Chondrogenic Bone Tumors: The Importance of Imaging Characteristics

Chondrogene Knochentumoren: Bildgebung als Wegweiser?

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ABSTRACT

Background Chondrogenic tumors are the most frequent primary bone tumors. Malignant chondrogenic tumors represent about one quarter of malignant bone tumors. Benign chondrogenic bone tumors are frequent incidental findings at imaging. Radiological parameters may be helpful for identification, characterization, and differential diagnosis.

Methods Systematic PubMed literature research. Identification and review of studies analyzing and describing imaging characteristics of chondrogenic bone tumors.

Results and conclusions The 2020 World Health Organization (WHO) classification system differentiates between benign, intermediate (locally aggressive or rarely metastasizing), and malignant chondrogenic tumors. On imaging, typical findings of differentiated chondrogenic tumors are lobulated patterns with a high signal on T2-weighted magnetic resonance imaging (MRI) and ring- and arc-like calcifications on conventional radiography and computed tomography (CT). Depending on the entity, the prevalence of this chondrogenic pattern differs. While high grade tumors may be identified due to aggressive imaging patterns, the differentiation between benign and intermediate grade chondrogenic tumors is challenging, even in an interdisciplinary approach.

Key Points:

- The WHO defines benign, intermediate, and malignant chondrogenic bone tumors
- Frequent benign tumors: osteochondroma and enchondroma; Frequent malignant tumor: conventional chondrosarcoma
- Differentiation between enchondroma versus low-grade chondrosarcoma is challenging for radiologists and pathologists
- Pain, deep scalloping, cortical destruction, bone expansion, soft tissue component: favor chondrosarcoma
- Potential malignant transformation of osteochondroma: progression after skeletal maturity, cartilage cap thickness (> 2 cm adult; > 3 cm child)
- Potentially helpful advanced imaging methods: Dynamic MRI, texture analysis, FDG-PET/CT

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ZUSAMMENFASSUNG

Hintergrund Chondrogene Tumoren sind die häufigsten primären Knochentumoren. Maligne chondrogene Tumoren repräsentieren etwa ein Viertel der malignen Knochentumoren. Benigne chondrogene Knochentumoren sind häufige radiolo-

gische Zufallsbefunde. Radiologische Parameter können hilfreich sein zur Identifikation, Charakterisierung und Differenzialdiagnostik.

Methode Systematische Literaturrecherche mittels PubMed. Identifikation und kritische Beurteilung von Studien, welche die Bildgebung chondrogener Knochentumoren analysieren oder beschreiben.

Ergebnisse und Schlussfolgerung Nach der World-Health-Organization (WHO)-Klassifikation von 2020 werden benigne, intermediäre (lokal aggressiv oder selten metastasierend) und maligne chondrogene Tumoren unterschieden. Das typische radiologische Bild chondrogen differenzierter Tumoren ist gekennzeichnet durch ein lobuliertes Wachstumsmuster mit einem hohen Signal in T2-gewichteten Sequenzen in der Magnetresonanztomografie (MRT) und durch ein meist ring- und bogenförmiges Verkalkungsmuster in der Projektionsradiografie und der Computertomografie (CT). In Abhängigkeit der Entität ist dieses typische Muster unterschiedlich ausgeprägt. Während hochmaligne Tumoren häufig ein eindeutig malignes Wachstumsmuster zeigen, ist die Differenzierung zwischen benignen und intermediären chondrogenen Tumoren auch interdisziplinär schwierig.

Introduction

Bone tumors and tumor-like lesions are frequent incidental findings in the radiologist's clinical routine. The World Health Organization (WHO) classification of bone tumors is based on the histological structure of the primary tissue or the primary cell type. This article discusses chondrogenic bone tumors which represent the largest group of bone tumors. A well differentiated chondroid matrix is characterized by a lobulated growth pattern and calcification patterns that are typical for cartilaginous tumors (▶ **Fig. 1**). The typical calcification patterns are the result of endochondral ossification. They are primarily popcorn-like or ring- and arc-like and can be visualized on conventional radiography and computed tomography (CT) [1]. However, according to Lodwick, the chondroid matrix is visible on conventional radiography only in 65 % of chondrosarcomas, 30 % of chondroblastomas, and 2 % of chondromyxoid fibromas [2]. Due to its high water content, hydrophilic cartilage tissue is clearly hyperintense in T2-weighted MRI sequences [3, 4]. Calcifications are hypointense both in T2- and T1-weighted sequences. The cartilage tissue is supplied with blood via the capillaries in the septa and via the perichondrium so that ring- and arc-like contrast enhancement occurs after contrast administration [5].

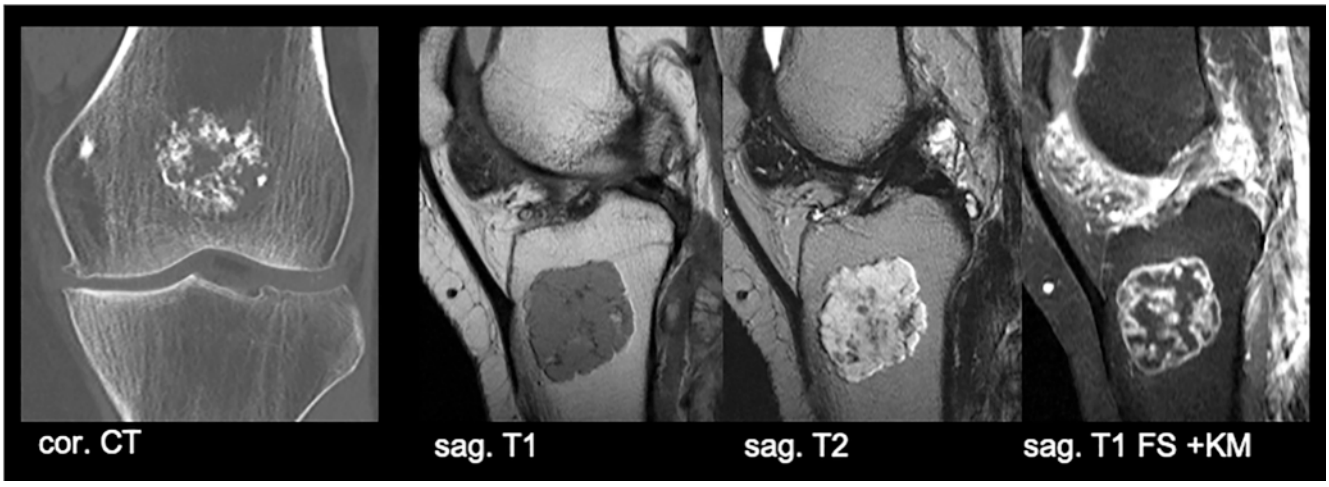
WHO classification

In the 2020 World Health Organization (WHO) classification, the various entities of chondrogenic bone tumors are categorized as benign, intermediate (locally aggressive and/or rarely metastasizing), or malignant (▶ **Table 1**) [6]. In the 2013 WHO classification, the group of benign chondrogenic tumors including osteochondromas and chondromas/enchondromas was expanded to include osteochondromyxoma, subungual exostosis, and bizarre parosteal osteochondromatous proliferation (BPOP, Nora's lesion) [7]. Chondroblastomas and chondromyxoid fibromas were moved from the intermediate to the benign group in the 2020 WHO classification. Synovial chondromatosis was moved from the benign to the intermediate group to reflect the locally aggressive growth pattern and the high risk for local recurrence [8]. The intermediate group also includes atypical cartilaginous tumors (ACTs) of the extremities due to their locally aggressive growth pattern [9]. While the term "chondrosarcoma grade I" was replaced by "ACT" in the 2013 WHO classification and was assigned to the intermediate group, both terms are used depending on location in the new 2020 WHO classification [6, 10]: When located in the appendicular skeleton (long and short tubular bones), these tumors are categorized as ACT and assigned to the intermediate group; when located in the axial skeleton (including the pelvis and base of the skull), tumors with the same histology are designated as chondrosarcoma grade I and assigned to the malignant group to reflect the difference in biological behavior [11, 12].

Benign chondrogenic tumors

Osteochondroma

Osteochondromas (osteocartilaginous exostoses) are among the most common benign bone tumors (approximately 20–50 %). It must be assumed here that the true prevalence is underestimated due to asymptomatic lesions [13]. Most osteochondromas are diagnosed in the second decade of life. Men are affected more often than women [14]. Mutations in tumor suppressor genes EXT1 and EXT2 are usually found in the cartilage cap [15]. Osteochondromas are often located in the region of the knee joint and the proximal humerus. The distal femur is most commonly affected. The location is usually metaphyseal or metadiaphyseal. The tumor can manifest either (i) in a broad-based manner (sessile) or (ii) as a pedunculated, spur-like expansile growth from the bone surface. It is encompassed by a cartilage cap [9]. This expansile growth points in the direction of the diaphysis. There is pathognomonic continuity of the medullary cavity from the bone to the osteochondroma as well as direct continuity of the cortex. This helps to differentiate Osteochondromas from parosteal osteosarcomas. The growth arises from the cartilage cap as the actual tumor (component), which often shrinks on a relative basis during adolescence due to increasing ossification [16]. A malignant transformation in children is extremely rare. Cartilage cap thicknesses of > 3 cm in children and > 2 cm in adults are considered suspicious [16]. In an analysis of 67 osteochondromas and 34 secondary peripheral chondrosarcomas, Bernard et al. did not find any chondrosarcomas with a cartilage cap thickness of less than 2 cm [17]. MRI is the imaging method of choice for measuring the cartilage cap thickness (on T2-weighted images) and evaluating soft tissues. In addition to cartilage cap thickness, further



▶ **Fig. 1** Enchondroma of the distal femur (**a**: 62 years old, female) and the proximal tibia (**b–d**, 38 years old, female) in two different patients. **a** The typical ring- and arc-like matrix calcifications can be seen on CT. **b–d** The calcifications are hypointense on native T1-weighted and T2-weighted MRI and the lobulated hydrophilic cartilage matrix components are hyperintense on T2-weighted MRI. In addition, pathognomonic ring- and arc-like contrast enhancement is seen. CT: computed tomography; cor: coronal; sag: sagittal.

criteria that can indicate a malignant transformation are local pain, growth after skeletal maturity, cartilage surface irregularities, focal osteolysis inside the lesion, and erosion of the adjacent cortex or the peduncle of the osteochondroma [1]. Hereditary multiple osteochondroma (HMO; multiple cartilaginous exostoses) is a syndrome involving multiple osteochondromas (▶ **Fig. 2**). It is usually an autosomal-dominant hereditary disease [15] with an elevated risk of malignant transformation. Osteochondromas can result in mechanical compression of soft tissues and thus functional impairment and pain [18]. They can affect adjacent epiphyseal plates often resulting in shorter, partially deformed extremities particularly in the case of HMO. In the case of two or more osteochondromas, whole-body MRI is indicated and should be repeated after skeletal maturity depending on the location of the osteochondromas [19]. Usually, no intravenous contrast is needed. Diffusuion weighted sequences may be helpful [20, 21]. In the case of solitary and multiple osteochondromas, clinical follow-up and possibly supplementary imaging should be performed every one to three years depending on the location. In the case of HMO, clinical follow-up of lesions that still have a cartilage cap should be performed every year and MRI imaging should be performed every one to two years [19].

