progressive structural damage, thereby exposing the repair chondrocytes to excessive loads that additionally compromise their ability to restore the matrix. Experimental studies of osteochondral healing and clinical experience with patients who suffer comminuted displaced intra-articular fractures and regain excellent joint function suggest that chondral repair tissue occasionally progressively remodels to form a functional joint surface. However, in most large osteochondral injuries, the chondral repair tissue does not follow this course. Instead, it begins to show evidence of degeneration, including depletion of matrix proteoglycans, fragmentation and fibrillation, increasing collagen content, and loss of cells with the appearance of chondrocytes within 1 year or less. The remaining cells often assume the appearance of fibroblasts as the surrounding matrix comes to consist primarily of densely packed collagen fibrils. This fibrous tissue usually fragments and often disintegrates, thus leaving areas of exposed bone. The inferior mechanical properties of chondral repair tissue may be responsible for its frequent deterioration.

HEALING RESPONSES: MENISCUS

The key factor in the process of tissue repair is accessibility of cells and inflammatory mediators to the site of injury. The formation of a clot is an initial phase that provides a scaffold for matrix formation and is a chemotactic stimulus for the cellular elements involved in wound healing.[36] In adult menisci, only the peripheral 20% to 30% is vascular.[30] This leaves the injured central 70% to 80% absent of hematoma. Therefore, tears in the vascular zone tend to heal, whereas tears in the avascular central region do not. Because of the vascular anatomy, classification of meniscal tears into red-red, red-white, and white-white zones is common as a means of predicting healing potential. Tears in the red zone are in the vascular region and usually heal, but the most common tears and the dilemma occur in the red-white zone. In this zone a significant portion of the meniscus is usually involved, but healing is also precarious. Therefore, in an attempt to get these tears to heal, every aspect of the process is important: technical suturing to provide a stable repair, postoperative cautious rehabilitation and return to activity, and stimulation of the repair site by hematoma. Webber et al[45] showed in tissue culture that meniscal cells can proliferate and synthesize an extracellular matrix when exposed to factors that are normally present in wound hematoma. To promote healing, many have investigated the use of a fibrin clot, fibrin glue, cell growth factors, and creation of traumatic vascular access channels and adjacent synovial bleeding by various methods. Currently, many investigators are looking at the effect and function of extrinsic mediators and growth factors that may affect healing. At this point, abrading the synovium adjacent to the tear and "freshening up" the tear site by rasps or shavers is the common method of providing a hematoma at the tear site.[36] However, this naturally occurring clot may be ineffective if it is dissolved by synovial fluid. Nonetheless, we do know that clinically, the healing rate of meniscal tears is higher in knees with concurrent ACL reconstruction versus isolated meniscal tears, thus indicating that a significant hematoma may help healing, obviously in addition to other factors. Besides stability of the joint, other factors that seem to positively affect healing include the acuity of the tear and younger age of the patient. The presence of degeneration within the meniscal tear (probably correlated with age) has a negative impact on the ability of the tear to heal.[7,20] In terms of rehabilitation and healing response, the meniscus and tear site probably respond to normal physiological stress. Immobilization of the knee joint seems to decrease collagen content in the meniscus, and knee motion tends to prevent collagen loss.[18] With advancing age a normal degenerative process occurs within the meniscus, and therefore its ability to withstand stress is reduced. Consequently, isolated degenerative meniscal tears occur less traumatically and in the older population, that is, usually those older than 30 years. In contrast, younger patients tend to have more traumatic knee injuries and are more likely to sustain combined meniscal and ligamentous injury.

In summary, the menisci are important structures with substantial joint-protective properties. Accordingly, the current approach is to preserve meniscal tissue as much as possible. A clear understanding of the function, biology, and healing capacity of the meniscus is important to allow proper decision making in the clinical setting.

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