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Review Article

Enchondromatosis: insights on the different subtypes

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Abstract: Enchondromatosis is a rare, heterogeneous skeletal disorder in which patients have multiple enchondromas. Enchondromas are benign hyaline cartilage forming tumors in the medulla of metaphyseal bone. The disorder manifests itself early in childhood without any significant gender bias. Enchondromatosis encompasses several different subtypes of which Ollier disease and Maffucci syndrome are most common, while the other subtypes (metachondromatosis, genochondromatosis, spondyloenchondrodysplasia, dysspondyloenchondromatosis and cheirospondyloenchondromatosis) are extremely rare. Most subtypes are non-hereditary, while some are autosomal dominant or recessive. The gene(s) causing the different enchondromatosis syndromes are largely unknown. They should be distinguished and adequately diagnosed, not only to guide therapeutic decisions and genetic counseling, but also with respect to research into their etiology. For a long time enchondromas have been considered a developmental disorder caused by the failure of normal endochondral bone formation. With the identification of genetic abnormalities in enchondromas however, they were being thought of as neoplasms. Active hedgehog signaling is reported to be important for enchondroma development and *PTH1R* mutations have been identified in ~10% of Ollier patients. One can therefore speculate that the gene(s) causing the different enchondromatosis subtypes are involved in hedgehog/PTH1R growth plate signaling. Adequate distinction within future studies will shed light on whether these subtypes are different ends of a spectrum caused by a single gene, or that they represent truely different diseases. We therefore review the available clinical information for all enchondromatosis subtypes and discuss the little molecular data available hinting towards their cause.

Keywords: Ollier disease, Maffucci syndrome, enchondroma, metachondromatosis, enchondromatosis, central chondrosarcoma

Introduction

Enchondromas are common, benign, and usually asymptomatic hyaline cartilage forming neoplasms in the metaphyses and diaphyses of the short and long tubular bones of the limbs, especially the hands and feet [1,2]. They usually occur as a single lesion (solitary enchondroma) which is most often found incidentally when radiographic studies are performed for other reasons.

Occasionally patients present with multiple enchondromas causing severe deformity of the affected bones, generally defined as enchondromatosis [2,3]. The distribution of the enchondromas, and other accompanying symptoms as well as the mode of inheritance define the different subtypes of enchondromatosis (**Figure 1**), which mainly includes Ollier disease, Maffucci syndrome, metachondromatosis, genochondromatosis, spondyloenchondrodysplasia, cheirospondyloenchondromatosis and dysspondyloenchondromatosis. These subtypes should be distinguished and adequately diagnosed, not only to guide therapeutic decision and genetic counseling, but also to enable future studies to shed light on whether these are different ends of a spectrum caused by a single gene, or that they represent true different diseases. We therefore review the available clinical information for all enchondromatosis subtypes and discuss the little molecular data available hinting towards their cause.

