2 The Illustrative Anatomy and the Histology of the Healthy Hyaline Cartilage

Tamás Oláh, Tunku Kamarul, Henning Madry, and Malliga Raman Murali

2.1 Introduction

Hyaline articular cartilage is a 2–4 mm thick, avascular and aneural tissue, consisting of chondrocytes (only 1–2% of the total cartilage volume) embedded in an extracellular matrix [1, 2]. Its principal function is to provide a smooth, lubricated surface for articulation and to facilitate the transmission of loads with a low frictional coefficient [1]. The extracellular matrix contains mainly water (>70%) and two major organic components: type II collagen and the proteoglycan aggrecan, which provide tensile strength and compressive resilience to the tissue [2–4]. Histologically, the articular cartilage can be divided into the superficial, transitional, and deep (radial) zones based on the general orientation of the collagen fibrils, the morphology and arrangement of the chondrocytes, and the staining properties of the matrix [4–6]. Between the deep zone and the calcified cartilage layer, a radiologically denser, 5 μm thin discrete band of mineralized cartilage, called tidemark, can be found. Located below the tidemark, the calcified cartilage is a 20–250 μm thick transitional zone, which reduces the "stress riser" between the much stiffer bone and cartilage. Its physiological function is to form an interface between the cartilage and the bone for the transmitting forces, attaching cartilage to bone, and limiting diffusion from the bone to the deeper layers of cartilage [4, 7]. Under the calcified cartilage lies the subchondral bone which provides mechanical and metabolic support to the articular cartilage, absorbs shock, and maintains the joint shape [4, 5]. The subchondral bone consists of two parts with different macroscopic structures: the subchondral bone plate and the subarticular spongiosa [4]. The subchondral bone plate is a dense bony lamella, similar to the cortical bone of other bony structures, separating the calcified cartilage from the marrow cavity. The subarticular spongiosa is a more porous and metabolically active network of trabecular bone containing innervation and blood vessels [4]. This chapter describes the normal gross anatomy and histological characteristics of the hyaline articular cartilage that give the tissue its extraordinary load-bearing characteristics.

T. Oláh
Center of Experimental Orthopaedics, Saarland University, Homburg, Germany
e-mail: tamas.olah@uni-saarland.de

T. Kamarul · M. R. Murali
Tissue Engineering Group, Department of Orthopedics Surgery, NOCERAL, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia
e-mail: tkzrea@um.edu.my; drmurali@um.edu.my

H. Madry (✉)
Center of Experimental Orthopaedics, Saarland University, Homburg, Germany

Department of Orthopaedic Surgery, Saarland University Medical Center, Homburg, Germany
e-mail: henning.madry@uks.eu

