1 Basic Science and Injury in Growing Athletes: Cartilage, Menisci, and Bone

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In the last few years, competitive sports participation among western children has increased [1–3], with a rise in related injuries [4] because top-ranking young competitors undergo rigorous training for many hours a day [5, 6].

1.1 Articular Cartilage

1.1.1 Basic Science

Articular cartilage covers the surfaces of synovial joints and plays an important role in load distribution, shock absorption, and reducing friction during motion. Articular cartilage is composed of hyaline cartilage and has no blood or lymphatic vessels and no innervations, so its healing potential after an injury is very limited [7]. Nourishment for the articular cartilage comes mainly from the synovial fluid. Maroudas has demonstrated that there is no permeability of the bone/cartilage interface to water and solutes in adults and no detectable material transfer occurs across this zone; in the child, on the other hand, the bone/cartilage interface is permeable to water and solutes [8]. Although articular cartilages in the human body have the same structure and function, some properties, such as cartilage thickness, cellular density, composition of the extracellular matrix, and mechanical features, may vary between different joints and between different areas of the same joint. Articular cartilage consists of one cellular type, the chondrocytes, surrounded by the extracellular matrix [7].

The extracellular matrix is made up of a variety of structural macromolecules and fiber components that give the cartilage its biomechanical properties of rigidity, elasticity, and resiliency. The extracellular matrix is composed of 80 % water, which can move in and out of the tissue during compression and relaxation. Volume, concentration, and behavior of the water within the tissue depend mainly on interaction with the structural macromolecules (i.e., proteoglycans) that keep the fluid within the joint by regulating the concentration of electrolytes. The fluid of the extracellular matrix also contains gases, small proteins, metabolites, and a high concentration of cations to counterbalance the negatively charged proteoglycans. Structural macromolecules of the cartilage, namely collagen, proteoglycans, and non-collagenic proteins, are about 20 % of the dry weight of the tissue: collagen accounts for 55–60 %, proteoglycans for 25–35 %, and non-collagenic proteins for 15–20 %. Collagen is a glycoprotein representing the fibrous part of the extracellular matrix; its fibers are mainly Type II (90–95 %) with

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small amounts of Types VI, IX, X, and XI. Proteoglycans can be preset as small chains (i.e., decorin, biglycan, and fibromodulin) or large complexes (aggrecan); the most important non-collagenic proteins are fibronectin and tenascin.

Collagen fibers form a tridimensional scaffold of fibrils that give resistance and rigidity to cartilage. Proteoglycans are macromolecules with a protein core, and many lateral glycosaminoglycans (GAGs), which are long unbranched chains of amino sugars and acid monosugars, that have a negative charge. More than 100 proteoglycan molecules can be connected to a single chain of hyaluronic acid by small junction proteins, forming a big complex called aggrecan. Hyaluronic acid is a long chain of glucuronic acid and N-acetylglucosamine without any protein core, with a high hydration that helps in load distribution and protects chondrocytes from mechanical stress. Proteoglycans, hyaluronic acid, and aggrecan are highly hydrated and interwoven and entrapped into the scaffold of collagen fibers. As water volume in the extracellular matrix increases due to hydration of the macromolecules, the collagen fibers tighten, thereby avoiding swelling and softening of the cartilage and maintaining its biomechanical properties.

There are three different regions in the extracellular matrix of the cartilage [9, 10] (Fig. 1.1):

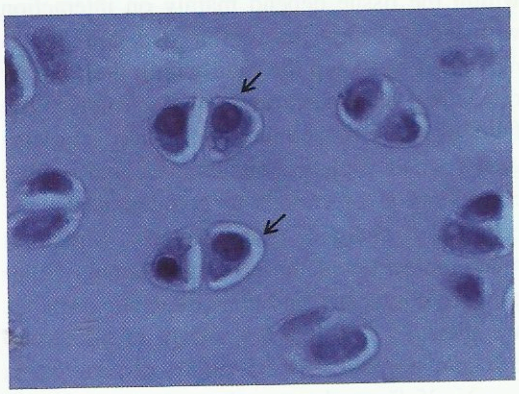

Fig. 1.1 Chondrocytes embedded in the cartilage matrix. The thin layer of pericellular matrix (*arrows*) is surrounded by the territorial and interterritorial matrix (Alcyan-PAS; x 100 objective)

- the pericellular matrix is a thin layer around the chondrocyte, rich in proteoglycans and non-collagenic proteins, but without collagen fibers;
- the territorial matrix is located around the pericellular matrix and is formed of thin collagen fibrils;
- the interterritorial matrix, which forms most of the extracellular matrix, has large collagen fibers and many proteoglycans.

In articular cartilage, there are four different highly organized regions, and each one has distinct composition, mechanical properties, cellular density, and morphology [11–15] (Fig. 1.2). The most superficial is the tangential superficial zone that, although very thin, is made up of two layers. The first one is lamina splendens that has thin fibrils, few polysaccharides and no chondrocytes. The second layer is also composed of thin fibrils but has few elliptically shaped chondrocytes, with the major axis parallel to the articular surface. The extracellular matrix is very rich in collagen fibrils parallel to the articular surface and poor in proteoglycans.

The subsequent region is the intermediate or transitional zone (superior and inferior) that has features of both the superficial zone (superior) and the underlying deep zone (inferior). It is thicker than the superficial zone and has many round-shaped chondrocytes that are very active metabolically, producing a considerable amount of extracellular matrix with large and irregularly arranged collagen fibers, a higher concentration of proteoglycans and a lower content of water than the superficial zone.

In the deep zone, known as radial zone, the chondrocytes are round-shaped, even more active metabolically and tend to form columns of 4–8 elements perpendicularly to the articular surface. The extracellular matrix is made up of very thick collagen, high content of proteoglycans, and very low content of water. The collagen fibers are arranged obliquely to the articular surface in the superior radial zone and perpendicularly in the inferior radial zone.

Collagen fibers cross the calcification area, called the tidemark, a basophilic line that separates the deep zone from the underlying calcified