Enchondroma

Beside osteochondromas, enchondromas common benign bone tumors. Enchondromas are hypocellular tumors. The chondrocytes are surrounded by a mature hyaline matrix (▶ **Fig. 1**). In the case of isolated enchondromas, somatic mutations in the isocitrate dehydrogenase 1 and 2 gene (IDH-1 and IDH-2) are found in approximately 50 % of cases [22]. Enchondromas can be diagnosed at any age but they are most frequently diagnozed in the second to third decade of life. Since enchondromas are usually asymptomatic, the true prevalence is underestimated and varies in the literature [14, 23, 24]. Previously, it was assumed, that enchondromas are most commonly located in the short tubular bones of the hands and feet. However, Davies et al. found an incidence of 0.07 % on conventional radiographs in these regions, while the incidence of enchondromas in shoulder and knee MRI examinations was approximately 2.5–2.9 %, with the visibility on the radiographs being between 17–77 % depending on the size of the lesion [24, 25]. Thus, enchondromas located in the long tubular bones, particularly in the proximal humerus and proximal and distal femur, seem to be more commun (▶ **Fig. 3**). The location of enchondromas in the short tubular bones is usually diaphyseal, while the location in the long tubular bones is typically metadiaphyseal, rarely epiphyseal. They are typically located in the center of the medullary cavity of tubular bones [9]. Enchondromas in flat bones are very rare [9]. Particularly in the region of the pelvis, a chondrosarcoma should be assumed unless proven otherwise [14]. The matrix calcifications of enchondromas appear popcorn-like (ring- and arc-like), comma-shaped or flaky on imaging. Osteolysis is also possible. Expansive tumor growth can result in thinning of the cortex. This is referred to as endosteal scalloping. In the case of deep scalloping, an ACT/chondrosarcoma grade I should be considered as a differential diagnosis (see below). Enchondromatosis subtypes include Ollier disease and Maffucci syndrome, which usually occur before the 20thyear of life [26]. IDH-1 and IDH-2 mutations can be seen in up to 90 % of cases in these diseases [20–22]. Multiple enchondromas with an often asymmetrical distribution are present on Ollier disease [26]. In Maffucci syndrome, soft tissue vascular malformations additionally occur. The risk of a malignant transformation in the case of solitary enchondromas is up to 4 % [27]. It is significantly higher in Ollier disease and Maffucci syndrome [28]. Peripheral solitary enchondromas without initial clinical or imaging-based morphological suspicion of malignancy should be examined again if pain develops [14]. In the case of enchondromas located in the proximal femur, humerus, scapula, or pelvis and in the case of enchondromas greater than 5 cm even in a peripheral location, annual clinical follow-up should be performed (and MRI should

▶ **Table 1** 2020 WHO classification of chondrogenic bone tumors [6].

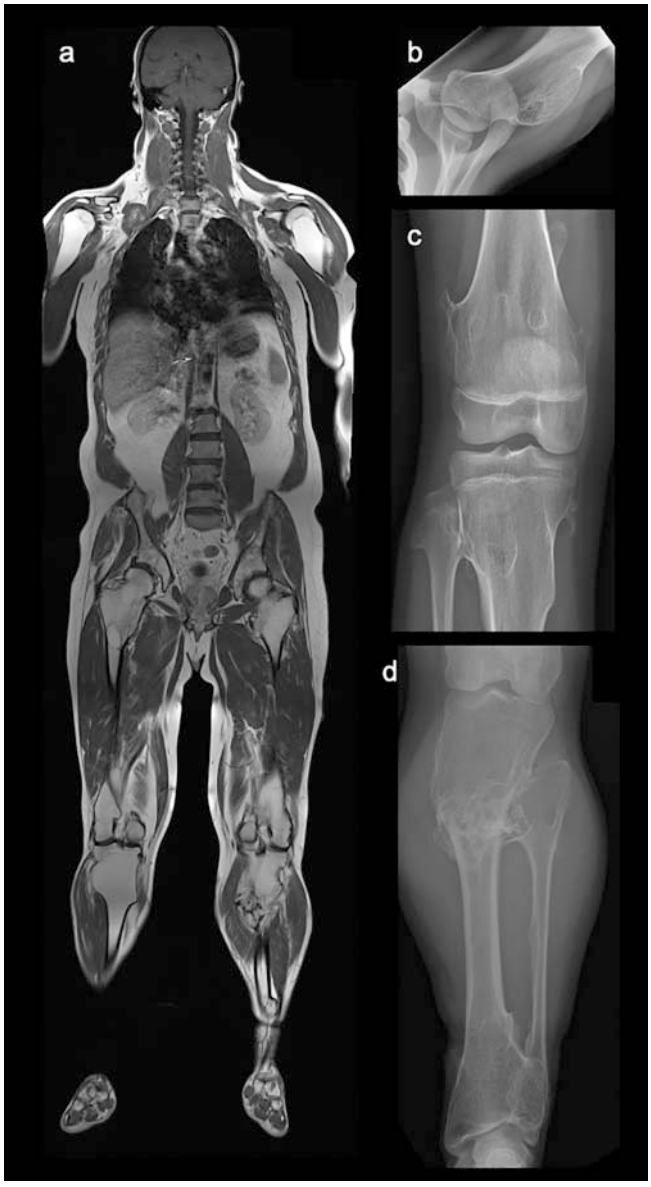
entity		percentage of cartilage tumors (%)[a]
benign	osteochondroma	28.5
	enchondroma	29.1
	periosteal chondroma	3.3
	osteochondromyxoma	*
	subungual exostosis	4.8
	bizarre parosteal osteochondromatous proliferation (BPOP)	
	chondromyxoid fibroma	1.8
	chondroblastoma	5.1
intermediate	atypical cartilaginous tumor (ACT)	*
	synovial chondromatosis	*
malignant	conventional chondrosarcoma grade I-III	21.7
	dedifferentiated chondrosarcoma	2.7
	mesenchymal chondrosarcoma	0.9
	clear cell chondrosarcoma	1

WHO = World Health Organization.

[a] The percentages are from the registry of the Basel Bone Tumor Reference Center (1972–2015) [49]. Due to the fact that benign chondrogenic tumors are often asymptomatic, the data do not represent the true prevalence in the population.

* Not explicitly stated.

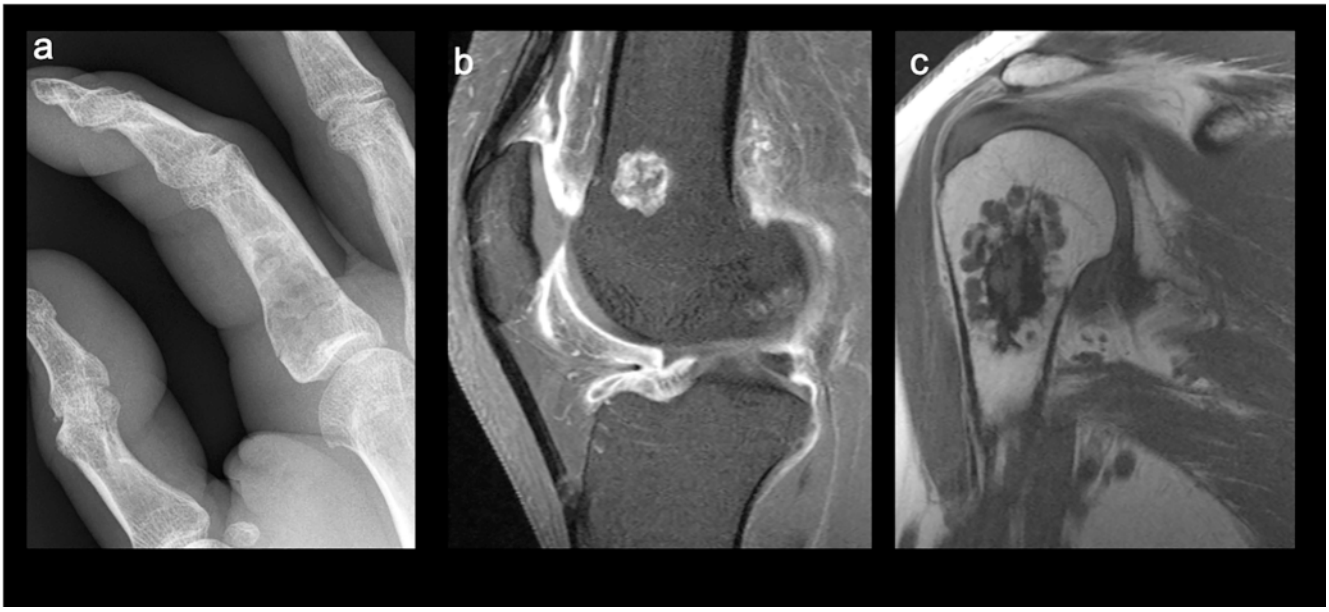
be performed at least every two years) [14]. In the case of two or more lesions, whole-body MRI should initially be performed. In the case of enchondromatosis, whole-body MRI should ideally be used for follow-up imaging. If there is clinical suspicion of malignancy, immediate imaging in the form of conventional radiography and supplementary local MRI is indicated [14]. If there is suspicion of malignancy based on morphological imaging data, an interdisciplinary discussion is needed in order to plan the biopsy access in the region of the subsequent surgical access and to define the exact sampling points to avoid sampling errors. Tumor components with potentially invasive growth must be included in the biopsy. Moreover, it is essential to biopsy various parts of the tumor, e. g. to identify a dedifferentiated chondrosarcoma (see below) [29].