D. R. Goyal (ed.), *The Illustrative Book of Cartilage Repair*,
https://doi.org/10.1007/978-3-030-47154-5_2

2.2 The Illustrations

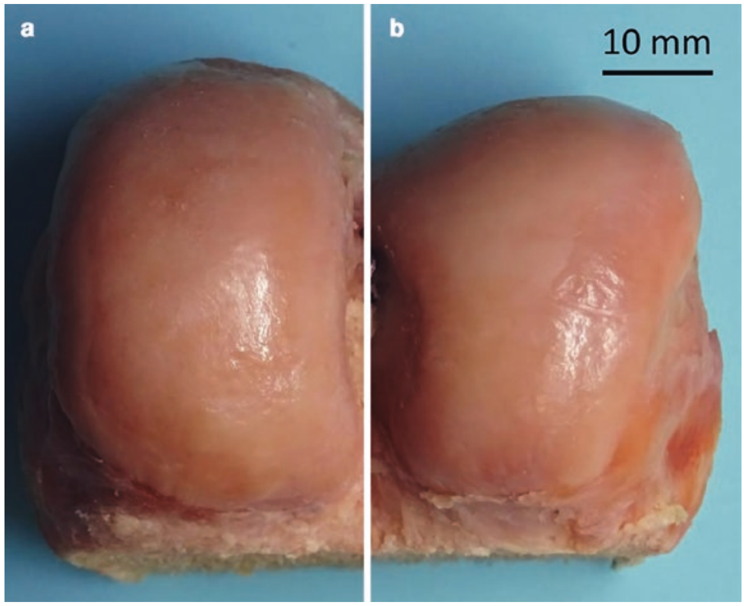

Figure 2.2.1: The Healthy Hyaline Cartilage: The Gross Anatomy of the Femoral Condyles. The gross anatomy of the healthy hyaline cartilage of the femoral condyles from a cadaveric specimen. Macroscopic image of a left (**a**) medial and (**b**) lateral normal human femoral condyle sample of a 96-year-old woman. The medial femoral condyle is larger and more oval than the lateral femoral condyle. The condyles and their radiuses are larger in males than in females, depending on the body height [8]. Healthy hyaline cartilage forms a smooth, shiny, and glassy surface on the diarthrodial joints, such as the femoral condyles and the tibial plateaus of the knee. (Picture Courtesy—Henning Madry)

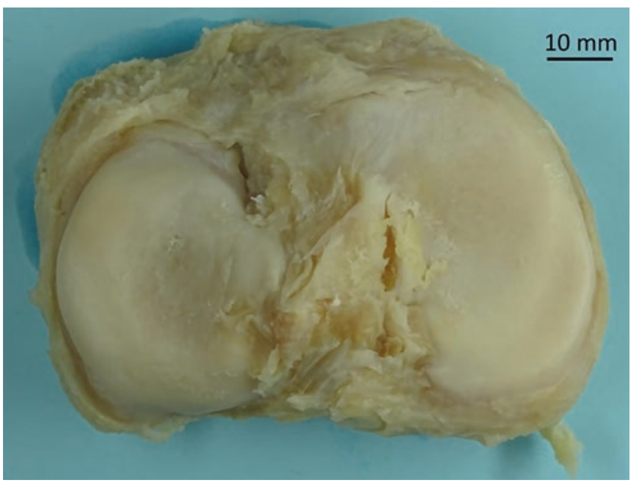

Figure 2.2.2: The Healthy Hyaline Cartilage: The Gross Anatomy of the Tibial Plateau. The gross anatomy of the healthy hyaline cartilage of the tibial plateau from a cadaveric specimen of a 52-year-old man. The proximal tibia is composed of the medial and lateral tibial condyles. The superior surface of these condyles (the tibial plateau) consists of the superior articular surfaces (facets) and the fossae. The central portion of the superior articular surface is the intercondylar eminence (the spine of the tibia). The spine is characterized by two prominences, the medial and lateral tubercles [9]. The macroscopic image of a left normal human tibial plateau shows largely smooth, intact articular cartilage surface and the remnants of the meniscal roots and ligaments which were removed in order to obtain better view of the cartilage. Since the articular cartilage and the underlying subchondral bone forms a very tight functional unit, called the osteochondral unit, studying them simultaneously is desirable [4]. (Picture Courtesy—Henning Madry)