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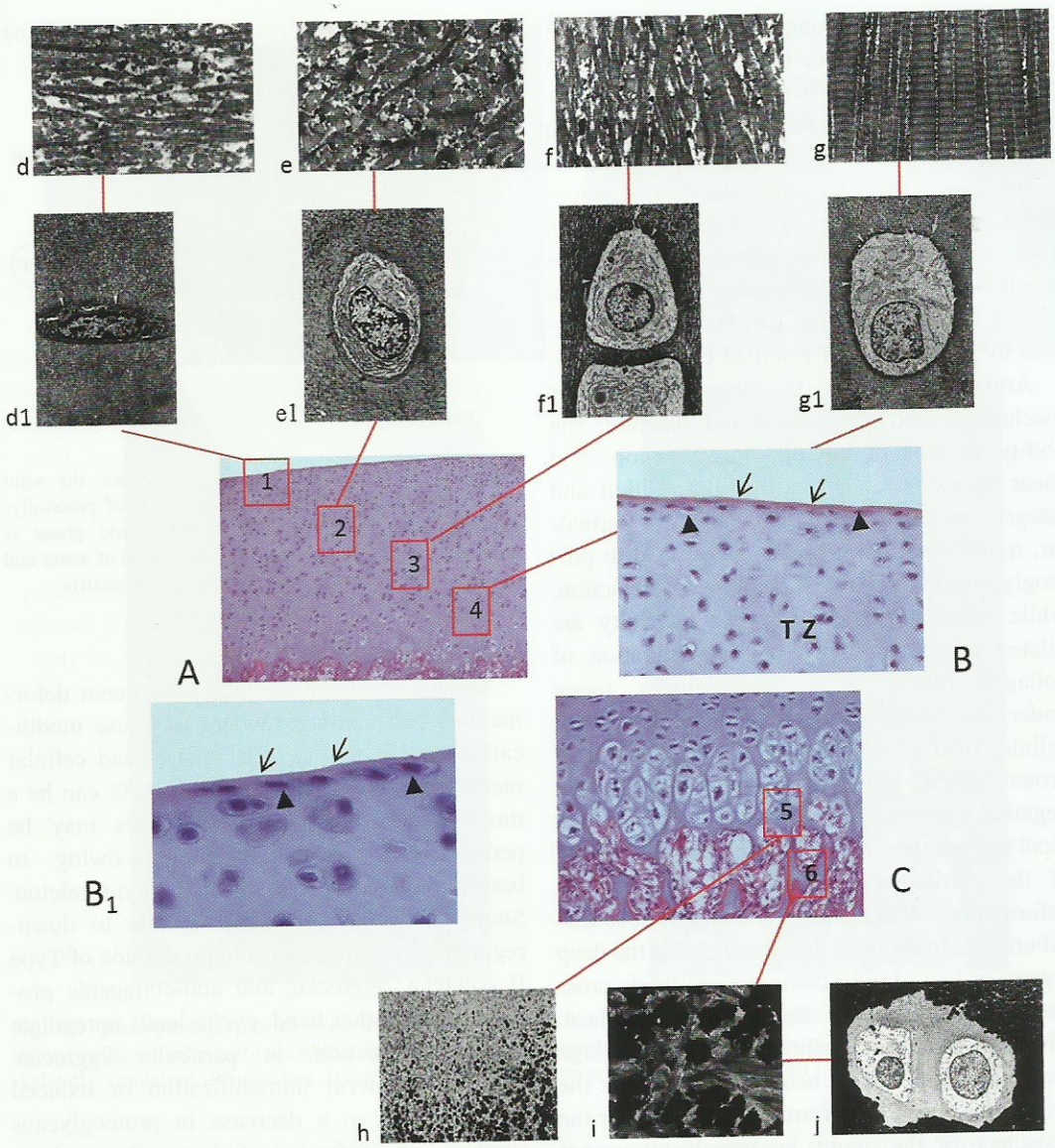


Fig. 1.2 A Microphotograph of normal articular cartilage obtained from a rabbit femoral head (H and E, x 2.5 objective). **B**–**B**$_1$ High magnification of the most superficial tangential zone with its "lamina splendens" (*arrows*) and the underlying elliptically shaped chondrocytes (*arrowheads*); the area below is the intermediate or transitional zone with its round-shaped chondrocytes (TZ), (x 40; x 100 objective); **C** deep and calcified zone with the perpendicular columns of round-shaped chondrocytes and the underlying hypertrophic chondrocytes (x 40 objective). **d**–**j** Electron microphotographs from articular cartilage. **d**–**d**1 tangential zone (zone 1 in **A**) with the longitudinally oriented collagen fibers (**d**) and the elliptic chondrocytes (**d**1); **e**–**e**1 Transitional zone (zone 2 in **A**) with the oblique collagen fibers and the round-shaped chondrocytes; **f**–**f**1 Superior radial zone (zone 3 in **A**) showing the slightly oblique collagen fibers and the chondrocytes in the radial columns; **g**–**g**1 Inferior radial zone (zone 4 in A) with the collagen fibers vertically oriented and the hypertrophic chondrocytes; **h** matrix in the tidemark (zone 5 in **C**); **i**–**j** mineralized matrix and the mineralized chondrocytes (zone 6 in **C**)

cartilage, thereby joining two tissues with different rigidity. The calcified cartilage separates the articular cartilage from the underlying subchondral bone; it has fewer chondrocytes than the deep zone, but they are hypertrophic and less active. Furthermore, a small number of osteoblasts and osteoclasts, Type I and X collagen fibers and small blood vessels coming from the subchondral bone are present in this region (Fig. 1.2). The immature cartilage is characterized by the absence of calcified cartilage.

Articular cartilage is subject to various mechanical loads, both static and dynamic. The ability to sustain compression, traction, and shear forces is related to the composition and integrity of the extracellular matrix; in particular, rigidity and permeability are related to proteoglycans, collagen fibers and their interaction, while resistance to tension and elasticity are related to the tridimensional configuration of collagen fibers. When cartilaginous tissue undergoes compression, the fluid of the extracellular matrix tends to leave the reticulum of proteoglycans, reducing the hydration of the negative charges of these macromolecules that repel one another, thereby increasing the rigidity of the cartilaginous tissue and reducing its deformation. Water allows a homogeneous distribution of loads from the superficial to the deep layers; in fact, during compression, fluids cross the cartilage up to the articular surface. Although fluid movements across the cartilage are not easy, this tissue behaves as a sponge: the greater the speed of deformation, the greater the resistance of the tissue, because water cannot flow away very fast. This phenomenon has led to the concept that cartilage has two phases, the solid phase formed of proteoglycans, collagen fibers, and cells; and the fluid phase made up of water that can move across the extracellular matrix. The solid phase is elastic and uncompressible and absorbs just 5 % of the loads applied to the joint, while the fluid phase is compressible and non-viscous and absorbs the remaining 95 % (Fig. 1.3). After an impact, the whole cartilage behaves as a solid uncompressible phase, because fluid has no time to flow across the solid phase [16, 17].

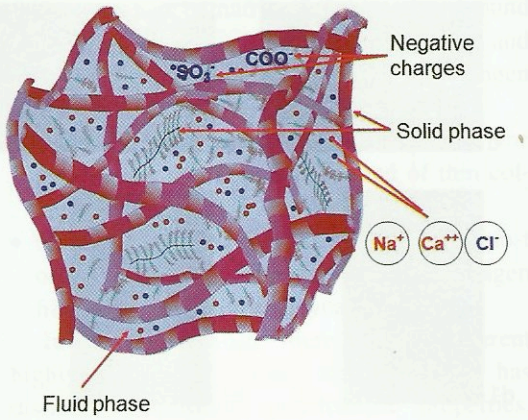
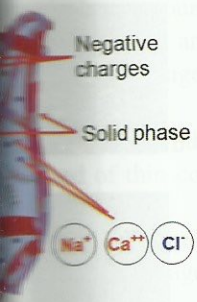


Fig. 1.3 Articular cartilage has two phases: the solid phase is uncompressible and is made up of proteoglycans, collagen fibers, and cells. The fluid phase is compressible and non-viscous and is formed of water and ions that can move across the extracellular matrix

Mechanical loads and the subsequent deformations that cartilage undergoes cause modifications in the extracellular matrix and cellular metabolism. Compression of 25–30 % can be a threshold after which chondrocytes may be permanently deformed, perhaps owing to breakage or reorganization of the cytoskeleton. Static compression forces are able to downregulate gene expression and production of Type II collagen, aggrecan, and non-collagenic proteins; on the other hand, cyclic loads upregulate protein production, in particular aggrecan. Finally, long-term immobilization or reduced loading leads to a decrease in proteoglycans synthesis and softening of the cartilage (chondromalacia) [18].