Enchondroma

On conventional radiographs enchondromas

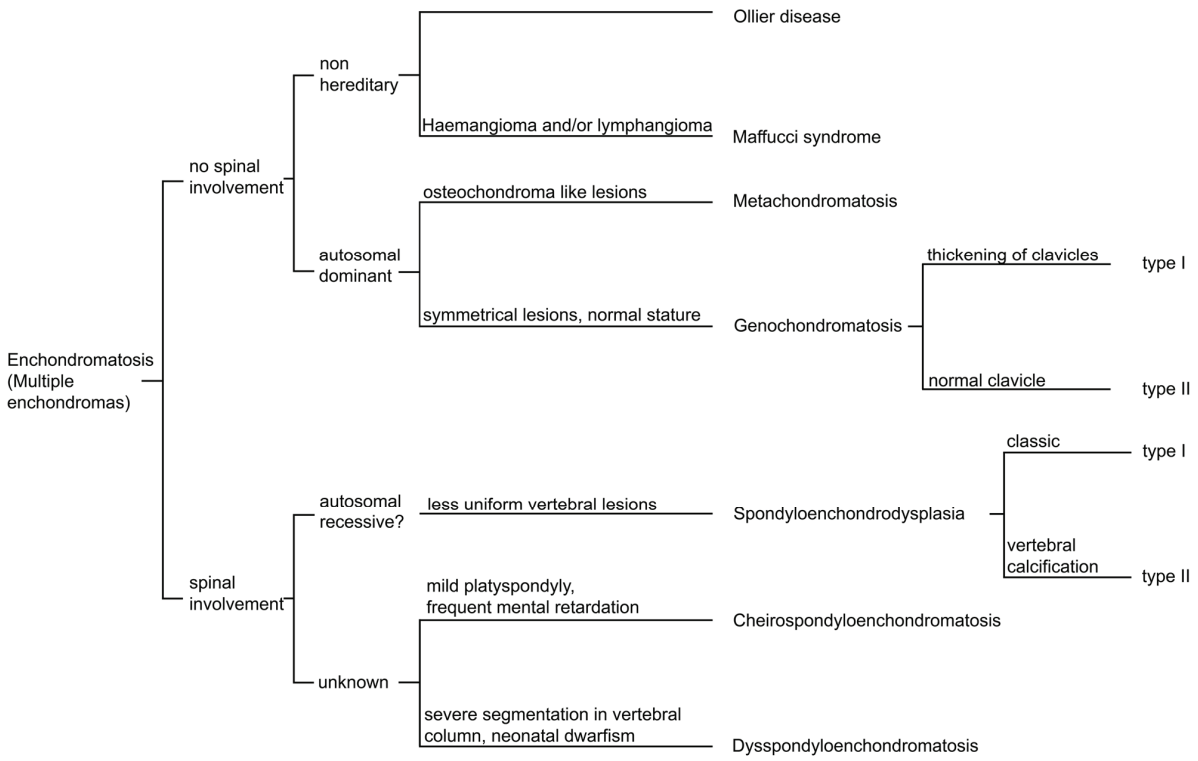

Figure 1. Enchondromatosis sub-types. Classification diagram for patients with multiple enchondromas based on spinal involvement and genetic transmission.

present as multiple, oval-shaped, linear and/or pyramidal osteolytic lesions with well-defined margins in the metaphysis and/or diaphysis of the long tubular and in the flat bones [4]. Magnetic resonance (MR) studies demonstrate lobulated lesions with intermediate signal intensity on T1-weighted images and predominantly high signal intensity on T2-weighted sequences [5]. Histologically enchondromas show low cellularity with an abundant hyaline cartilage matrix sometimes with extensive calcifications [1]. When enchondromas are located in the phalangeal bones or when they occur in enchondromatosis patients, cellularity is increased and more worrisome histological features are tolerated, since they are not correlated with malignant behavior in this specific context (**Figure 2**) [1].

Treatment of solitary enchondroma is surgical but only in case of complaints or cosmetic deformity [6]. In case of enchondromatosis, the deformities as well as malignant progression of enchondromas may require multiple surgical interventions [7-12].

Secondary central chondrosarcoma

While solitary enchondromas almost never progress to secondary central chondrosarcoma, malignant transformation in enchondromatosis is estimated to occur in 25-30% of the patients [1]. Central chondrosarcoma is a malignant bone tumor forming hyaline cartilage and arising centrally in the medullary cavity of bone [13]. The distinction between enchondroma and low grade chondrosarcoma is difficult on conventional radiographs [14]. Fast contrast-enhanced dynamic MRI is more helpful in this regard [15]. At the histological level the distinction can also be very difficult and is subject to interobserver variability [16] [17]. Low grade chondrosarcomas (grade I) can be treated surgically with local curettage combined with cryosurgery or phenol treatment while resection and reconstruction is obligatory in case of grade II or III chondrosarcoma [18].