▶ **Fig. 2** Osteochondromas in a 54-year-old man with hereditary multiple osteochondromas in the region of the proximal humerus (bilateral), the proximal and distal femur (bilateral), and the proximal and distal tibia and fibula (bilateral). **a** Coronal T1-weighted whole-body MRI. **b** Broad-based osteochondroma on the proximal humerus. **c** Pedunculated osteochondromas on the distal femur and the proximal tibia; the osteochondromas point in the direction of the diaphysis. **d** Deformities of the left lower leg in the case of multiple osteochondromas. Pathognomonic continuity of the medullary cavity from the bone to the osteochondroma as well as direct continuity of the cortex.

Differentiating between enchondroma and ACT/chondrosarcoma

Despite intensive research efforts, the differentiation between an enchondroma and an ACT/chondrosarcoma grade I continues to be a major diagnostic challenge [14]. This is because the histological features between the two entities overlap [30, 31]. A histopathological characteristic used for differentiation is the permea-



▶ **Fig. 3** Enchondromas. **a** Pathological fracture in enchondroma in the proximal phalanx DII (52 years old, male). Expansile growth, which is not considered a criterion of malignancy in small bones. **b** Incidental finding of a typical enchondroma in the distal femur without criteria of malignancy (54 years old, male). Unchanged at one-time 6-month follow-up. **c** Enchondroma in the proximal humerus as an incidental finding (64 years old, female). In contrast to ▶ **Fig. 4a–c**, the maximum diameter of the chondrogenic tumor is < 5 cm and does not reach the cortex. It was not clinically symptomatic. There was no increase in size over time. sag: sagittal; cor: coronal; fs + KM: with fat saturation after contrast administration.

tive growth seen in ACT/chondrosarcoma grade I [6]. This is defined by growth around at least three sides of the original spongy bone trabeculae. Infiltrative growth into cortical bones or destruction of the cortical bone and spread to the periosteal soft tissue also indicate ACT/chondrosarcoma grade I. In addition, ACT/chondrosarcoma grade I can have increased cellularity, irregular cell distribution, and binuclear cells. However, binuclear cells can also occur in enchondromas. Moreover, myxoid changes of > 20 % favor a diagnosis of ACT/chondrosarcoma grade I. However, it can be very difficult to differentiate between enchondroma and ACT/chondrosarcoma grade I based on small biopsies or curettage material. A clinical-radiological correlation is essential [6]. Thus, an interdisciplinary consensus decision between orthopedist, radiologist, and pathologist is indispensable for diagnosis and treatment planning in case of chondrogenic tumors [32]. Since radiological assessment is included when determining the diagnosis, a confounding effect can occur in scientific studies [33–35].

The main parameters that are suitable for differentiation are summarized in ▶ **Table 2**. In 187 cases Murphey et al. identified features for differentiating between enchondromas and chondrosarcomas of the extremities (without consideration of the grading). Advanced patient age (50 versus 40 years on average), male sex, and pain symptoms are clinical parameters associated with a chondrosarcoma [35–37]. Pain often represents a better discriminator than imaging features [33, 38]. The further proximal the enchondroma, the higher the probability of a malignant transformation. A chondrogenic tumor at the axial skeleton is to be considered a chondrosarcoma until proven otherwise (▶ **Fig. 4**). Further criteria that can indicate malignancy are an epimetaphyseal location (versus metadiaphyseal), a large tumor size (> 5 cm), and growth of the lesion after skeletal maturity (▶ **Fig. 5**). Further typical imaging-based criteria that argue against a benign enchondroma include deep endosteal scalloping (> 2/3 of the cortical thickness) or a periosteal reaction [35, 37]. According to Douis et al., deep endosteal scalloping is the most sensitive imaging criterion for low-grade chondrosarcomas [38]. However, deep endosteal scalloping can also occur in the case of eccentric enchondromas without increased biological activity, growth, or malignancy [39]. In addition, the ability to evaluate scalloping at the proximal fibula and at the medial proximal humerus is limited due to the thin cortex (▶ **Fig. 6**) [40]. Cortical thickening and bone expansion (excluding short tubular bones) are rare but also possible signs of chondrosarcoma [33]. An extraosseous soft tissue component penetrating the periosteum indicates the presence of a chondrosarcoma. An intermediate signal in T1-weighted sequences, discontinuous (versus continuous) visualization after contrast administration, a pathological fracture, adjacent bone marrow edema, and signal alterations of the adjacent soft tissue can indicate an intermediate or malignant process [35, 37]. Compared to conventional radiography, on MRI a higher rate of true-positive (57.8 % versus 20.8 %) as well as false-positive (14.1 % versus 3.1 %) diagnoses of a chondrosarcoma was seen in [33]. The sensitivity of the described parameters is lower for ACT/chondrosarcomas grade I than for higher-grade chondrosarcomas [38].

Moreover, newer imaging methods including dynamic MRI examinations, MRI diffusion imaging, PET-CT, and computer-aided texture analyses are used to differentiate between benign and malignant lesions. While MR-based diffusion imaging cannot differentiate between enchondromas, low-grade chondrosarcomas, and higher-grade chondrosarcomas [41], dynamic contrast-en-

▶ **Table 2** Relevant parameters characterizing potential enchondromas (benign), atypical cartilaginous tumors (intermediate), and central chondrosarcomas [29].

	benignity more likely	intermediate grade or malignancy more likely
symptoms	no symptoms	pain
		pathological fracture
location	peripheral extremities	near the trunk; in the axial skeleton
size	< 5 cm	> 5 cm
extent on T1 weighted MRI	continuous	discontinuous
MRI contrast dynamic	slower and minor contrast enhancement	fast and increased relative contrast enhancement
expansion	none	expansion of a large bone
periosteum/bone	unremarkable	endosteal scalloping (> 2/3 of the cortical thickness)
		periosteal reaction
		cortical hyperostosis
		cortical destruction
soft tissue	no soft tissue component	extraosseous soft tissue component

MRI: magnetic resonance imaging.

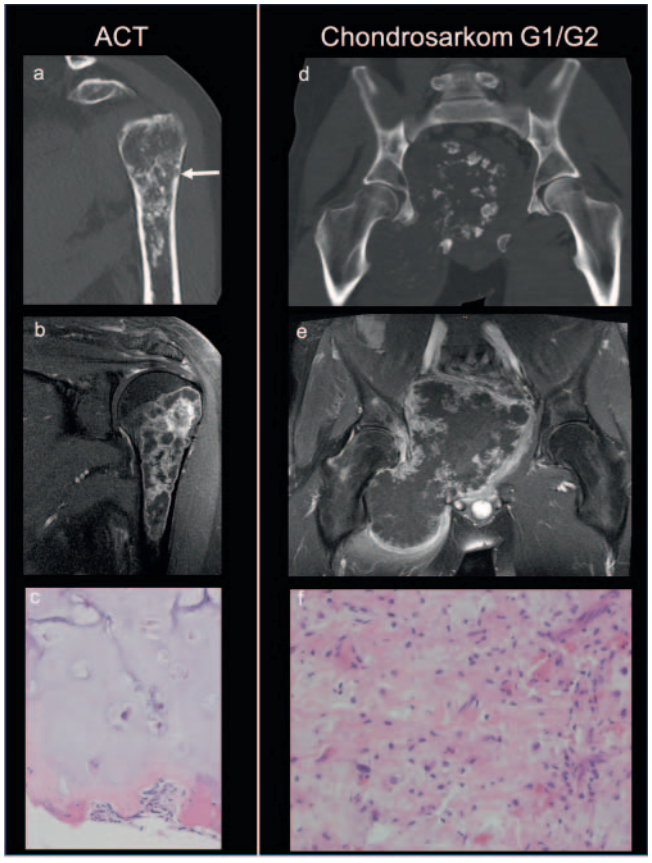
hanced MRI examinations can increase the specificity for the diagnosis of a chondrosarcoma [38, 42, 43]. Quick and increased relative contrast enhancement (compared to muscle tissue) is typical for a chondrosarcoma. However, the ability to differentiate between low-grade chondrosarcomas and enchondromas is also limited with this technique [38]. Tumor heterogeneity is known to be associated with an unfavorable tumor biology [39, 40]. MRI texture analyses of tumor heterogeneity may be able to differentiate between enchondromas and low-grade chondrosarcomas [44, 45]. Using a combination of texture analysis and MRI imaging criteria, an accuracy regarding the differentiation between benign and low-grade chondrogenic tumors of 91.2 % can be achieved [45]. Since these studies identified different predictive texture parameters, it seems that additional studies are needed to validate these promising results. Some studies showed that the SUV_{max} value (maximum standardized uptake value) in FDG-PET/CT correlates with the histological grading of chondrogenic tumors [46, 47]. However, there is a relevant overlap between the SUV_{max} values of enchondromas and low-grade chondrosarcomas resulting in poor specificity particularly in case of an SUV_{max} value in the range of 2–4.5 [46, 48]. In case of tumor recurrence, FDG-PET/CT can potentially provide information regarding disease-specific survival [47]. Despite these studies, FDG-PET/CT is currently not of major clinical importance.