1.1.2 Injury

Injuries to the articular cartilage with or without involvement of the subchondral bone represent a serious problem, because cartilage has a low healing potential. The reparation process leads to fibrocartilage, rather than hyaline cartilage, which has different biomechanical properties that cannot deal with the stress applied to a joint [19]. It is well known that only small lesions can



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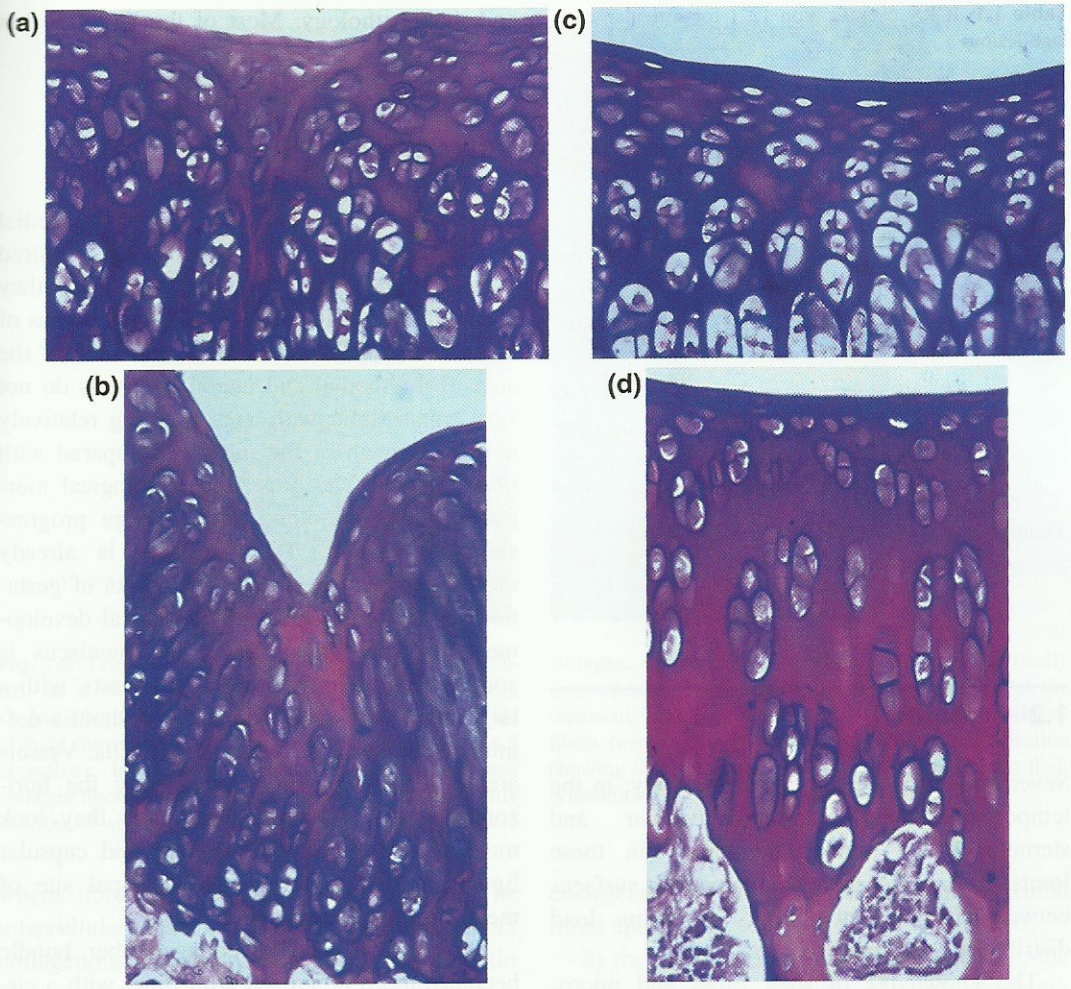

Fig. 1.4 Microphotographs of experimentally induced lesions in the articular cartilage of the femoral trochlea in skeletally immature Wistar rats taken 14 (**a**) and 50 (**b**) days after surgery. Microphotographs of the non-operated knee (control group) 14 (**c**) and 50 (**d**) days after surgery (Alcyan-PAS; x 40 objective)

heal; larger lesions and full-thickness lesions rarely heal spontaneously [20] (Fig. 1.4).

In the young population, two mechanisms of chondral lesions are possible: an acute lesion (chondral or osteochondral fracture) or a chronic overload or overuse (osteochondritis dissecansand microtrauma). Several classifications of articular cartilage lesions have been described in the literature, but the two most popular are the Outerbridge [21] and the International Cartilage Research Society (ICRS) classifications [22, 23]. The Outerbridge classification [21] was published in 1961 to describe chondral and osteochondral lesions of the patella. Nowadays, it is widely applied to all the compartments of the knee and also to other joints. Lesions are divided into 4 grades:

1. softening and swelling of the cartilage,
2. fragmentation and fissuring in an area half an inch or less in diameter,
3. the same as grade 2, but an area more than half an inch in diameter is involved,
4. erosion of cartilage down to bone.

The ICRS classification can be applied to osteochondritis dissecans [22] or to cartilage lesions [23]. It comprises four grades and several subgroups (Table 1.1).

Table 1.1 ICRS classification [22] for articular cartilage lesions

Grade 0	Normal
Grade 1	Nearly normal—superficial lesions
	a. Soft indentation
	b. Superficial fissures and cracks
Grade 2	Abnormal—lesions extending down to <50 % of cartilage depth
Grade 3	Severely abnormal
	a. Cartilage defects extending down >50 % of cartilage depth
	b. Down to calcified cartilage
	c. Down to but not through the subchondral bone
	d. Blisters
Grade 4	Severely abnormal—cartilage defects extending down to the subchondral bone

1.2 Menisci

Several menisci are present in the body: in the temporomandibular, acromioclavicular and sternoclavicular joints, and knees. In these joints, the menisci increase the contact surfaces between incongruent bones, improving load distribution and stability.

The knowledge of their gross and microscopic anatomy and biochemical composition is fundamental for understanding their function and their pathology. Most of the literature has been written on the menisci of the knee.

1.2.1 Basic Science

The characteristics and properties of the medial and lateral meniscus of the knee are acquired during prenatal development, and then, they change throughout growth. The ratio of areas of the medial and lateral tibial plateau and of the area of the medial and lateral meniscus do not vary significantly with age, implying relatively uniform growth of the menisci compared with tibial growth. The gross and histological morphology, on the other hand, change progressively with age. The meniscus is already identifiable between 7.5 and 8 weeks of gestation. In the embryonic and early fetal development of the human knee, the meniscus is composed of densely packed fibroblasts, with a large nucleus-to-cytoplasm ratio, without a definite arrangement of the meniscal cells. Vessels are extremely numerous, traversing the horizontal width of both menisci, and they look more prominent in the coronary and capsular ligaments that represent the principal site of meniscal blood supply (Fig. 1.5).

During fetal life, the collagen fiber bundle becomes more organized with time, with a circumferential orientation in the middle and an oblique orientation at the attachment sites,

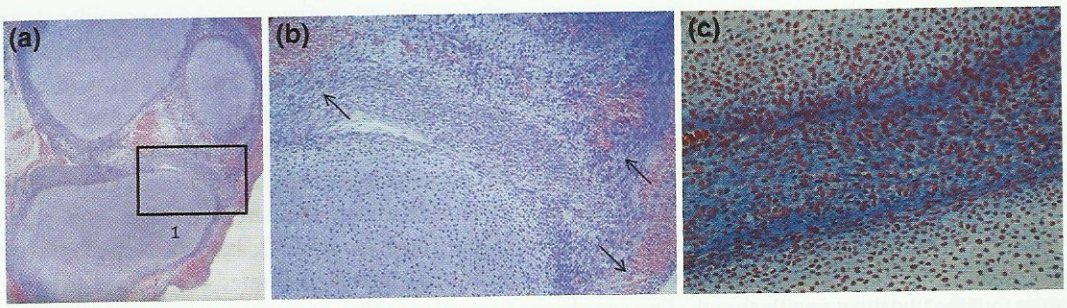

Fig. 1.5 Microphotographs of a developing knee obtained from a 17-week human fetus. **a** embryonic cartilage of the distal end of the femur, proximal end of the tibia, menisci, and joint cavity (H and E x 1.5 objective); **b** a higher magnification of area 1 shows the medial meniscus with blood vessels prominent along the peripheral margin of the meniscus (*arrows*), (x 20 objective); **c** a higher magnification of the medial meniscus shows the densely packed fibroblasts with a large nucleus-to-cytoplasm ratio (Masson trichrome; x 40 objective)