Enchondromagenesis

The underlying mechanism for enchondroma

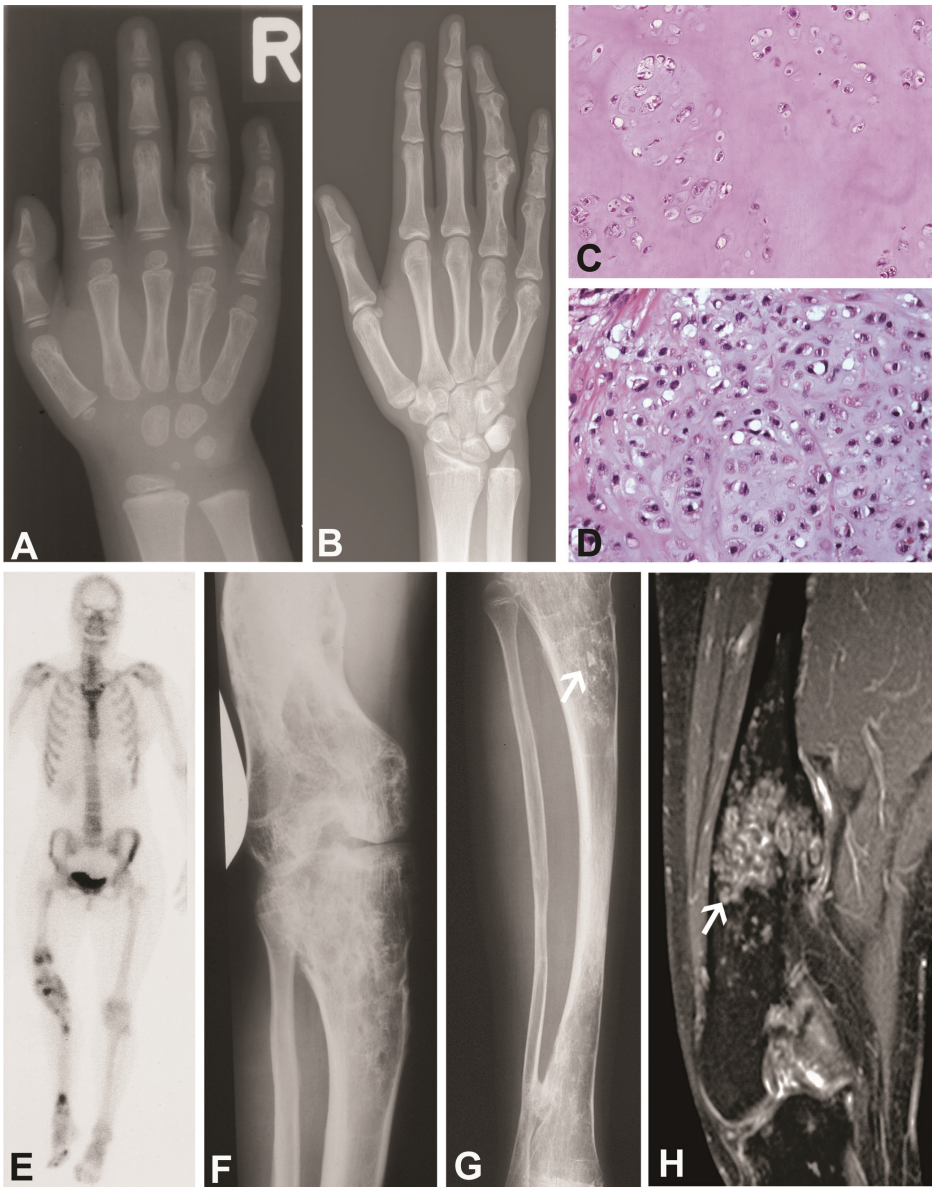

Figure 2. Ollier disease. (A) 4-year-old female patient with Ollier disease. Multiple enchondromas, manifesting as central end eccentric osteolytic lesions and deformities in the metacarpals and phalanges of the fourth and fifth ray of the right hand. (B) Same patient as in Fig. 2A 13 years later. The enchondromas have increased in size and some are more evidently visible compared to the previous study. This has resulted in deformity of the fourth finger. (C) Histology of enchondroma of long bone from Ollier patient showing moderate cellularity and abundance of hyaline cartilage matrix (200 times magnification). (D) Histology of chondrosarcoma grade II of the long bone from Ollier patient showing increased cellularity and atypical chondrocytes (200 times magnification). (E) Technetium-99m bone scintigraphy, anterior projection, demonstrates shortening of the right lower limb. Varus deformity of the femur and valgus deformity of the tibia. Multiple areas of focally increased uptake of the tracer in femur and tibia. (F-G) Anteroposterior radiograph of the right knee and lower leg of same patient as 2E. Deformity of both the distal femur and the tibia and fibula. Structural changes in the marrow cavity and cortical bone of femur and tibia consisting of osteolysis and osteosclerosis. Specifically in the proximal tibia areas with mineralization in the sense of calcifications can be appreciated (arrow). The appearance is consistent with multiple chondromatous tumors. (H) Coronal fat-suppressed T1-weighted magnetic resonance image after intravenous contrast administration of the femur. Varus deformation of the femur. Multiple, partially lobulated, areas with increased signal intensity due to enhancement of the chondromatous lesions. Large lesion in the distal diaphysis of the femur, of which histology showed a chondrosarcoma (arrow). The enhancement demonstrates rings and arcs (also known as septal or nodular enhancement) consistent with the chondromatous nature of the lesions.

development is largely unknown. Several cytogenetic/genetic reports are present in the literature using solitary enchondromas, suggesting these lesions to be neoplastic (http://atlasgeneticsoncology.org//Tumors/EnchondromaID5333.html). Enchondromas in Ollier disease are comparable to solitary enchondromas at m-RNA expression level [19]. Since enchondromas arise in the metaphysis in close proximity to the growth plate, they may result from failure of terminal