Periosteal chondroma

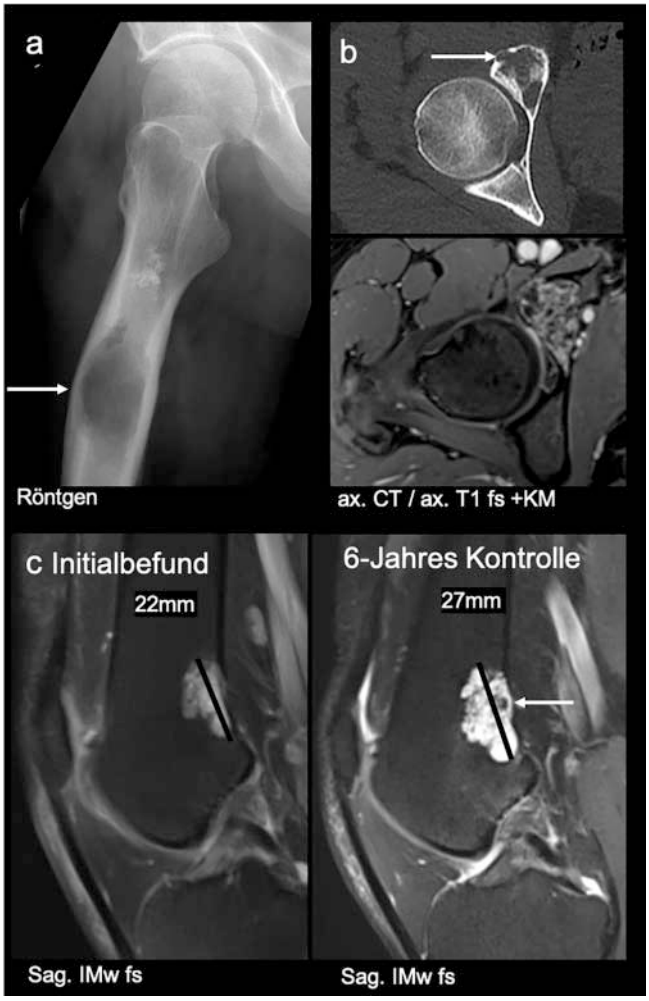
Periosteal chondroma (synonym: juxtacortical chondroma, parosteal chondroma) is a rare benign cartilaginous tumor. It develops on the surface of the bone under the periosteum. According to the registry of the Basel Bone Tumor Reference Center (1972–2015), 3.3 % of benign chondrogenic tumors are periosteal chondromas [49]. According to the WHO, they comprise less than 2 % of all chondromas, affect children as well as adults, and occur slightly more frequently in men than women [6]. Long tubular bones, particularly the proximal humerus, are frequently affected. Short tubular bones are sometimes also affected. A circumscribed ovoid soft tissue mass adjacent to the surface of the bone which can have matrix calcifications can be seen on imaging (33–75 %). Pressure erosion with saucerization of the cortex with a saucer-shaped margin, peripheral cortical thickening, and marginal sclerosis can occur (▶ **Fig. 7**). However, there is no penetration of the cortex. It is difficult to differentiate between periosteal chondromas and periosteal chondrosarcomas [50].

Osteochondromyxoma

Since the 2013 WHO classification, the osteochondromyxoma has been categorized as part of the group of benign chondrogenic tumors. It is an extremely rare tumor that occurs in approx. 1 % of patients with Carney complex (see below) and is a diagnostic criterion for this disorder. Osteochondromyxomas can occur at any age and/or be present already at birth. In addition to the original study by Carney, there are only few case reports describing osteochondromyxomas located in the diaphyses of long tubular bones, in the nose, in the paranasal sinus, in the thoracic wall, and in the spine [10, 50, 51]. Although the osteochondromyxoma is classified as a benign cartilaginous tumor, locally aggressive and infiltrative growth is possible [49]. Carney complex is a precancerous hereditary disease. Among other things, patchy pigmentation of the skin and mucous membranes is seen. Endocrine tumors, cardiac, cutaneous, and intramammary myxomas, psammomatous melanotic schwannomas, and Sertoli cell tumors occur.



▶ **Fig. 4** Atypical cartilaginous tumor (ACT) **a–c** and chondrosarcoma **d–f** on imaging and histology. **a** (CT), **b** (MRI T1 fs + KM): ACT in the proximal humerus (54 years old, female). Imaging-based morphological criteria favouring ACT as opposed to enchondroma: pain symptoms, location near the torso, maximum diameter of > 5 cm, scalloping of the cortex > 2/3 the thickness (arrow). **c** Histology. **d** (CT), **e** (MRI T1 fs + KM): Chondrosarcoma grade I and focal grade II in the pelvis, arising from the right ramus ossis pubis superior with extensive extraosseous tumor component (28 years old, male). **f** Histology of a chondrosarcoma grade I, focal grade II. fs + KM, with fat saturation after contrast administration.



▶ **Fig. 5** Image criteria that argue against a purely benign enchondroma. **a** Location near the trunk, expansion of long tubular bone (femur), size > 5 cm, male, and scalloping > 2/3 of the cortical thickness (54 years old, male). Histological chondrosarcoma grade I. **b** Located in the pelvis/axial skeleton (anterior acetabulum), scalloping (arrow) > 2/3 of the cortical thickness and minor cortical destruction (20 years old, female). Histological chondrosarcoma grade I. **c** Increase in size, pain, and scalloping (arrow) > 2/3 of the cortical thickness. Histological enchondroma; due to the increase in size it was classified as ACT. fs + KM: with fat saturation after contrast administration; IMw fs: intermediate (IM) weighted with fat saturation.

Subungual exostosis

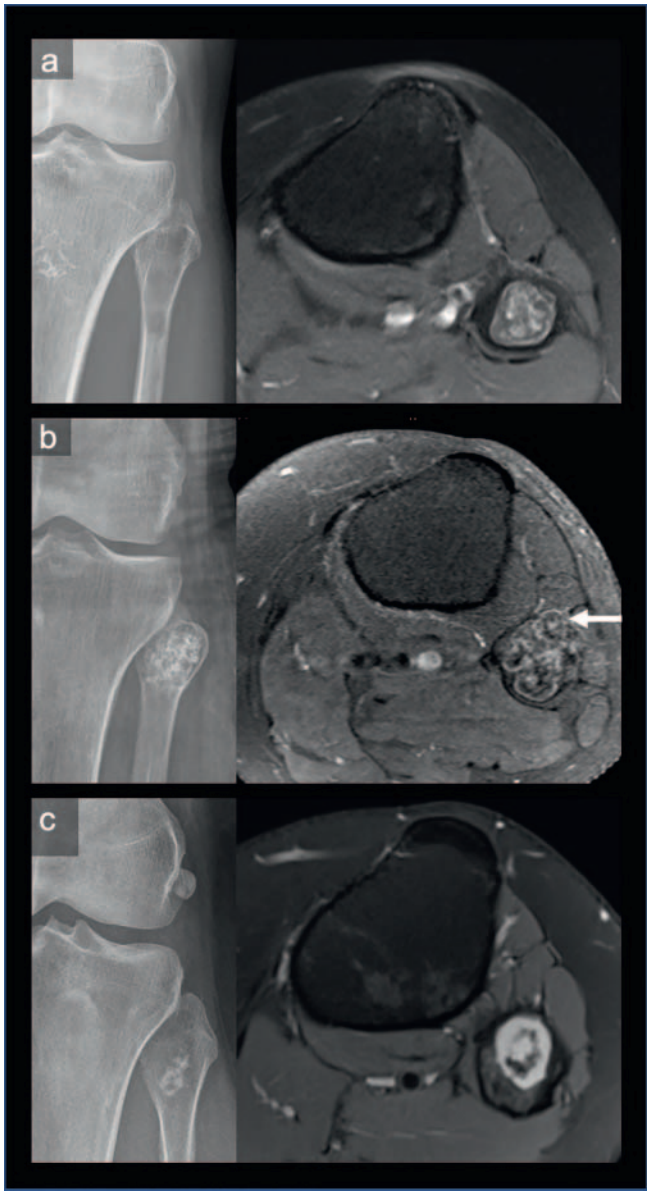
Benign subungual exostosis commonly occurs in children and adolescents and is associated with trauma and infection. The dorsomedial distal phalanx of the great toe is the most common location. The lesion is an exophytically growing, reactive cartilage proliferation at the tip of the distal phalanges (▶ **Fig. 8a**). In contrast to osteochondroma, no medullary continuity between the lesion and the medullary cavity of the bone is visible in subungual exostosis. Due to the fibrocartilaginous components, subungual exostosis appears hypointense on all MRI pulse-sequences and does not have a T2 hyperintense cartilage cap [52, 53].

Bizarre parosteal osteochondromatous proliferation

Benign bizarre parosteal osteochondromatous proliferation (BPOP, Nora's lesion) occurs most frequently in the 3rd to 4 decade of life. The short tubular bones in the hands and feet are usually affected (▶ **Fig. 8b**). The long tubular bones are affected in approximately 1/5 of cases. BPOP is typically located in a metadiaphyseal position on the surface of the bone. It forms cartilage and bone and the maximum diameter is < 3 cm. It appears as a radiopaque mass with sharp margins adjacent to the surface of the bone on conventional radiography. It is typically in contact with the cortex but does not arise from it and there is no continuity with the medullary cavity (in contrast to osteochondromas) [54, 55]. BPOP usually does not cause pain.