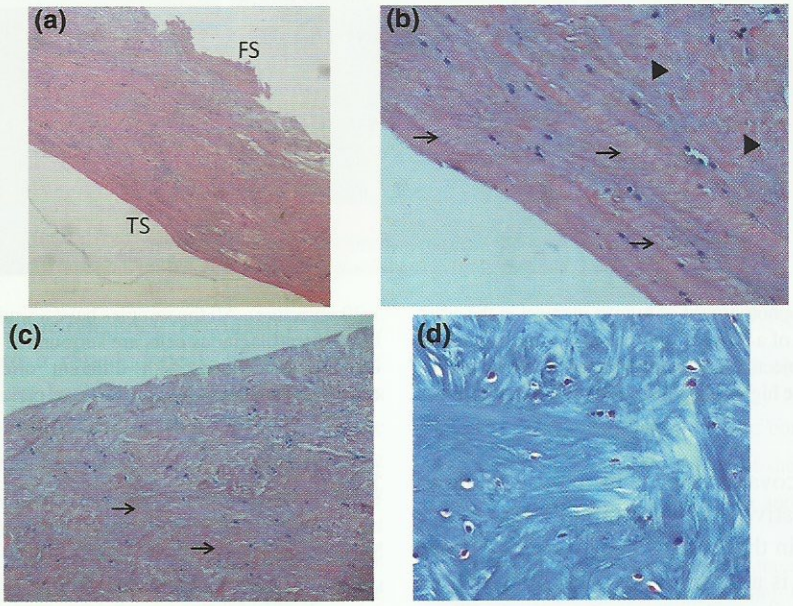

Fig. 1.6 Longitudinal section through a human meniscus of a 9-year-old child. **a** full-thickness section showing both the tibial side (*TS*) and the femoral side (*FS*) of the inner part of the meniscus (H and E x 4.5 objective); **b** tibial side with the radially oriented collagen fibers (*arrows*); the meniscal cells are uniformly distributed without a definite arrangement. The aforesaid collagen fibers change direction and run vertically (*arrowheads*) (x 40 objective). **c** peripheral part of the meniscus with the circumferentially distributed collagen fibers (*arrows*) (x 20 objective). **d** high magnification showing the area where the collagen fibers change their orientation (Masson trichrome; x 40 objective)

where fibrocartilage starts to be present. The intercellular matrix gradually becomes more collagenous and the nucleus-to-cytoplasm ratio decreases.

After birth, the menisci show a higher collagen content. The fibroblasts look more mature, with relatively smaller nuclei, and they are arranged in a more orderly fashion. The blood vessels are less represented in the menisci and appear to be predominantly located in the peripheral part.

In the toddler age, vascularity continues to progressively decrease, proceeding from the inner to the outer part of the meniscus, with a reduction in cellularity and an increase in collagen content. The fiber pattern progresses to the vertical direction of the radial fibers in relation to the weight-bearing stresses. From a biomechanical point of view, circumferentially arranged fibers withstand tension force, while the radially oriented fibers resist longitudinal splitting of the meniscus. Growth of each meniscus follows enlargement of the distal femoral and proximal tibial epiphysis.

In the childhood and in the adolescence, the menisci are similar to those of adults, but with vessels still represented, exclusively in the outer one-third of the periphery, adjacent to the coronary ligaments, and with an abundant intercellular matrix (Fig. 1.6).

In adult life, the menisci are fibrocartilaginous semicircular-shaped structures made up of collagen (75 %) and non-collagenic proteins (8–13 %), namely glycoproteins and GAGs. Type I collagen is the most frequent (90 % of all collagen chains). Type II collagen is also present in the inner avascular portion of the meniscus. Type III, V, and VI collagen fibers have been described in small quantities. This last one seems to connect different proteins of collagen I fibers, thereby creating a net among collagen fibers.

Proteoglycans, a non-collagenic protein, are 1 % of the dry weight of the meniscus. They are made up of a polypeptide, hyaluronic acid,

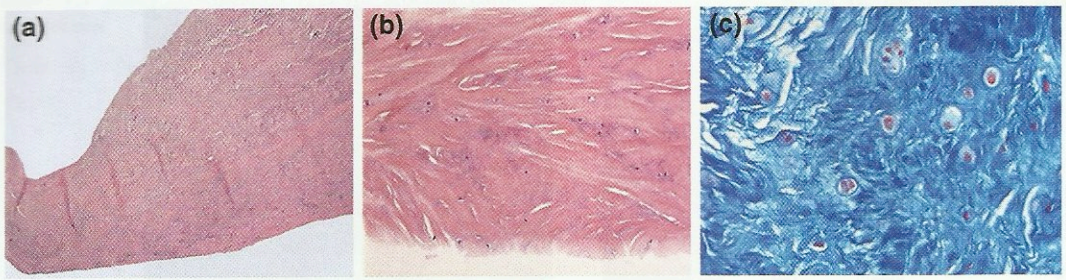

Fig. 1.7 Microphotographs of human menisci in the adult age. **a** meniscus of a 35-year-old man at low magnification (H and E; x 4 objective); **b** higher magnification (H and E; x 10 objective); **c** higher magnification (Masson trichrome; x 20 objective). All the samples have a similar appearance: the fibrocartilaginous cells are surrounded by an abundant extracellular matrix with different orientation of the collagen fibers. No blood vessels are present

linked by a covalent link with polysaccharides (GAGs), negatively charged amino sugars that attract water in the matrix. The most represented proteoglycan is aggrecan, but decorin (a smaller proteoglycan) has also been described. Fibromodulin and thrombospondin, on the other hand, are the glycoproteic component; they can be linked to the proteoglycan aggregates stabilizing the matrix organization.

At histological examination, fibroblasts and fibrocartilaginous cells are surrounded by an extremely abundant extracellular matrix of collagen fibers that have a circumferential direction, ideal for load distribution during compression. Radial fibers are also present to increase structural integrity and probably to prevent longitudinal tears [24]. Elastic fibers (0.6 % of the dry weight of the meniscus) seem to improve the return to the original shape after a deformation [25] (Fig. 1.7).

Every meniscus covers about two-thirds of the articular surface of the joint. In section, the meniscus is triangular-shaped; it is thicker on the peripheral part and adherent to the joint capsule, and thinner on the free edge. Blood vessels are present only in the one-third of the peripheral menisci, adjacent to the coronary ligaments.

The meniscus has important biomechanical functions. It is important in the transmission and absorbance of mechanical stresses. Moreover, because of its heterogenic composition, it has a fundamental role in sustaining compression (inner avascular part) and tension forces (outer vascularized zone).

1.2.2 Injury

Meniscal lesions are extremely frequent in sports players. Men are more affected than women (2.5–1); the medial meniscus (74 %) and the right knee (52 %) are more often involved. The meniscal lesion is usually the consequence of an incorrect movement of the menisci in the flexion–extension of the knee joint mainly due to lack of synchronism during the range of motion of the knee, knee traumas, or knee hyperflexion with a sudden extension. In these cases, the menisci are torn by vertical compression forces and/or horizontal rotational forces.