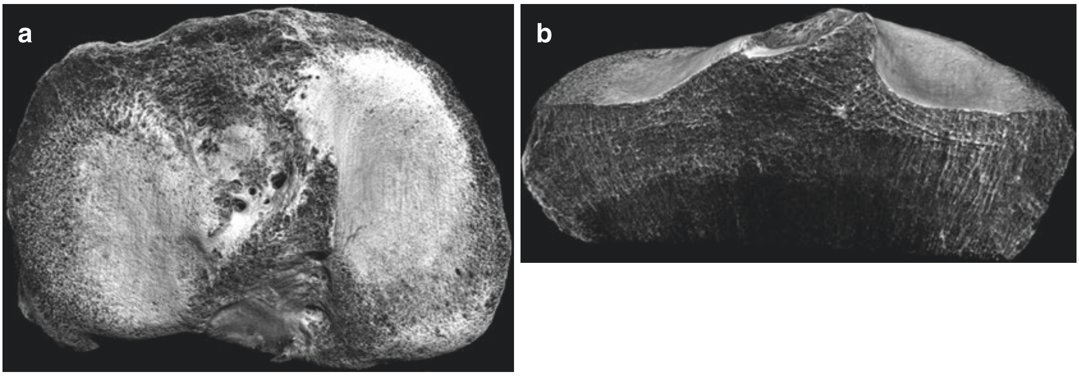

Figure 2.2.3: The Healthy Subchondral Bone: The Gross Anatomy. The gross anatomy of the healthy subchondral bone of the left tibial plateau from a cadaveric specimen of a 52-year-old man shown in Figure 2.2.2. (**a**) A superior view of the 3D reconstructed micro-CT (computed tomography) image showing the subchondral bone plate of the articulating surface. Micro-CT allows to study the morphology of the bone, normally hidden by soft tissues at high resolution. Note the absence of osteophytes on the margins of this healthy specimen, which are generally present in diseases like osteoarthritis. (**b**) The sample was cut in the coronal plane to illustrate the microstructure of the subchondral bone. Below the thin subchondral bone plate, the intricate trabecular architecture of the subarticular spongiosa following the Wolff's law is visible. The datasets of the micro-CT images allow to retrieve the detailed 3D characteristics (including bone volume fraction, bone surface/volume ratio, bone surface density, trabecular number, trabecular separation, connectivity density, structure model index, degree of anisotropy) of the bone microarchitecture using specific analyzing software. (Picture Courtesy—Henning Madry)

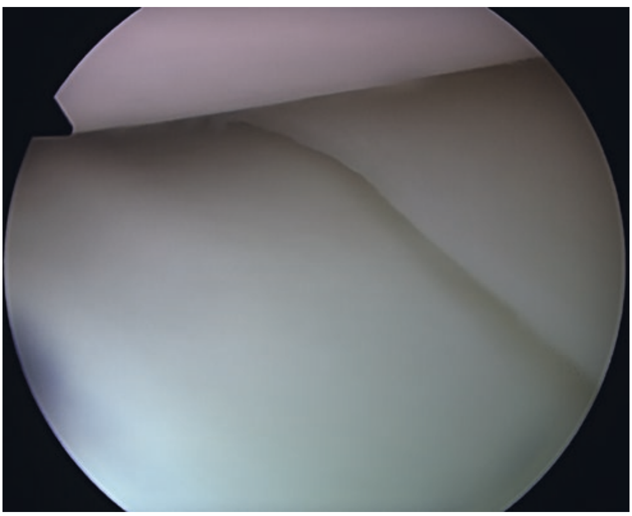

Figure 2.2.4: The Healthy Hyaline Cartilage: The Arthroscopic View. The gross anatomy of the healthy hyaline cartilage of the tibial plateau and femoral condyles from an arthroscopy surgery of a 17-year-old male. The smooth shiny articular cartilage surface of medial femoral condyle (top) and medial tibial plateau (bottom) is seen from the anterolateral portal, without evidence of cartilage defects or osteoarthritis changes. A normal medial meniscus is seen on the right corner. (Picture Courtesy—Henning Madry)