differentiation of growth plate chondrocytes. In support of this, transgenic mice expressing the hedgehog (Hh) regulated transcription factor *Gli2* in chondrocytes, which mimics activated Hh signaling, develop lesions similar to human enchondromas [20]. Hedgehog signaling is a crucial regulator of normal chondrocytes proliferation and differentiation within the normal growth plate. Enchondromas indeed demonstrate levels of hedgehog signaling that are comparable to normal growth plate [20-23].

Additionally, ten percent of patients with enchondromatosis harbour a mutation in the PTHLH receptor, *PTH1R,* in their tumor tissue [20,22,23]. The mutations were shown to decrease the function of the PTHLH receptor with ~30% [22]. PTH1R is a receptor for parathyroid hormone and for parathyroid hormone-related peptide which acts in a negative feedback loop with Indian Hedgehog (IHH) regulating normal endochondral bone formation [24-26]. PTHLH signaling is active in solitary enchondromas and in chondrosarcomas [27].

In parallel, multiple osteochondromas (MO) syndrome (multiple benign cartilaginous tumors arising from the surface of bone) is an autosomal dominant disorder caused by mutations in the *EXT1* and *EXT2* genes, leading to disturbed hedgehog signaling based on their involvement in heparan sulphate (HS) biosynthesis [28-30]. The *EXT* genes are not affected in central chondrosarcomas and their m-RNA expression is normal [21]. It may be hypothesized that the genes causing the different enchondromatosis subtypes also affect the HS dependent signaling pathways.

Ollier disease

Ollier disease (also known as dyschondroplasia, multiple cartilaginous enchondromatosis, enchondromatosis Spranger type I), is the most common subtype, first described in 1889. It is defined by the presence of multiple enchondromas with asymmetric distribution (**Figure 2**) [4,31-34]. Ollier disease is non-familial and mostly encountered early in childhood, affecting both sexes equally. The estimated prevalence of Ollier disease is 1/100,000 [2]. The true incidence can be higher since mild phenotypes without skeletal deformities can go undetected. Few cases of familial occurrence have been reported (OMIM 166000) [35-37] There is large clinical variability with respect to size, number, location, age of onset, and requirement of surgery [1,2,4,34]. Lesions are usually distributed unilaterally and may involve the entire skeleton, although the skull and vertebral bodies are very rarely involved. Sometimes lesions are bilateral or present in only one extremity [4].