Different classifications are used for meniscal lesions. One is related to the presence of the lesion in one of the 3 different zones of vascularization of the meniscus: the red/red zone, the most peripheral one, with abundant vascular support; the red/white zone, the intermediate zone, with scanty vascularization; and the white/white zone, the central one, completely avascular. This classification has a prognostic value for the possible healing of the lesions in relation to the presence of vascular supply [26] Meniscal sutures should be systematically performed in children and adolescents with meniscal tears; meniscal resection, even if partial, should be avoided, to prevent the development of degenerative osteoarthritis [27] (Fig. 1.8a).

Another classification is based on the type of lesion [28]. Vertical lesions are the longitudinal and the radial lesions. A neglected radial tear,

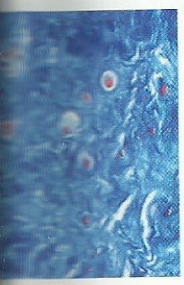

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Fig. 1.8 **a** Arthroscopic suture of a longitudinal peripheral lesion of the medial meniscus. **b** Flap lesion of the medial meniscus. **c** «Bucket-handle» lesion of the medial meniscus

usually an oblique one, may try to heal itself and round off into a rounded beak like a parrot's beak (the parrot-beak or flap tear), and this can catch in the joint (Fig. 1.8b). "Bucket-handle tears" are particular longitudinal lesion running from the anterior to the posterior horns, causing the central portion of the meniscus (the bucket handle) to displace into the joint (Fig. 1.8c). Horizontal lesions, on the other hand, are those with a horizontal opening of the meniscus that can be complete or partial. There are also complex lesions that are a combination of the foregoing ones.

1.3 Bone

In the growing athlete, bone is composed of cartilaginous and bone tissues. Bone growth occurs by several mechanisms that differ from long bones to short and flat bones. Furthermore, particular mechanisms are involved in epiphyseal and apophyseal growth and development (Table 1.2). Genetic, hormonal, and environmental factors modulate bone growth during childhood and adolescence, and knowledge of the morphofunctional aspects of the epiphysio-metaphyseal growing cartilage mechanisms and speed of bone growth is important for understanding the treatment and prognosis of many injuries in these patients.

Table 1.2 Mechanisms of enchondral ossification

Type 1	Columns of proliferating and degenerating cartilaginous cells
	a. Growth plates of long bones
	b. Triradiate cartilage of the pelvis
Type 2	Clusters of proliferating and degenerating cartilaginous cells
	a. Epiphyseal aspect of the secondary ossification centers of long bones
	b. Growth cartilage of short bones
	c. Growth plates of vertebral bodies up to 4 years
Type 3	Clusters of proliferating and degenerating cartilaginous cells separated by septa with thick collagen fibers
	a. Growth cartilage of the iliac crest
	b. Growth plates of vertebral bodies after 4 years
Type 4	Direct ossification from cartilage
	a. Metaphyseal aspect of secondary ossification centers of long bones
	b. Apophyseal ossification nuclei (iliac crest, vertebral plates, tuberosity of the calcaneus, etc.)
Type 5	Ossification from fibrocartilage
	a. Insertions of ligaments and tendons

1.3.1 Basic Science

1.3.1.1 Long Bones

Long bones are basically composed of two epiphyses separated by the diaphysis, which have different growth mechanisms. Diaphyseal growth occurs both longitudinally (increased length) and radially (increased diameter). The growth in length of the long bones is the consequence of enchondral ossification of the epiphyseal-metaphyseal centers located at the extremities of the long bones, whereas radial growth is due to enchondral ossification of the periosteum.

Epiphyses have particular growth mechanisms. After birth, the epiphysis of long bones is made up of a cartilaginous scaffold that

increases its diameters by interstitial growth. In a given age range (that is typical of each epiphysis), a secondary ossification center appears in the epiphyseal cartilage, and this nucleus grows by enchondral ossification of the surrounding cartilaginous layer. The epiphyseal cartilage is formed of two qualitatively different portions, one toward the joint and one toward the metaphysis (lamina or placca terminale).

The articular portion of the epiphyseal cartilage is made up of two different layers:

1. A peripheral one is the articular cartilage that will be present all through life
2. A deeper one is the epiphyseal cartilage that will grow by interstitial enchondral ossification until adolescence (the end of skeletal growth).

It is possible to differentiate these two parts only by particular immunohistochemical stainings. On the articular surface, chondrocytes are stretched and parallel to the surface. In the deeper layers, they are round shaped and distributed regularly. Near the secondary ossification center, there are clusters of chondrocytes that undergo the same processes of maturation, hypertrophy and degeneration as the chondrocytes of the growth plates. These clusters are separated by thick septa of mineralized matrix, forming a scaffold for osteoblasts to produce bone matrix. The new bone trabeculae have a direction that is parallel or oblique to the ossification center, whereas in the metaphyseal growth, plate trabeculae are perpendicular to the growth center (Fig. 1.9).

These histological differences can explain why the growth rate of the epiphysis is much slower than that of growth plates. The same enchondral ossification observed on the articular side of the epiphysis of long bones is present in short bones and vertebrae up to the age of 4 [29, 30].

The metaphyseal side of the cartilaginous layer around the secondary ossification center bone seems to ossify directly from cartilage. Chondrocytes do not undergo hypertrophy and degeneration, and the extracellular matrix is not degraded. Bone formation is anticipated by loss of its staining with Alcyan Blue , but it is strongly PAS positive. In this area, it is possible to observe cells that are located between bone and cartilaginous matrixes, with features in between osteocytes and chondrocytes. This enchondral ossification model, that is even slower, is also observed in the ossification center of the iliac crest, in the epiphyseal center of the vertebrae and in the accessory centers of the acetabulum [31, 32] (Fig. 1.10).

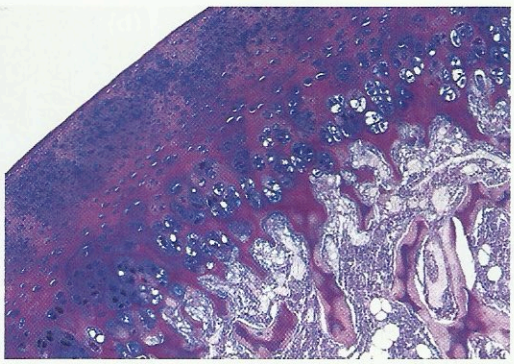
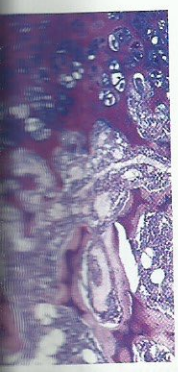


Fig. 1.9 Microphotograph of the articular portion of the epiphyseal cartilage obtained from a rabbit femoral head (Alcyan-PAS; x 20 objective). The chondrocytes differ in shape and distribution from the articular surface to the deep zone. The different histochemical affinities in this area can be observed. (Masson trichrome; x 40 objective)

The metaphyseal growth cartilage (growth plate) is adjacent to the metaphyseal portion of the epiphyseal cartilage, toward the diaphyseal side. Different layers of cartilagineous cells can be observed in the growth plate:

- Germinal layer: it is close to the epiphysis, and chondroblasts are arranged in the extracellular matrix in a jumble. An injury to this layer results in a halt in growth.
- Proliferation and maturation layer : chondrocytes duplicate and are typically arranged in columns.
- Hypertrophic and degenerating layer : chondrocytes increase their volume and die.
- Ossification layer: this is the terminal part of the cartilage, where vessels arrive and provide oxygen and preosteoblasts at the level of longitudinal and transverse septa.