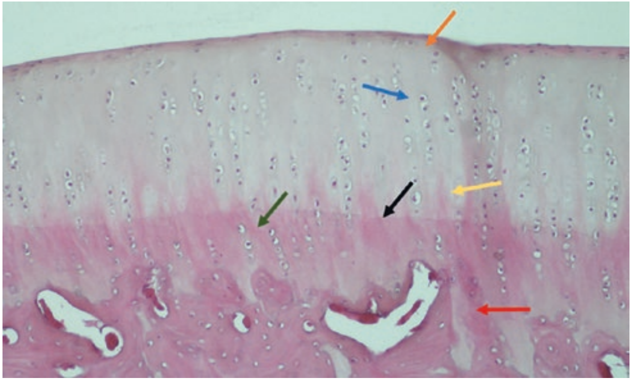

Figure 2.2.5: The Histology of the Healthy Hyaline Cartilage: The Routine Stains. All four zones of cartilage; the superficial zone (orange arrow), the middle zone (blue arrow), the deep zone (yellow arrow), and the calcified zone (green arrow) is seen along with the tidemark (black arrow) and the subchondral bone (red arrow) in the hematoxylin-eosin stained sample of the healthy hyaline cartilage. Superficial zone has the highest proportion of collagen, mainly collagen type II arranged in parallel direction to the surface of the tissue. The main function of high collagen content in superficial zone is to resist the shear stress applied on the cartilage tissue. Middle zone will have randomly oriented collagen fibers and proteoglycans to keep the tissue hydrated, and deep zone will have collagen fibers aligned perpendicular to the surface. Chondrocytes are the cellular components in the cartilage that are responsible for synthesizing and maintaining the extracellular matrix of the cartilage and are located in the matric cavities known as the lacunae. (Picture Courtesy—Tunku Kamarul)

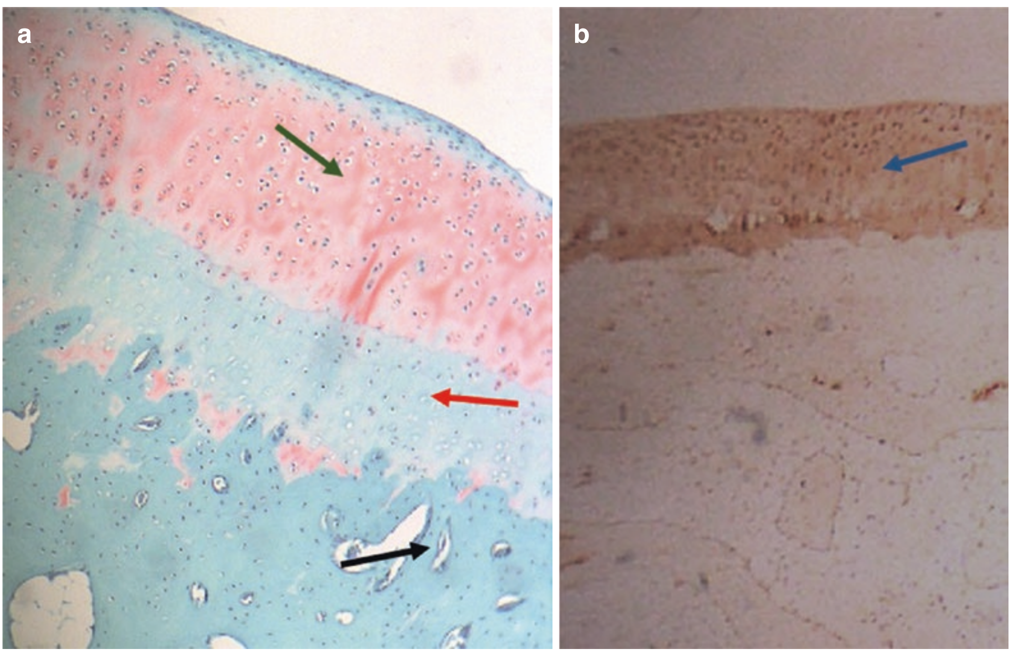

Figure 2.2.6: The Histology of the Healthy Hyaline Cartilage: The Special Stains. The special stains for histological examination of the healthy hyaline cartilage. (**a**) The healthy cartilage and the healthy subchondral bone are stained using a special staining technique, the safranin O technique, where cartilage is stained orange to red (green arrow) and all other areas such as bone is stained blue (red arrow). Safranin O is a basic stain which binds with the proteoglycans in the cartilage with a strong affinity, forming an orange to red complex, and the nuclei are stained black. Note that by controlling the quantity of stain to the adequate levels, the subchondral bone and the cortical bone regions can be clearly differentiated (black arrow). (**b**) The IHC stains for histological examination of the healthy hyaline cartilage can include a number of staining types, for example, picrosirius red (to detect cartilage). Immunostaining using antibodies against collagen type II (the predominant collagen of the cartilage tissue) has been used in this image. Higher intensity of brown color denotes a higher presence of collagen type II (blue arrow). (Picture Courtesy—Tunku Kamarul)