Malignant transformation of one or more enchondromas towards secondary central chondrosarcoma is estimated to occur in 5-50% of the patients and can be life threatening [38-42]. Malignant transformation most frequently occurs in long tubular and flat bones while this is far less common in the small bones of hands and feet (**Figure 2**). This is interesting since enchondromas preferentially occur at the hands and feet. In addition to the risk of developing chondrosarcoma, Ollier patients also seem to have an increased risk for the development of non-skeletal malignancies as reported in **Table 1**, especially intracranial tumors of glial origin [43]. There is at present no curative or preventive treatment option for patients with Ollier disease.

The underlying cause of Ollier disease is so far unknown. The non-hereditary asymmetrical polyostotic distribution of the lesions might suggest a somatic mosaic mutation [14]. This is similar to McCune-Albright syndrome / polyostotic fibrous dysplasia in which an activating mutation in *GNAS1* occurs during early embryogenesis leading to a somatic mosaic state resulting in fibrous dysplasia affecting several bones [44,45].

Not many genetic studies are reported for Ollier tumors due to the rarity of the disease (summarized in **Table 2**). As discussed above, four different heterozygous mutations, affecting either the germ line or only the tumor tissue, were found in the *PTH1R* gene (R150C, R255H, G121E and A122T) [20,22,23] in 5 of 48 Ollier

Table 1. Non-cartilaginous malignancies associated with Ollier disease

Associated tumors	No. of patients	References
Glioma	17	[38,43,90-99]
Juvenile granulosa cell tumor	7	[38,100-105]
Non-small cell lung cancer	1	[106]

Table 2. Genetic findings in Ollier enchondromas and chondrosarcoma

Tumor per patient	Technique used	Results of chromosomal abnormality	References
low grade CS	cytogenetics	deletion at 1p	[108]
high grade CS	microsatellite marker, SSCP, IHC	LOH at 13q14 (*RB1*), 9p21 and over expression of TP53	[109]
Enchondroma	array-CGH	no alteration	[110]
Enchondroma	array-CGH	deletion of 6	
CS II	array-CGH	gain at 1, 2, 5, 7, 8, 9, 15, 16, 17, 18, 19, 20, 21 and 22	[110]
CS II	array-CGH	gain at 6, 7, 12, 14, 15, 16, 17, 18, 19 and loss at 1, 3, 4, 6, 9, 10, 13, 15, 16 and 22	[110]

patients (~10%). Thus, *PTH1R* mutations may contribute to the disease in a small subset of Ollier patients but is probably not causative for the disease [22].

Maffucci syndrome

Maffucci syndrome (also known as dyschondrodysplasia with haemangiomas, enchondromatosis with multiple cavernous haemangiomas, Kast syndrome, haemangiomatosis chondrodystrophica, enchondromatosis Spranger type II) was first described in 1881[32,46,47]. It is non-hereditary and characterized by the presence of multiple enchondromas combined with multiple haemangiomas of soft tissue or, less commonly, lymphangiomas (**Figure 3**) [34,48]. Lesions are asymmetrically distributed and there is no gender discrimination. The disease appears to develop in 25% of cases from the time of birth or during the first year of life, in 45% of cases symptoms start before the age of 6 and in 78% of cases symptoms developed before puberty [49,50]. Lewis et al reviewed ninety-eight cases and showed that hand, foot, femur, tibia, and