In this particular cartilage, chondrocytes are arranged in columns, each cell separated from the other by thin transversal septa, while the



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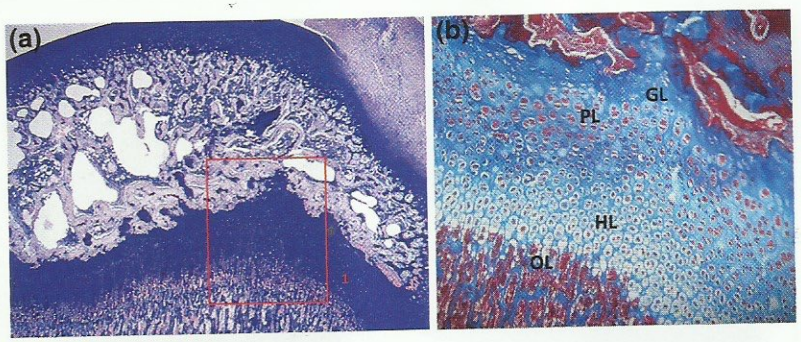

Fig. 1.10 **a** Microphotograph of a proximal femoral epiphysis of a skeletally immature rabbit (Alcyan-PAS; x 10 objective). **b** Higher magnification of area 1 showing the cartilagineous metaphyseal layer. Near the secondary ossification center the condrocytes do not change their aspect; the underlining growth plate shows 4 different layers: germinal layer (*GL*); proliferation layer (*PL*); hypertrophic layer (*HL*); ossification layer (*OL*) (Masson trichrome; x 40 objective)

columns of chondrocytes are separated by thick longitudinal septa. Histochemical staining and ultrastructural observations have shown a different structural organization of the longitudinal septa compared with the transversal ones [33]. They also perform different functions. The transversal septa are progressively reabsorbed at the level of the degenerating layer to allow blood vessel penetration. The longitudinal septa, on the other hand, are the cartilaginous model on which ossification by the osteoblasts, coming from the new vessels, starts to take place (Fig. 1.10).

In conclusion, during skeletal growth, in the epiphyseal cartilage, with the chondroblasts organized in clusters, and in the metaphyseal cartilage, with the chondroblasts organized in columns, we can observe the following processes with different morphological expressions:

1. Matrix degradation of the thin transversal septa
2. Mineralization of the matrix of the longitudinal septa and of the thick transversal septa
3. Blood vessel penetration into the space obtained by the matrix degradation of the thin transversal septa
4. Calcium deposit on the calcified septa by the osteoblasts coming from the blood vessels.

These phenomena are strictly related to one another, and the growth rate of the skeleton is regulated by their speed.

1.3.1.2 Perichondrial Groove

The perichondrial groove (groove of Ranvier) is located around the boundaries between the epiphysis and the metaphysis and is responsible for remodeling the epiphyso-metaphysis of long bones. It is composed of a group of cells and vessels proliferating and differentiating in several ways. Different types of cells are present in the perichondrial groove:

a. The "bone mark": this is a deep, thick layer of cells that will differentiate into osteoblasts that will make the cortical bone surrounding and sustaining the metaphysis. This shell surrounds the metaphyseal cartilage and takes part in bone remodeling of the metaphyseal region of the bone, due to an osteoclastic resorption of its inner part.
b. A superficial layer of cells that will differentiate into chondroblasts, which are responsible for the radial growth of the epiphyses.
c. A more superficial layer of cells that will differentiate into fibroblasts, which will make an external fibrous shell, continuous with the perichondrium and the periosteum [34] (Fig. 1.11). A trauma of the perichondrial groove during skeletal growth could be responsible for the final altered shape and volume of the metaepiphysis of that particular long bone.

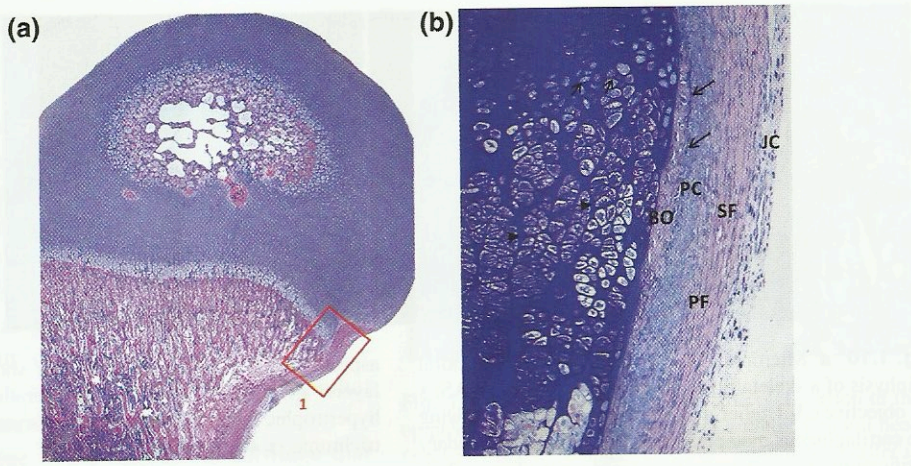

Fig. 1.11 **a** Microphotograph of a proximal femoral epiphysis of a skeletally immature rabbit (H and E; x 2.5 objective). **b** Perichondral groove (high magnification of area *1*): (Alcyan-Pas; 40 x objective). The growth plate is surrounded by the ring of Ranvier. Bone layer (*BO*); osteoblasts (*thin arrows*); prechondroblasts (*PC*); prefibroblasts (*PF*); superficial fibrous layer (*SF*); joint capsule (*JC*); Between the chondrocytes, in the growth plate, the transversal cartilaginous septa (*thick arrows*) and the longitudinal cartilaginous septa (*arrowheads*) can be observed

1.3.1.3 Vascularization

Metaepiphyses have 3 different types of vascularization.

1. Diaphyseal-endosteal vessels that supply blood to the ossification process of the metaphyseal cartilage.
2. Perichondrial vessels that supply blood to the perichondrium and also to the perichondrial groove.
3. Epiphyseal vessels that supply blood to the different ossification centers of the epiphysis: the superficial layers of the metaphyseal cartilage and the epiphyseal cartilage toward the metaphyseal side and toward the articular side.

The superficial cells of the articular cartilage get their nourishment by diffusion of the synovial fluid from the articular space. It has been confirmed, in experimental models, that an interruption of the blood supply of the epiphyseal vessels causes distress for the osteogenetic processes of the epiphyseal ossification center and of the metaphysis growth plate but not for the chondrogenetic process of the articular cartilage [35].

The epiphyseal vessels of growing long bones reach the nucleus of ossification first through the joint ligaments and capsula and then through the peripheral cartilaginous epiphysis, initially following an extra-articular pathway, without crossing the metaphyseal growth plate (type B vascularization). The epiphyseal vessels of the proximal femoral epiphysis and of the proximal radial epiphysis, on the other hand, are mainly intra-articular and reach the cartilaginous epiphyseal nucleus by crossing the metaphyseal growth plate (type A vascularization). These last epiphyses are more exposed to vascular lesions as a consequence of traumatic injury of the metaepiphyseal complex (Fig. 1.12).

1.3.1.4 Short and Pelvic Bones

The growth of short bones of the tarsus and carpus is regulated by the cartilaginous envelope around the ossification nucleus. Chondrocytes closer to the nucleus are arranged in clusters as occurs in the epiphyseal cartilage of long bones, but the organization of the cartilage is the same all around the nucleus because the metaphyseal cartilage is missing. The most external part of the cartilaginous envelope forms the articular cartilage.

In vertebrae, the growing cartilage has a structure similar to that of the other short bones up to the age of 4. The vertebral body grows with an enchondral mechanism around the

blasts (*PC*); prefibro- (*SF*); joint capsule (*JC*); growth plate, the trans- and the longitudinal can be observed

pathway, without growth plate (type B yseal vessels of the and of the proximal her hand, are mainly the cartilaginous ing the metaphyseal ization). These last ed to vascular lesions matic injury of the Fig. 1.12).