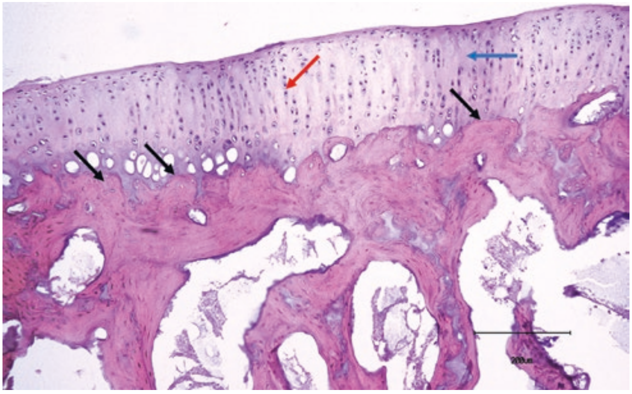

Figure 2.2.7: The Histology of the Healthy Subchondral Bone: The Routine Stains. Healthy cartilage and the healthy subchondral bone sample is stained using hematoxylin and eosin staining method (H&E staining). The cell nuclei were stained in blue-purple (red arrow) and the cartilage matrix was stained in purple-pinkish (blue arrow) color. Areas of high proteoglycan in general appear bluish as seen in this picture. Black arrows marks tidemark in the subchondral bone plate connecting the cartilage to the bone, and the green arrow shows the fenestrae connecting to the bone marrow. (Picture courtesy—Tunku Kamarul)

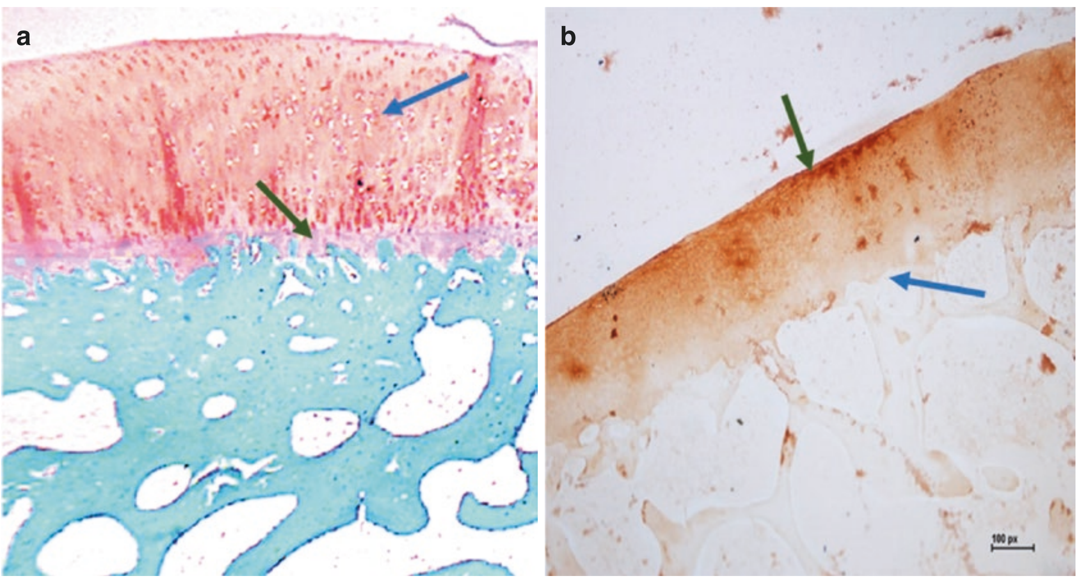

Figure 2.2.8: The Histology of the Healthy Subchondral Bone: The Special Stains. Safranin O is a cationic dye that stains the proteoglycan as well as the glycosaminoglycan. The staining also provides a proportional dye intensity to the proteoglycan content, thereby providing some form of indication of the proteoglycan quantity. (**a**) A high intensity of orange-red staining is observed in the cartilage tissue due to the presence of higher amount of proteoglycans (indicated by blue arrow) as compared to a lower intensity of staining in the cartilage-bone interphase due to a poor glycoprotein content (indicated by the green arrow). The subchondral bone region shows only a light green counterstain indicating the absence of proteoglycans. (**b**) The IHC stains are also used for the histological examination of the healthy subchondral bone. An image of the cartilage to the subchondral bone can be observed in a smooth nice transition of color intensity, as noted in the areas which are of high collagen type II from the surface region (green arrow) to the area where the collagen type II is diminished at the subchondral region (blue arrow). (Picture courtesy—Tunku Kamarul)