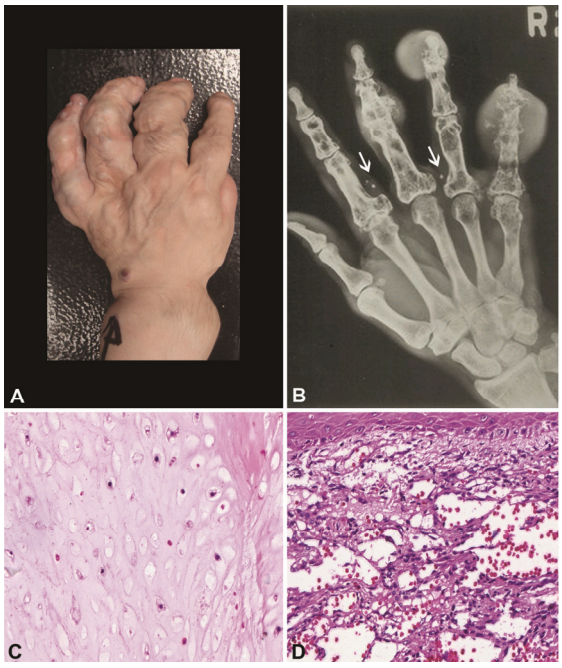

Figure 3. Maffucci Syndrome: (A) Hand of a patient with Maffucci syndrome showing deformities due to multiple enchondromas and a superficial haemangioma. (B) Radiograph of a patient with Maffucci syndrome. Multiple enchondromas with and without soft tissue extension in the second to fifth digit and the fifth metacarpal bone. In addition phleboliths in the soft tissue at the basis of the second and fourth finger (arrows) indicating haemangiomas. (C) Histology of enchondroma and (D) Haemangioma (400 times magnification).

Table 3. Non-cartilaginous and non-vascular neoplasms associated with Maffucci syndrome

Associated tumors	No. of patients	References
Astrocytoma	6	[38,50,111-113]
Pituitary adenoma	4	[50,114-116]
Juvenile granulosa cell tumor	6	[50,117-120]
Pancreatic adenocarcinoma	3	[38,50,121]
Adrenal adenoma	1	[50]
Intracranial chordoma	1	[122]
Biliary adenocarcinoma	1	[38]
Olfactory neuroblastoma	1	[123]
Paraganglioma	1	[124]
Fibrosarcoma	1	[50]
Thyroid adenoma	1	[51]
Hepatic adenocarcinoma	1	[121]
Fibro adenoma breast	2	[125]
Breast carcinoma	1	[114]
Squamous cell carcinoma	1	[126]
Fibroadenoma of thorax and canalicular adenoma	1	[127]
Acute myeloblastic leukemia	1	[51]
Lymphoid leukemia	1	[128]
Ovarian fibrosarcoma	1	[129]

fibula were most frequently affected by enchondromas [50].

Haemangiomas are benign vascular tumors which often protrude as bluish or reddish soft nodules. They can be found anywhere in the body. In addition to the enchondromas, radiographs can show phleboliths, associated with soft tissue calcifications in haemangiomas. Histologically, haemangiomas can be of the capillary or cavernous subtype. Spindle cell haemangioendothelioma is more specific for Maffucci syndrome [51,52]. Both the enchondromas and the vascular lesions may progress to malignancy. The risk of malignancy is higher than in Ollier disease [2,49]. When considering intracranial tumors, the majority is of mesenchymal origin and includes secondary central chondrosarcoma and angiosarcoma associated with Maffucci syndrome [43]. Non-mesodermal tumors associated with Maffucci syndrome are summarized in Table 3. While in Ollier disease intracranial tumors other than chondrosarcomas of the cranium are exclusively of glial origin, in Maffucci syndrome different tumor types are encountered [43]. Also, patients with Maffucci syndrome are almost 10 years older when developing intracranial tumors, and are more likely to live in Asia or South America as compared to Ollier disease [43].

Genetic studies on Maffucci syndrome are sparse. An inversion of chromosome bands p11 and q21 of chromosome 1 were reported in one patient with Maffucci syndrome [53]. Robinson et al showed an increased number of nerve fibers in tumors as well as in normal tissue of Maffucci patients, while in enchondroma and haemangioma tissue numerous methionine enkephalin positive nerves were detected, serving as a growth factor for cartilage proliferation [54]. In total, 26 patients with Maffucci syndrome were screened for mutations in *PTH1R* and revealed absence of mutation [23,55].