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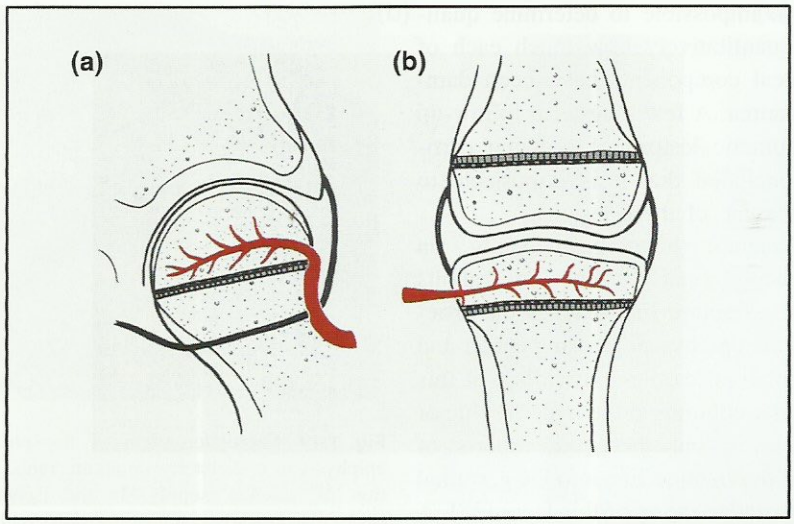


Fig. 1.12 Different types of vascularization of the epiphyseal vessels in growing long bones. **a** Type **a** vascularization: the epiphyseal vessels reach the nucleus of ossification by crossing the metaphyseal growth plate. **b** Type **b** vascularization: the epiphyseal vessels reach the nucleus of ossification without crossing the metaphyseal growth plate

ossification nucleus. At the age of 4, the growing cartilage disappears and the radial growth of the vertebral body occurs by intramembranous ossification from the periosteum.

In the superior and inferior parts of the vertebral body, a hyaline cartilage disk is present. This last one is made by two different structures: the vertebral plate, where the annulus fibrosus is inserted, and the vertebral growth plate. The first one is important to contrast the mechanical loads, whereas the second one, made by short columns of chondrocytes separated by thick extracellaluar matrix septae, is responsible for the longitudinal vertebral growth.

1.3.1.5 Functional Aspects

The metaepiphyseal complexes of the long bones do not participate with the same percentage in the growing process. In the lower extremity, the knee metaphyses are more active regarding lower extremity growth than the hip and the ankle metaphysis, with the distal femoral metaphysis contributing 70 % and the proximal tibial metaphysis 55 %. In the upper extremity, on the other hand, the metaphyses away from the elbow are the more active ones, with the humeral contributing 80 % to upper extremity growth, the distal radial 75 % and the distal ulnar 80 % [36].

It is also important, as Green and Anderson [37] reported in their tables, that the amount of growth of the long bones is not constant but varies with age: it is quite rapid in the lower extremities, especially distally, during childhood and then slows down until the pubertal period, when the growth plates are under the stimulus of sex hormones. At the pubertal growth spurt, vertebral and pelvis plates are especially active, while the limb growth plates tend to reduce their contribution to growth.

1.3.2 Injury

The longitudinal growth of the bone can be temporarily or permanently damaged by traumatic, vascular, metabolic, infectious, thermal, or iatrogenic factors. Traumatic lesions of the epiphyso-metaphyseal area have an unpredictable prognosis. In fact, the traumatic lesion involves the metaepiphysis but sometimes the articular cartilage as well, with bone growth disorders and also degenerative changes of the

joint. It is also impossible to determine qualitatively and quantitatively how much each of these anatomical components have been damaged by the trauma. A few long-term follow-up studies of traumatic lesions of growing cartilages have concluded that it is impossible to predict the outcome of these lesions.

An experimental histological study on induced metaepiphyseal lesions in rabbits showed that the fracture line reaches the articular cartilage, the epiphyseal growing center and then the metaphyseal cartilage, dividing, at this level, the cellular columns at the hypertrophic or degenerative layer, but there are reports of propagation of the fracture line into the germinal layer with devascularization of this layer [38]. A lesion of the vessels at the fracture line produces a hematoma with a consequent inflammatory reaction. Necrotic cartilage cells are present around this area.

In areas where the blood supply was interrupted or the physis was incorrectly aligned, trabecular bone will eventually replace the cartilage and form a bony bridge between metaphysis and epiphysis (Fig. 1.13).

Regardless of the type of fracture, if the epiphyseal blood supply is interrupted as a consequence of the fracture, the subsequent ischemia of the germinal cells of the affected physis can lead to serious growth disorders.

Experiments demonstrating damage to the physis after epiphyseal vessel occlusion were reported by Trueta and Amato [39] and more recently by Kim and Su [40]. In experimentally induced ischemia of the proximal femoral epiphysis in rabbits, Tudisco et al. [35] showed that an ischemic insult to the femoral capital epiphysis results in necrosis of the epiphyseal growth plate which is more severe if the ischemia is induced before the appearance of the secondary ossification center. Small ectopic centers of ossification in the epiphyseal cartilage, around the epiphyseal ossification nucleus, are the result of the revascularization process after the ischemic insult; their presence jeopardized the uniformity of the proximal femoral epiphysis causing the femoral head deformity (Fig. 1.14).

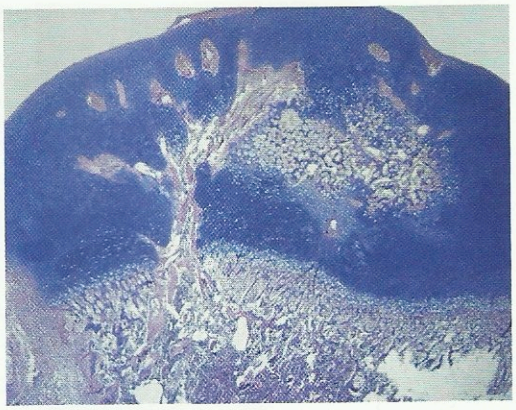


Fig. 1.13 Microphotograph of the proximal femoral epiphysis in a skeletally immature rabbit after interruption of vascular supply. In the ischemic and then revascularized areas, trabecular bone replaced the cartilage and formed a bony bridge between metaphysis and epiphysis

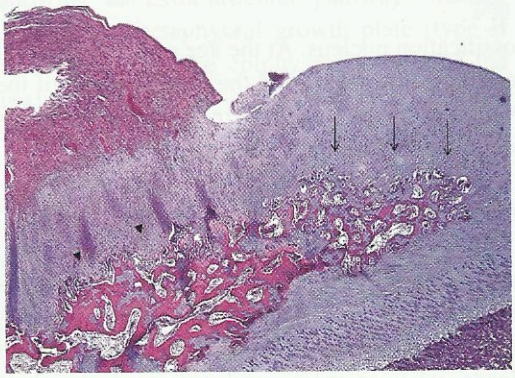
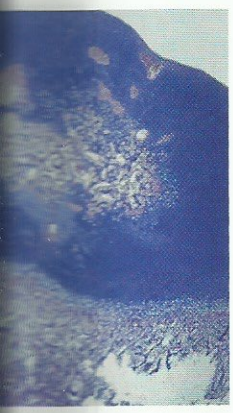


Fig. 1.14 Microphotograph of experimentally induced ischemia in the proximal femoral epiphysis in a skeletally immature rabbit. Small ectopic centers of ossification in the epiphyseal cartilage (*arrows*), around the epiphyseal ossification nucleus (*arrowheads*), are the result of the revascularization process after the ischemic insult