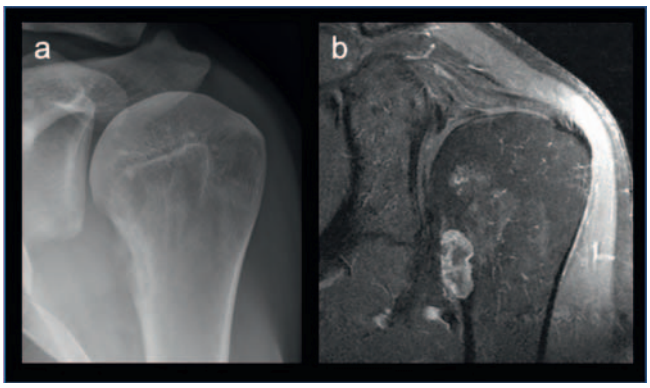
Chondromyxoid fibroma

Chondromyxoid fibromas (CMFs) are very rare benign chondrogenic tumors (less than 1 % of all primary bone tumors) [56]. They consist of three tissue components: 1. a fibrous matrix in



▶ **Fig. 6** Differential diagnosis enchondroma versus ACT at the fibula head. **a** 37 years old, female. The chondrogenic tumor reaches the cortex. The ability to evaluate scalloping is limited due to the physiologically thin cortex at the proximal fibula. Penetration of the cortex is not visible. Due to the presence of pain, a biopsy was performed. Histology indicated an ACT. **b** 61 years old, female. The chondrogenic tumor penetrates the anterior cortex (arrow). The patient also had clinical symptoms. Histology indicated the presence of an enchondroma. Despite, the final diagnosis was an ACT due to the penetration of the cortex on imaging (possible sampling error). **c** 40 years old, female, no symptoms. Incidental finding of an enchondroma without cortical scalloping. fs + KM: with fat saturation after contrast administration; IMw fs: intermediate (IM) weighted with fat saturation.

the periphery, 2. a myxoid matrix and 3. a chondroid matrix in the center. Chondromyxoid fibromas exhibit a locally aggressive growth pattern [9]. They can occur at any age, but most CMFs are diagnosed in the second decade of life [1]. The long tubular bones in the region of the metaphyses and diaphyses are common

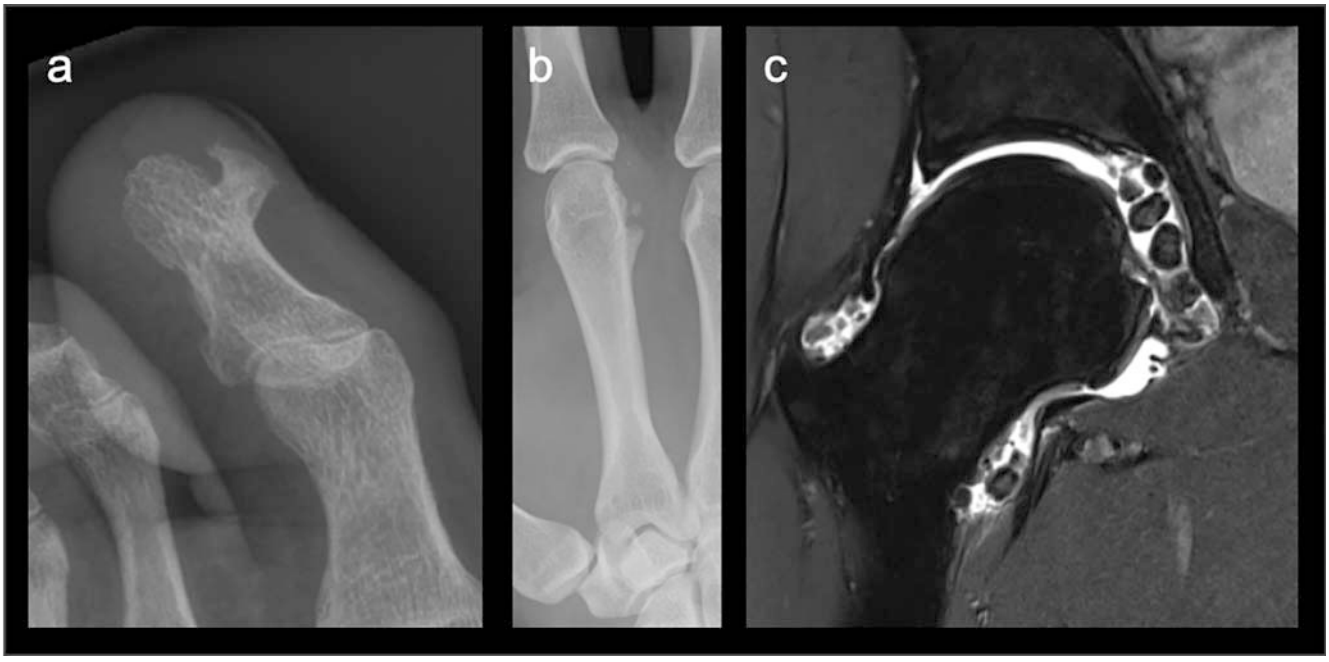


▶ **Fig. 7** Periosteal chondroma at the proximal humerus (25 years old, male). **a** Saucerization of the cortex and minimal marginal sclerosis on conventional radiology. **b** Periosteal ovoid mass in the region of the bone surface with perilobular contrast enhancement (MRI, coronal T1 weighting with fat saturation after contrast administration).

locations. Approximately 50 % occur in the region of the knee joint. Moreover, the hands, feet, and flat bones (primarily the pelvic ring) can be affected [57]. The tumors are typically located eccentrically in the bone. Imaging shows oval, lobulated, and geographic osteolyses with a sclerotic margin and with the longitudinal axis parallel to the bone axis (▶ **Fig. 9**). They can result in thinning and bulging of the cortex. In addition periosteal reaction or cortical destruction may occur [58]. The appearance on MRI varies. A highly hyperintense signal in the center on T2-weighted images corresponds to the myxoid components. There is usually no contrast enhancement in these areas [58]. The amount of cartilage is often minimal and a completely differentiated hyaline cartilage matrix is rare. Matrix mineralization can be seen in only up to 10 % of cases. Hemorrhagic-cystic degeneration (previously: secondary aneurysmatic bone cyst) is possible as in chondroblastoma [59].

Chondroblastoma

Chondroblastomas (synonym: Codman's tumor) are rare (< 1 %) benign cartilaginous tumors. They are comprised of immature cartilage cells and secrete prostaglandins. In rare cases (< 2 %) they can metastasize, particularly in the case of recurrence. Risk factors for local recurrence that occur in 10–21 % of cases are incomplete tumor resection, biological activity of the tumor, and location in the pelvis [6]. Chondroblastomas characteristically occur in adolescence (10–25 years old). Men are affected more than twice as often as women. The proximal tibia, the proximal and distal femur, and the proximal humerus are typical locations. The bones in the hands and feet (talus and calcaneus), flat bones, and the craniofacial skeleton can also be affected. In older patients (40–50 years), chondroblastomas are typically located in the craniofacial skeleton [9, 61]. Chondroblastomas typically occur in the epiphysis and apophysis, which distinguishes them from the majority of other bone tumors. The reason for clinical presentation of patients is usually persistent local pain due to prostaglandin production. On plain radiographs osteolyses with clear margins possibly with marginal sclerosis and/or a periosteal



▶ **Fig. 8** **a** Conventional radiography of a subungual exostosis on the dorsomedial distal phalanx of the great toe. **b** Conventional radiography of a bizarre parosteal osteochondromatous proliferation (Nora's lesion) located metadiaphyseally on the ulnar side of the distal second metacarpal bone (19 years old, male). **c** Synovial chondromatosis on the hip joint (46 years old, male; MRI coronal intermediate (IM) weighted with fat saturation).

reaction in an eccentric location may be depicted. Calcification of the partly trabeculated internal structure, which is not popcorn-like or arc-like but usually speckled, can be seen in 30–50 % of cases. Chondroblastomas are inhomogeneously hypointense on T1-weighted MRI and inhomogeneously hypointense and partially hyperintense on T2-weighted MRI. Due to the prostaglandin production, there is edema in the adjacent bone marrow, soft tissue edema, and also joint effusion if located juxtaarticular (▶ **Fig. 10**) [1, 61]. Like chondromyxoid fibromas, they can have areas of hemorrhagic-cystic degeneration (previously: secondary aneurysmatic bone cyst) (approximately 20 % of cases) [1].

Intermediate chondrogenic tumors

Atypical cartilaginous tumor

According to the 2020 WHO classification, chondrogenic tumors in the pelvis and in the axial skeleton are referred to as chondrosarcomas grade I while chondrogenic tumors in the region of the extremities with the same histology are referred to as "atypical cartilaginous tumors" (ACTs) due to the more favorable prognosis. The entity showes locally agressive growth and is rarely metastasizing. Therefore, it is classified as an intermediate tumor [9]. The differentiation between enchondroma and ACT/chondrosarcoma grade I is described in detail in the previous section.