Metachondromatosis

This rare hereditary condition displays a combination of multiple enchondromas with multiple osteochondroma-like lesions [32,56,57] (MIM 156250, enchondromatosis Spranger type III). The enchondromas mainly involve the iliac crests and metaphyses of the long bones of the lower extremities while the osteochondroma-like

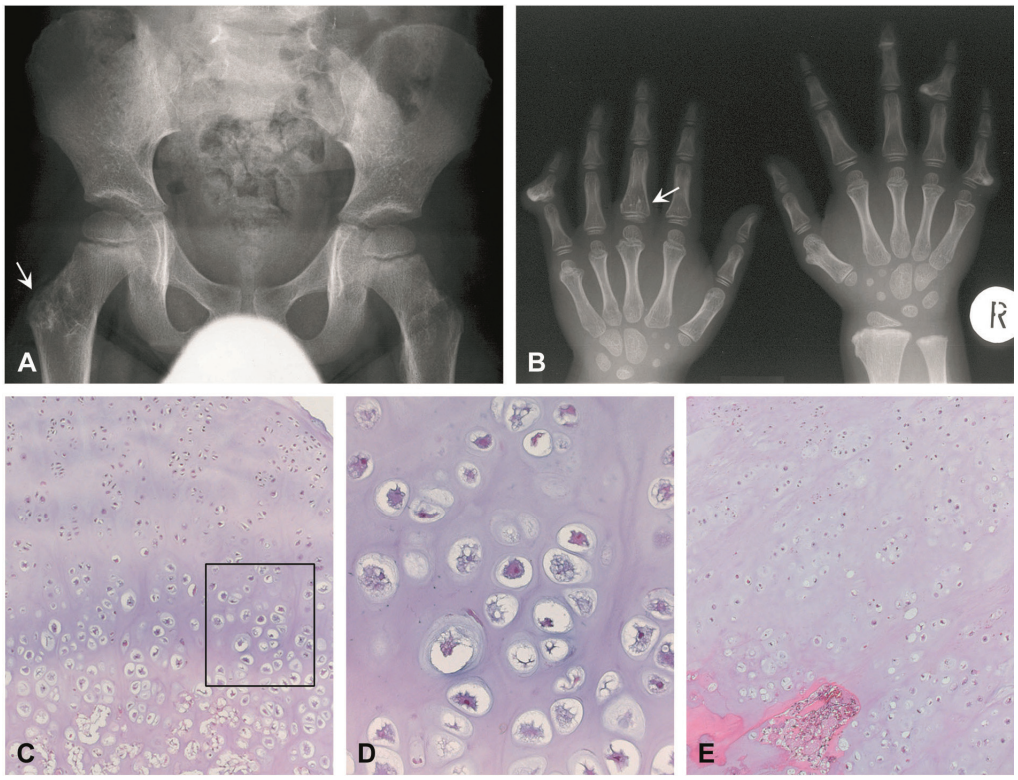

Figure 4. Metachondromatosis. (A) Radiograph of the pelvis with an enchondroma in the right proximal femur (arrow) adjacent to the apophysis of the greater trochanter; (B) radiograph of both hands showing multiple osteochondromas pointing towards the epiphyses. Enchondroma in the proximal phalanx of the left third digit (arrow); (C, E) micrographs of osteochondroma-like lesions (D) magnification of C. These lesions are histologically indistinguishable from conventional osteochondroma recapitulating the normal growth plate architecture (reproduced with permission from [64]).

lesions are mainly located in hands and feet [58]. The syndrome manifests early in childhood [59,60]. In contrast to conventional osteochondromas, the osteochondroma-like lesions in metachondromatosis point towards the joint, do not cause bone deformities, and may regress spontaneously [3,59] (**Figure 4**). Importantly, malignant transformation has not been reported. Avascular necrosis of the femoral epiphysis can be found due to interference with the integrity of the lateral epiphyseal vessels by enchondromas [59,61-63].

The mode of inheritance is autosomal dominant but the underlying gene has not been identified so far, due to the extreme rarity of the disease. In a single case, mutations in the *EXT* genes causing multiple osteochondromas were absent and EXT mRNA expression levels were normal. IHH/PTHLH signaling was normally active in two cases. These data suggest that EXT related pathways are not involved in the pathogenesis of metachondromatosis [64].