The incidence of physeal fractures in relation to the totality of fractures in children is around 15 %, but some authors think this number could be closer to 30 % [41–43]. Regarding the age at occurrence, it is a well-known fact that the incidence is higher in ages close to puberty, and therefore, chronologically slightly sooner in girls than in boys [41, 44], and these fractures are more frequent in boys than in girls. The two most



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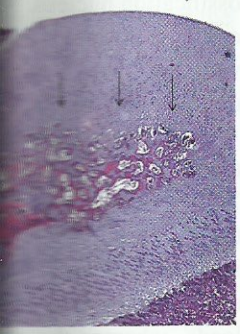

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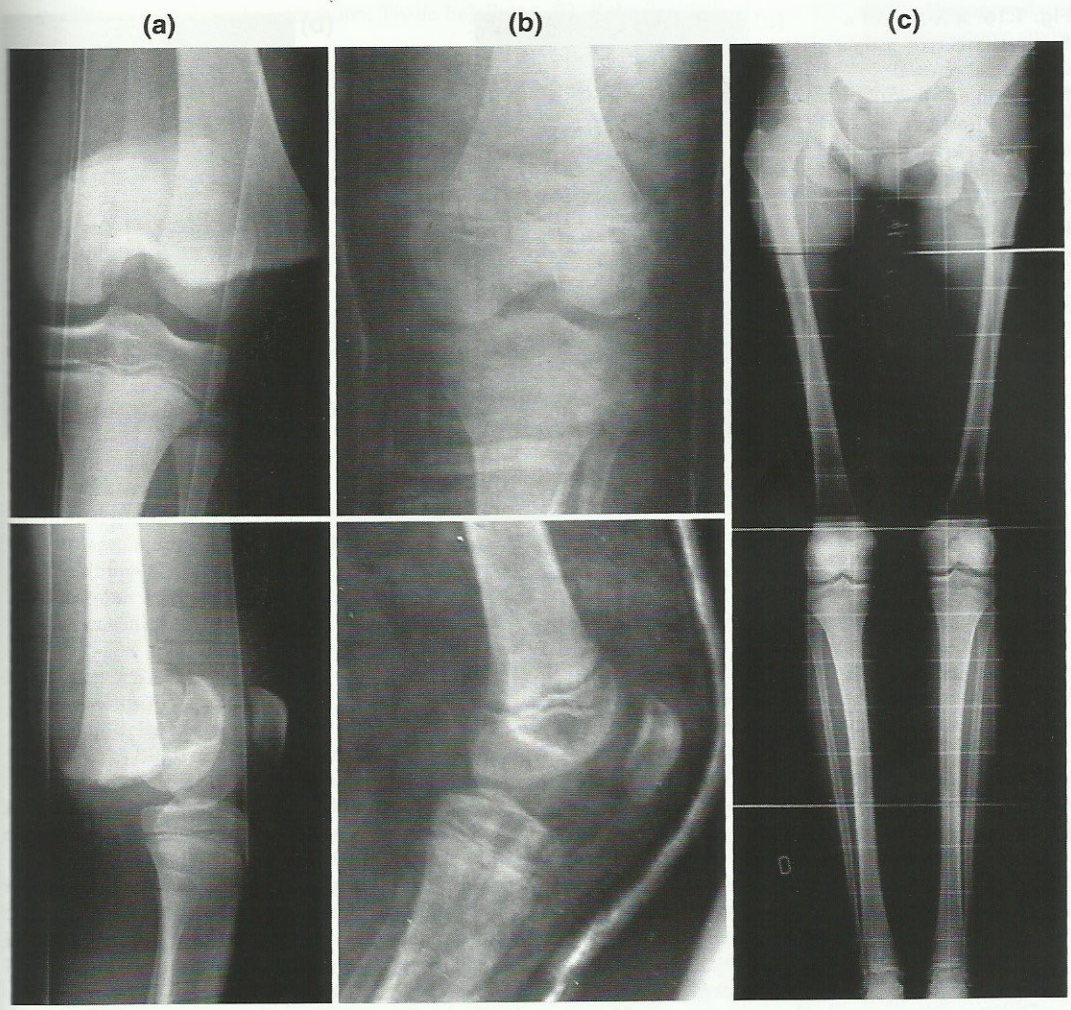

Fig. 1.15 **a** X-rays of a Salter–Harris type 2 left distal femoral physeal fracture in an 8-year-old girl. **b** The fracture was treated by a very good closed reduction and immobilization by a long-leg cast with flexed knee and without weight-bearing for 5 weeks, followed by a straight long-leg cast for additional 5 weeks. **c** The X-rays taken after 5 years showed a leg length discrepancy due to a left femur shortening of almost 4 cm

widely used classifications of fractures of the growth plate are from Salter and Harris [43] and Ogden et al. [45].

The prognosis for physeal fractures depends on a series of factors: the type of fracture, the amount of growth remaining, the displacement of the fragments, the anatomical reduction, and the severity of the injury. The most common sequelae of physeal fractures are partial or total cessation of bone growth, due to a premature physeal closure, or a delay in growth, with a consequent shortening and/or angular deformity of the bone segment involved (Figs. 1.15 and 1.16). In certain types of fractures, a stimulus of the growth plate closest to the fracture can occur.

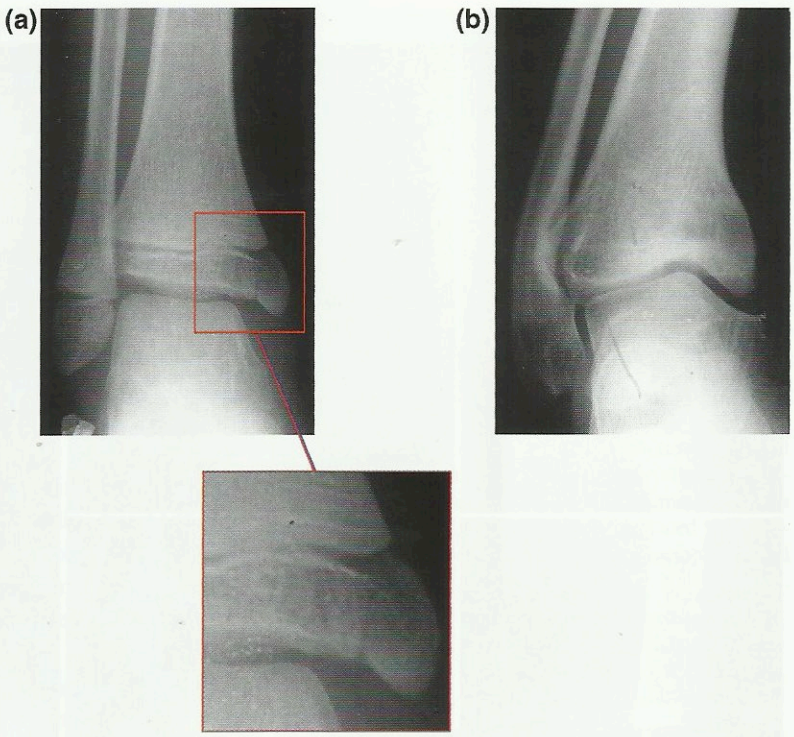

Fig. 1.16 **a** X-rays of a Salter–Harris type 3 right distal tibial physeal fracture in a 9-year-old boy. The fracture was treated by closed reduction and immobilization with a short-leg cast for 5 weeks. **b** The X-rays taken after 12 years showed a very severe varus deformity of the ankle

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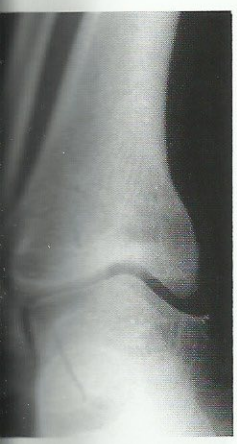

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