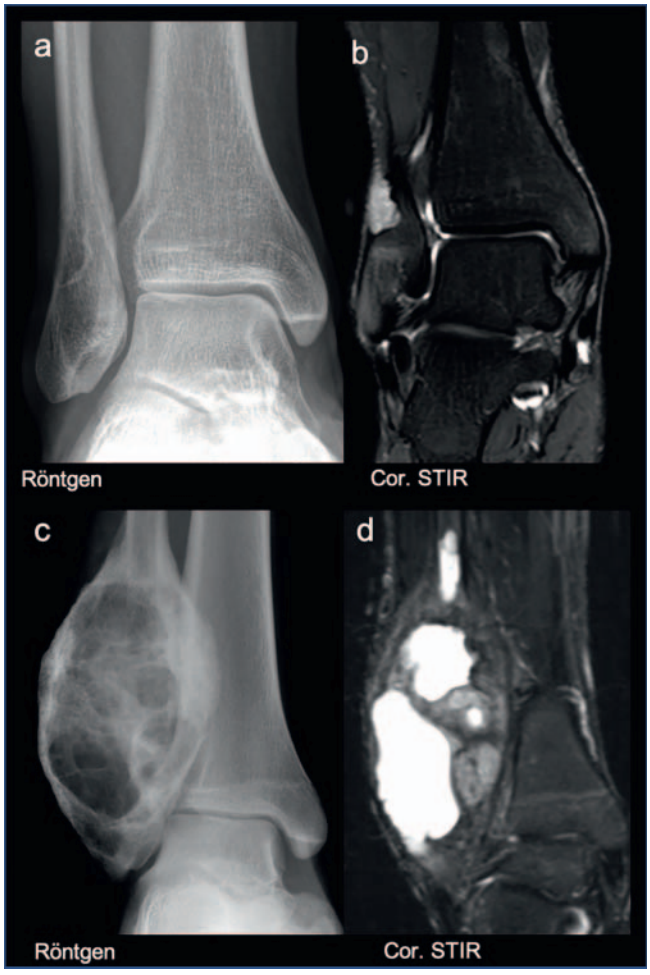
Synovial chondromatosis

In primary synovial chondromatosis, metaplasia of synovial tissue results in the formation of hyaline cartilage nodules with progressive calcification over time (▶ **Fig. 8c**). In the new 2020 WHO classification, the lesion is classified as intermediate grade due to the locally aggressive growth pattern and the high rate of local recurrence. Synovial chondromatosis can occur in joints, synovial bursae, or tendon sheaths. The knee and hip joints are affected most frequently. Primary synovial chondromatosis is idiopathic. Secondary synovial chondromatosis is caused, for example, by trauma, degenerative changes, or neuropathic arthropathy. Typical radiographic features include multiple intraarticular calcifications of similar size and shape (in 70–95 %) in the entire joint with a ring- and arc-like calcification patterns [62]. The MRI signal depends on synovial proliferation and the extent of calcification.

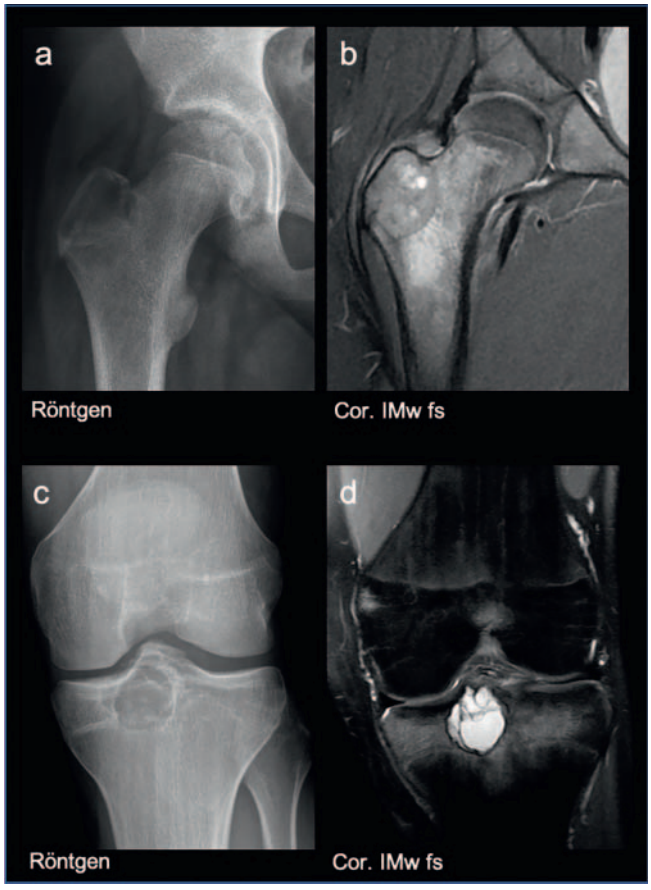
Malignant chondrogenic tumors

Chondrosarcoma

Chondrosarcomas are the third most common primary malignant bone tumor (20–27 %) following multiple myeloma (if considered as primary bone tumors) and osteosarcoma [63]. Chondrosarcomas are almost always symptomatic. They frequently metastasize, often late, and primarily to the lungs. It is a heterogeneous group of tumors. A differentiation is made between the more common conventional chondrosarcomas and less frequent subtypes (▶ **Table 3**; ▶ **Fig. 11, 12**). The subtypes include (i) dedifferentiated chondrosarcomas, which include both a well-differentiated chondrogenic tumor component and a highly malignant dedifferentiated sarcoma component (grade IV; it is essential to also obtain material from the dedifferentiated component during the biopsy); (ii) mesenchymal chondrosarcomas, which can also be extraosseous in approximately 30 % of cases and are comprised of carti-



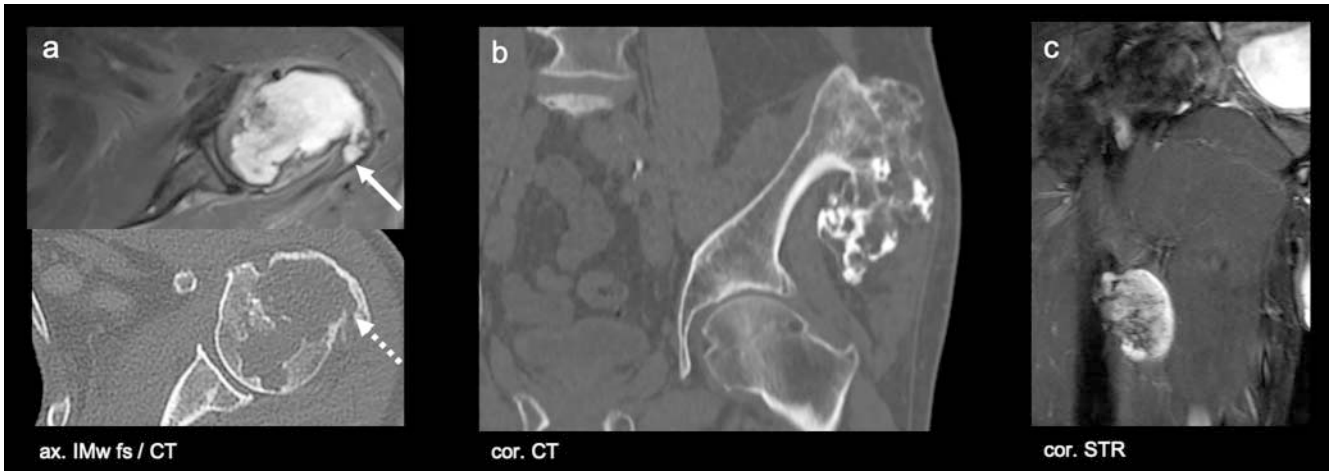
▶ **Fig. 9** Chondromyxoid fibromas on the distal fibula. **a, b** Small eccentric mass with adjacent bone marrow edema (29 years, female). **c, d** Large, expansile mass. Chondromyxoid fibroma with secondary aneurysmatic bone cyst. STIR: Short Tau Inversion Recovery MRI pulse sequence; cor: coronal.



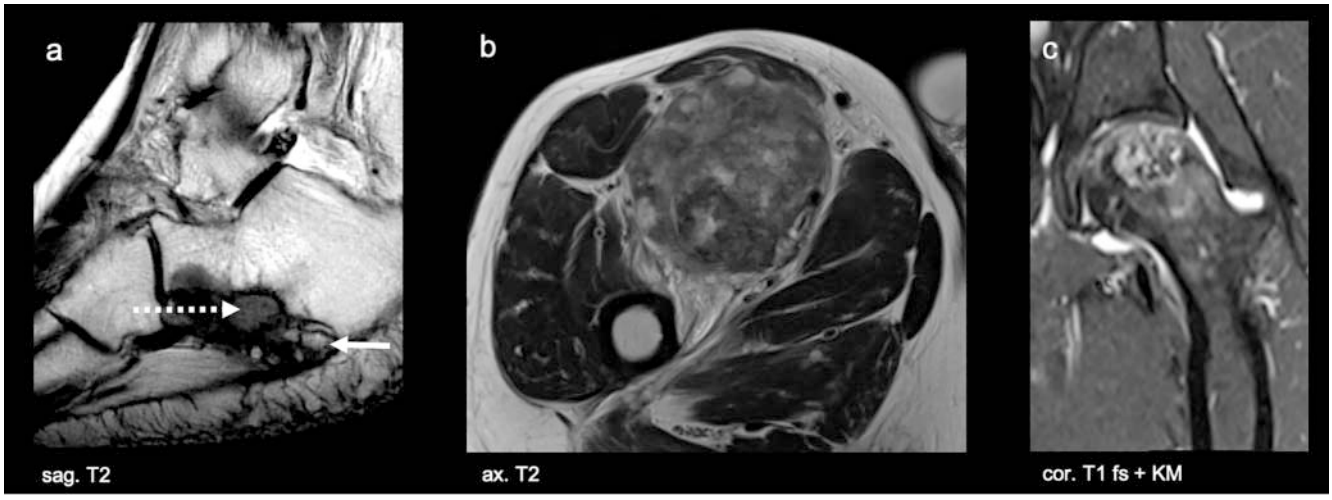
▶ **Fig. 10** Chondroblastomas in two different patients. **a, b** Location in the apophysis of the proximal femur (10 years old, female). **c, d** Central location in the proximal epiphysis of the tibia (16 years old, male). Observe the adjacent bone marrow edema on MRI. cor: coronal; IM fs: coronal intermediate weighted fat-saturated MRI pulse sequence.

lage tissue and an undifferentiated, highly vascularized stroma of round cells; (iii) low-grade clear cell chondrosarcomas, which occur between the 20th and 50th year of life and are typically located at the epiphysis of the long tubular bones (DD: chondroblastoma).