2.3 Take-Home Message

The osteochondral unit is a mechanically, physiologically, and biochemically interdependent, tight functional association of the articular cartilage, calcified cartilage, and the underlying subchondral bone [4]. Together they are responsible for transferring loads during weight-bearing and a smooth joint motion [4]. Hyaline articular cartilage is an important element of osteochondral unit ensuring smooth joint movements and a proper load transmission. Due to its avascular and aneural nature, it has limited intrinsic repair capability which makes it vulnerable to traumatic and aging-related injuries and degeneration.

Musculoskeletal disorders and diseases are a leading cause of disability. Over half of the adults aged 50 years and older, in the western world, have a chronic musculoskeletal condition [10]. In the USA, the economic burden is considerable; the cost of musculoskeletal conditions is approaching $1 trillion annually, which represents over 7.4% of the gross domestic product. The societal cost for the treatment for OA alone has surpassed that of both cardiovascular disease and cancer [10]. Understanding the anatomy, physiology, and the complex biomechanical and biochemical interactions of the articular cartilage and the underlying subchondral bone and their degeneration pattern in joint diseases, such as in osteoarthritis, is a major research question in order to be able to develop successful cartilage restoration strategies. Though still in its infancy, the biological treatments for this burdensome disorder have been a focus of intense investigations. In spite of the recent advances, a significant divergence of opinion on the future of early detection and biological treatments for orthopedic injuries remains. Even though new biomarkers for the early detection of OA are promising, there is a considerable need to improve the scientific knowledge, expand the technical capacities, and advance the clinical practice through the acceleration of translational research and an identification of the areas of high-yield research topics in this field [10].

References

1. Sophia Fox AJ, Bedi A, Rodeo SA. The basic science of articular cartilage: structure, composition, and function. Sports Health. 2009;1:461–8.
2. Goldring SR, Goldring MB. Changes in the osteochondral unit during osteoarthritis: structure, function and cartilage-bone crosstalk. Nat Rev Rheumatol. 2016;12:632–44.
3. Imhof H, Breitenseher M, Kainberger F, Rand T, Trattnig S. Importance of subchondral bone to articular cartilage in health and disease. Top Magn Reson Imaging. 1999;10:180–92.
4. Oláh T, Madry H. The Osteochondral unit: the importance of the underlying subchondral bone. In: Farr J, Gomoll AH, editors. Cartilage restoration: practical clinical applications. Cham: Springer International Publishing; 2018. p. 13–22.
5. Imhof H, Sulzbacher I, Grampp S, Czerny C, Youssefzadeh S, Kainberger F. Subchondral bone and cartilage disease: a rediscovered functional unit. Investig Radiol. 2000;35:581–8.
6. Madry H, van Dijk CN, Mueller-Gerbl M. The basic science of the subchondral bone. Knee Surg Sports Traumatol Arthrosc. 2010;18:419–33.
7. Oegema TR Jr, Carpenter RJ, Hofmeister F, Thompson RC Jr. The interaction of the zone of calcified cartilage and subchondral bone in osteoarthritis. Microsc Res Tech. 1997;37:324–32.
8. Biscevic M, Hebibovic M, Smrke D. Variations of femoral condyle shape. Coll Antropol. 2005;29:409–14.
9. McLeod WD, Moschi A, Andrews JR, Hugston JC. Tibial plateau topography. Am J Sports Med. 1977;5:13–8.
10. Madry H, Kon E, Condellao V, Peretti GM, Steinwachs M, Seil R, Berruto M, Engebretsen L, Filardo G, Angele P. Early osteoarthritis of the knee. Knee Surg Sports Traumatol Arthrosc. 2016;24:1753–62.