Conventional chondrosarcomas tend to occur in older people. More than 50 % of patients are > 50 years of age. However, chondrosarcomas can occur at any age. They are usually located close to the axial skeleton at the pelvis, femur, or humerus in the metaphysis. In the case of conventional chondrosarcomas, a histological differentiation is made between grade I (referred to as ACT at the extremities and assigned to the intermediate group), grade II and grade III. The histological grading is relevant for prognosis. Most conventional chondrosarcomas arise from stationary cells that undergo malignant transformation (primary). These are primary central chondrosarcomas. Secondary conventional chondrosarcomas occur due to malignant transformation of benign cartilaginous lesions. Enchondromas are considered precursor lesions for secondary central chondrosarcomas. Peripheral chondrosarcomas are usually caused by an osteochondroma as a precursor lesion. The terms central and peripheral relate to the location of the tumor in relation to the affected parent bone. There are typical imaging-based morphological criteria of malignancy. A moth-eaten pattern of osteolysis (Lodwick type II) is usually present. In some cases, permeative growth is observed (Lodwick type III). The cortex is often destroyed, and a periosteal reaction and extraosseous tumor components can be seen. The chondrogenic characteristics are histologically and morphologically less identifiable than in well-differentiated tumors due to the smaller percentage of chondroid matrix. Instead, inhomogeneous contrast enhancement and necrotic, myxoid, and cystic areas are seen. Calcifications are detected in approximately 50 % of cases. The calcification pattern is more irregular and spottier than in benign or low-grade chondrogenic tumors. To differentiate between high-grade and low-grade chondrosarcomas, bone expansion, active periostitis, a soft tissue tumor, and a large intraosseous tumor extent can potentially indicate a high potential for malignancy while fat islands trapped in the tumor tend to indicate low potential for malignancy [36, 64].



▶ **Fig. 11** Chondrosarcomas. **a** Central chondrosarcoma on the proximal humerus with cortical penetration (dotted arrow) and extraosseous soft tissue component (arrow; 73 years old, male). **b** Secondary peripheral chondrosarcoma caused by an osteochondroma in osteochondromatosis (74 years old, male). **c** Periosteal chondrosarcoma on the femoral shaft (29 years old, female). ax: axial; cor: coronal; IMw fs, intermediate weighted fat-saturated MRI pulse sequence; STIR: Short Tau Inversion Recovery.



▶ **Fig. 12** Rarer subtypes of chondrosarcomas. **a** Dedifferentiated chondrosarcoma at the calcaneus (53 years old, female). The two different tumor components may be depicted (arrow, T2 hyperintense chondroid component; pointed arrow, T2 isointense, contrast-enhanced dedifferentiated component). **b** Extraskeletal mesenchymal chondrosarcoma at the anterior thigh (33 years old, male) with inhomogeneous signal behavior in T2. **c** Clear cell chondrosarcoma at the epiphysis of the femoral head (34 years old, male). ax: axial; cor: coronal; sag: sagittal; fs + KM: with fat saturation after contrast administration.

Summary

Chondrogenic tumors may be assigned to the benign, intermediate, and malignant grade according to the 2020 WHO classification. Imaging plays an important role regarding the precise description of the location and affected structures and well as regarding the detection and characterization of chondrogenic bone tumors. In addition, imaging is used for follow-up examinations. The prevalence of benign chondrogenic tumors is significantly higher than the prevalence of malignant chondrogenic tumors. Besides rare entities, osteochondromas and enchondromas are the most common benign chondrogenic tumors. In adults, osteochondromas with a cartilage cap > 2 cm (or > 3 cm in children) are suspicious for malignancy. When differentiating between enchondroma, ACT, and chondrosarcoma, pain symptoms, location in the axial skeleton, pathological fracture, diameter > 5 cm, increase in size after skeletal maturity, endosteal scalloping > 2/3 of the cortical thickness, periosteal reaction, cortical destruction, hyperostosis, and bone expansion are suspicious for malignancy. Penetration into the soft tissues indicates a chondrosarcoma. Potentially helpful imaging parameters like dynamic contrast enhanced MRI (fast and increased relative contrast enhancement), analysis of texture parameters, and FDG-PET/CT are subject of further research investigations and are currently not established in the clinical routine. Close interdisciplinary collaboration between orthopedic surgeons, radiologists, and pathologists is essential for a most optimal management of patients with chondrogenic tumors.

▶ **Table 3** 2020 WHO classification of chondrosarcomas [6].

conventional chondrosarcomas	**possible precursor lesion**
central chondrosarcoma	enchondroma
peripheral chondrosarcoma	osteochondroma (100 %)
periosteal chondrosarcoma	
rare subtypes	**possible precursor lesion**
dedifferentiated chondrosarcoma	conventional chondrosarcoma
mesenchymal chondrosarcoma	
clear cell chondrosarcoma	

WHO = World Health Organization.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] Uhl M, Herget G, Kurz P. Cartilage tumors: Pathology and radiomorphology. Radiologe 2016; 56: 476–488. doi:10.1007/s00117-016-0112-z

[2] Lodwick GS. A probabilistic approach to the diagnosis of bone tumors. Radiol Clin North Am 1965; 3: 487–497

[3] Murphey MD, Walker EA, Wilson AJ et al. From the archives of the AFIP: imaging of primary chondrosarcoma: radiologic-pathologic correlation. Radiographics 2003; 23: 1245–1278. doi:10.1148/rg.235035134

[4] Lalam R, Bloem JL, Noebauer-Huhmann IM et al. ESSR Consensus Document for Detection, Characterization, and Referral Pathway for Tumors and Tumorlike Lesions of Bone. Semin Musculoskelet Radiol 2017; 21: 630–647. doi:10.1055/s-0037-1606130

[5] Aoki J, Sone S, Fujioka F et al. MR of enchondroma and chondrosarcoma: rings and arcs of Gd-DTPA enhancement. J Comput Assist Tomogr 1991; 15: 1011–1016. doi:10.1097/00004728-199111000-00021

[6] Board WCoTE. Soft Tissue and Bone Tumours WHO Classification of Tumours. 2020; 5th Edition, Volume 3

[7] Doyle LA. Sarcoma classification: an update based on the 2013 World Health Organization Classification of Tumors of Soft Tissue and Bone. Cancer 2014; 120: 1763–1774. doi:10.1002/cncr.28657

[8] Amary F, Perez-Casanova L, Ye H et al. Synovial chondromatosis and soft tissue chondroma: extraosseous cartilaginous tumor defined by FN1 gene rearrangement. Mod Pathol 2019; 32: 1762–1771. doi:10.1038/s41379-019-0315-8

[9] Fletcher C. World Health Organization, International Agency for Research on Cancer (Hrsg). WHO classification of tumours of soft tissue and bone. Lyon: IARC Press. 2013; 4th ed.

[10] Jundt G. Updates to the WHO classification of bone tumours. Pathologe 2018; 39: 107–116. doi:10.1007/s00292-017-0396-4

[11] Bus MPA, Campanacci DA, Albergo JI et al. Conventional Primary Central Chondrosarcoma of the Pelvis: Prognostic Factors and Outcome of Surgical Treatment in 162 Patients. J Bone Joint Surg Am 2018; 100: 316–325. doi:10.2106/JBJS.17.00105

[12] van Praag Veroniek VM, Rueten-Budde AJ, Ho V et al. Incidence, outcomes and prognostic factors during 25 years of treatment of chondrosarcomas. Surg Oncol 2018; 27: 402–408. doi:10.1016/j.suronc.2018.05.009

[13] Murphey MD, Choi JJ, Kransdorf MJ et al. Imaging of osteochondroma: variants and complications with radiologic-pathologic correlation. Radiographics 2000; 20: 1407–1434. doi:10.1148/radiographics.20.5.g00se171407

[14] Herget GW, Strohm P, Rottenburger C et al. Insights into Enchondroma, Enchondromatosis and the risk of secondary Chondrosarcoma. Review of the literature with an emphasis on the clinical behaviour, radiology, malignant transformation and the follow up. Neoplasma 2014; 61: 365–378. doi:10.4149/neo_2014_046

[15] Pannier S, Legeai-Mallet L. Hereditary multiple exostoses and enchondromatosis. Best Pract Res Clin Rheumatol 2008; 22: 45–54. doi:10.1016/j.berh.2007.12.004

[16] Biermann JS. Common benign lesions of bone in children and adolescents. J Pediatr Orthop 2002; 22: 268–273

[17] Bernard SA, Murphey MD, Flemming DJ et al. Improved differentiation of benign osteochondromas from secondary chondrosarcomas with standardized measurement of cartilage cap at CT and MR imaging. Radiology 2010; 255: 857–865. doi:10.1148/radiol.10082120

[18] Imai K, Suga Y, Nagatsuka Y et al. Pneumothorax caused by costal exostosis. Ann Thorac Cardiovasc Surg 2014; 20: 161–164. doi:10.5761/atcs.cr.12.01955

[19] Herget GW, Kontny U, Saueressig U et al. Osteochondroma and multiple osteochondromas: recommendations on the diagnostics and follow-up with special consideration to the occurrence of secondary chondrosarcoma. Radiologe 2013; 53: 1125–1136. doi:10.1007/s00117-013-2571-9

[20] Jurik AG, Jorgensen PH, Mortensen MM. Whole-body MRI in assessing malignant transformation in multiple hereditary exostoses and enchondromatosis: audit results and literature review. Skeletal Radiol 2020; 49: 115–124. doi:10.1007/s00256-019-03268-z

[21] Lee K, Park HY, Kim KW et al. Advances in whole body MRI for musculoskeletal imaging: Diffusion-weighted imaging. J Clin Orthop Trauma 2019; 10: 680–686. doi:10.1016/j.jcot.2019.05.018

[22] Roessner A, Smolle M, Schoeder V et al. Cartilage tumors: morphology, genetics, and current aspects of target therapy. Pathologe 2020; 41: 143–152. doi:10.1007/s00292-020-00752-5

[23] Hakim DN, Pelly T, Kulendran M et al. Benign tumours of the bone: A review. J Bone Oncol 2015; 4: 37–41. doi:10.1016/j.jbo.2015.02.001

[24] Walden MJ, Murphey MD, Vidal JA. Incidental enchondromas of the knee. Am J Roentgenol 2008; 190: 1611–1615. doi:10.2214/AJR.07.2796

[25] Davies AM, Shah A, Shah R et al. Are the tubular bones of the hand really the commonest site for an enchondroma? Clin Radiol 2020. doi:10.1016/j.crad.2020.02.004

[26] Silve C, Juppner H. Ollier disease. Orphanet J Rare Dis 2006; 1: 37. doi:10.1186/1750-1172-1-37

[27] Altay M, Bayrakci K, Yildiz Y et al. Secondary chondrosarcoma in cartilage bone tumors: report of 32 patients. J Orthop Sci 2007; 12: 415–423. doi:10.1007/s00776-007-1152-z

[28] Verdegaal SH, Bovee JV, Pansuriya TC et al. Incidence, predictive factors, and prognosis of chondrosarcoma in patients with Ollier disease and Maffucci syndrome: an international multicenter study of 161 patients. Oncologist 2011; 16: 1771–1779. doi:10.1634/theoncologist.2011-0200

[29] Delling G, Jobke B, Burisch S et al. Cartilage tumors. Classification, conditions for biopsy and histologic characteristics. Orthopade 2005; 34: 1267–1281; quiz 1281-1262. doi:10.1007/s00132-005-0886-6

[30] Eefting D, Schrage YM, Geirnaerdt MJ et al. Assessment of interobserver variability and histologic parameters to improve reliability in classification and grading of central cartilaginous tumors. Am J Surg Pathol 2009; 33: 50–57. doi:10.1097/PAS.0b013e31817eec2b

[31] Skeletal Lesions Interobserver Correlation among Expert Diagnosticians Study G. Reliability of histopathologic and radiologic grading of cartilaginous neoplasms in long bones. J Bone Joint Surg Am 2007; 89: 2113–2123. doi:10.2106/JBJS.F.01530

[32] Logie CI, Walker EA, Forsberg JA et al. Chondrosarcoma: A Diagnostic Imager's Guide to Decision Making and Patient Management. Semin Musculoskelet Radiol 2013; 17: 101–115. doi:10.1055/s-0033-1342967

[33] Crim J, Schmidt R, Layfield L et al. Can imaging criteria distinguish enchondroma from grade 1 chondrosarcoma? Eur J Radiol 2015; 84: 2222–2230. doi:10.1016/j.ejrad.2015.06.033

[34] Ferrer-Santacreu EM, Ortiz-Cruz EJ, Gonzalez-Lopez JM et al. Enchondroma versus Low-Grade Chondrosarcoma in Appendicular Skeleton: Clinical and Radiological Criteria. J Oncol 2012; 2012: 437958. doi:10.1155/2012/437958

[35] Choi BB, Jee WH, Sunwoo HJ et al. MR differentiation of low-grade chondrosarcoma from enchondroma. Clin Imaging 2013; 37: 542–547. doi:10.1016/j.clinimag.2012.08.006

[36] Douis H, Singh L, Saifuddin A. MRI differentiation of low-grade from high-grade appendicular chondrosarcoma. Eur Radiol 2014; 24: 232–240. doi:10.1007/s00330-013-3003-y

[37] Murphey MD, Flemming DJ, Boyea SR et al. Enchondroma versus chondrosarcoma in the appendicular skeleton: differentiating features. Radiographics 1998; 18: 1213–1237; quiz 1244-1215. doi:10.1148/radiographics.18.5.9747616

[38] Douis H, Parry M, Vaiyapuri S et al. What are the differentiating clinical and MRI-features of enchondromas from low-grade chondrosarcomas? Eur Radiol 2018; 28: 398–409. doi:10.1007/s00330-017-4947-0

[39] Bui KL, Ilaslan H, Bauer TW et al. Cortical scalloping and cortical penetration by small eccentric chondroid lesions in the long tubular bones: not a sign of malignancy? Skeletal Radiol 2009; 38: 791–796. doi:10.1007/s00256-009-0675-0

[40] Davies AM, Patel A, James SL et al. A retrospective validation of an imaging protocol for the management of solitary central cartilage tumours of the proximal humerus and around the knee. Clin Radiol 2019; 74: 962–971. doi:10.1016/j.crad.2019.08.017

[41] Douis H, Jeys L, Grimer R et al. Is there a role for diffusion-weighted MRI (DWI) in the diagnosis of central cartilage tumors? Skeletal Radiol 2015; 44: 963–969. doi:10.1007/s00256-015-2123-7

[42] Geirnaerdt MJ, Hogendoorn PC, Bloem JL et al. Cartilaginous tumors: fast contrast-enhanced MR imaging. Radiology 2000; 214: 539–546. doi:10.1148/radiology.214.2.r00fe12539

[43] De Coninck T, Jans L, Sys G et al. Dynamic contrast-enhanced MR imaging for differentiation between enchondroma and chondrosarcoma. Eur Radiol 2013; 23: 3140–3152. doi:10.1007/s00330-013-2913-z

[44] Lisson CS, Lisson CG, Flosdorf K et al. Diagnostic value of MRI-based 3D texture analysis for tissue characterisation and discrimination of low-grade chondrosarcoma from enchondroma: a pilot study. Eur Radiol 2018; 28: 468–477. doi:10.1007/s00330-017-5014-6

[45] Fritz B, Muller DA, Sutter R et al. Magnetic Resonance Imaging-Based Grading of Cartilaginous Bone Tumors: Added Value of Quantitative Texture Analysis. Invest Radiol 2018; 53: 663–672. doi:10.1097/RLI.0000000000000486

[46] Subhawong TK, Winn A, Shemesh SS et al. F-18 FDG PET differentiation of benign from malignant chondroid neoplasms: a systematic review of the literature. Skeletal Radiol 2017; 46: 1233–1239. doi:10.1007/s00256-017-2685-7

[47] Vadi SK, Mittal BR, Gorla AKR et al. 18F-FDG PET/CT in Diagnostic and Prognostic Evaluation of Patients With Suspected Recurrence of Chondrosarcoma. Clin Nucl Med 2018; 43: 87–93. doi:10.1097/RLU.0000000000001947

[48] Annovazzi A, Anelli V, Zoccali C et al. (18)F-FDG PET/CT in the evaluation of cartilaginous bone neoplasms: the added value of tumor grading. Ann Nucl Med 2019; 33: 813–821. doi:10.1007/s12149-019-01392-3

[49] Jundt G, Baumhoer D. Cartilage tumors of the skeleton. Pathologe 2008; 29 (Suppl. 2): 223–231. doi:10.1007/s00292-008-1025-z

[50] Afonso PD, Isaac A, Villagran JM. Chondroid Tumors as Incidental Findings and Differential Diagnosis between Enchondromas and Low-grade Chondrosarcomas. Semin Musculoskelet Radiol 2019; 23: 3–18. doi:10.1055/s-0038-1675550

[51] Golden T, Siordia JA. Osteochondromyxoma: Review of a rare carney complex criterion. J Bone Oncol 2016; 5: 194–197. doi:10.1016/j.jbo.2016.07.002

[52] Baek HJ, Lee SJ, Cho KH et al. Subungual tumors: clinicopathologic correlation with US and MR imaging findings. Radiographics 2010; 30: 1621–1636. doi:10.1148/rg.306105514

[53] DaCambra MP, Gupta SK, Ferri-de-Barros F. Subungual exostosis of the toes: a systematic review. Clin Orthop Relat Res 2014; 472: 1251–1259. doi:10.1007/s11999-013-3345-4

[54] Cocks M, Helmke E, Meyers CA et al. Bizarre parosteal osteochondromatous proliferation: 16 Cases with a focus on histologic variability. J Orthop 2018; 15: 138–142. doi:10.1016/j.jor.2018.01.028

[55] Adler D, Aigner T, von Salis-Soglio G et al. Nora's lesion. Discussion of a rare bone proliferation. Orthopade 2010; 39: 1065–1070. doi:10.1007/s00132-010-1648-7

[56] Cappelle S, Pans S, Sciot R. Imaging features of chondromyxoid fibroma: report of 15 cases and literature review. Br J Radiol 2016; 89: 20160088. doi:10.1259/bjr.20160088

[57] Meredith DM, Fletcher CDM, Jo VY. Chondromyxoid Fibroma Arising in Craniofacial Sites: A Clinicopathologic Analysis of 25 Cases. Am J Surg Pathol 2018; 42: 392–400. doi:10.1097/PAS.0000000000001019

[58] Kim HS, Jee WH, Ryu KN et al. MRI of chondromyxoid fibroma. Acta Radiol 2011; 52: 875–880. doi:10.1258/ar.2011.110180

[59] Gutierrez LB, Link TM, Horvai AE et al. Secondary aneurysmal bone cysts and associated primary lesions: imaging features of 49 cases. Clin Imaging 2020; 62: 23–32. doi:10.1016/j.clinimag.2020.01.022

[60] Chen W, DiFrancesco LM. Chondroblastoma: An Update. Arch Pathol Lab Med 2017; 141: 867–871. doi:10.5858/arpa.2016-0281-RS

[61] Jundt G, Baumhoer D. Chondroblastoma. Pathologe 2018; 39: 132–138. doi:10.1007/s00292-017-0397-3

[62] Murphey MD, Vidal JA, Fanburg-Smith JC et al. Imaging of synovial chondromatosis with radiologic-pathologic correlation. Radiographics 2007; 27: 1465–1488. doi:10.1148/rg.275075116

[63] Varma DG, Ayala AG, Carrasco CH et al. Chondrosarcoma: MR imaging with pathologic correlation. Radiographics 1992; 12: 687–704. doi:10.1148/radiographics.12.4.1636034

[64] Yoo HJ, Hong SH, Choi JY et al. Differentiating high-grade from low-grade chondrosarcoma with MR imaging. Eur Radiol 2009; 19: 3008–3014. doi:10.1007/s00330-009-1493-4