Genochondromatosis

Genochondromatosis is an extremely rare autosomal dominant disorder manifesting itself in childhood [65](MIM 137360). Patients have normal stature and enchondromas are distributed symmetrically with characteristic localization in the metaphyses of the proximal humerus and distal femur. Two subtypes are distinguished: genochondromatosis type I includes the presence of a chondroma on the medial side of the clavicle while in type II the short tubular bones of the hand, wrist and feet are affected while the clavicle is normal [65-68]. The enchondroma-like lesions will not lead to any bone deformities, may be discovered accidentally, and tend to regress in adulthood [65] in which they differ from the enchondromas in the

other subtypes. Moreover, no malignancies associated with genochondromatosis have been described in the literature. No spinal involvement is reported which emphasizes it being different from spondyloenchondrodysplasia, cheirospondyloenchondromatosis and dysspondyloenchondromatosis [3]. No genetic studies have been reported for this rare subtype.

Spondyloenchondrodysplasia

Spondyloenchondrodysplasia (SPENCD, enchondromatosis Spranger type IV) is an autosomal recessive inherited disorder characterized by vertebral dysplasia combined with enchondroma like lesions in the pelvis or long tubular bones (MIM 271550) [32,69-81]. Estimated prevalence is higher in Israel [77]. The spinal aberrations include platyspondyly; flat, often rectangular vertebral bodies are seen at radiography with irregular areas of increased and decreased mineralization, and short broad ilia. Spondyloenchondrodysplasia can manifest itself from birth to later infancy [71]. Patients usually have a short stature (short limbs), with increased lumbar lordosis, barrel chest and kyphoscoliosis, genua valga or vara, facial anomalies, and may show clumsy movements [3]. Type I is classic, and type II also affects the central nervous system including spasticity, developmental delay, and late-onset cerebral calcifications [76,81]. In addition, clinical manifestation of autoimmunity can be seen. The spine is less severely affected as compared with dysspondyloenchondromatosis and cheirospondyloenchondromatosis, in which the vertebral lesions are less uniform and the ilia are not short [3].

The clinical features of spondyloenchondrodysplasia are highly variable within and between the families; neurological and autoimmune manifestations were seen in different combinations within one single family suggesting remarkable pleiotropic manifestations of a single disease [81]. In addition, there are two reports suggesting an association of spondyloenchondromatosis with D-2-hydroxyglutaric aciduria, a neurometabolic disorder [82,83]. Although the disease is thought to be autosomal recessive, an autosomal dominant inheritance pattern has also been described [77,80].

Cheirospondyloenchondromatosis

Cheirospondyloenchondromatosis (generalized enchondromatosis with platyspondyly, enchondromatosis Spranger type VI) combines symmetrically distributed multiple enchondromas with marked involvement of metacarpals and phalanges resulting in short hands and feet with mild platyspondyly [3,32]. It occurs at very early age. There is mild to moderate dwarfism and joints, especially of the fingers, become enlarged. Mental retardation is frequently seen. Genetic transmission is unknown [3].

Dysspondyloenchondromatosis

Dysspondyloenchondromatosis (enchondromatosis with irregular vertebral lesions, enchondromatosis type V) is a non-hereditary disorder characterized by spondyloenchondromatosis combined with malformation of the spine [3,32,70,80,84]. The irregularity of the vertebral anomalies differentiates dysspondyloenchondromatosis from other enchondromatosis with spinal involvement. Severe segmentation abnormalities and secondary deformities of the vertebral column can be seen [3]. In addition, neonatal dwarfism, unequal limb length or asymmetric limb shortening, a flat midface with a frontal prominence, and progressive kyphoscoliosis can be found [3,80,85]. Multiple enchondromas are present in the long tubular and flat bones while the bones of hands and feet are not or only mildly affected. The disease manifests itself at birth. Haga et al reported a case with dysspondyloenchondromatosis along with Maffucci syndrome in one patient [86] which suggests that these two different syndromes may be part of one spectrum caused by a pleiotropic gene. Malignant transformation is not yet reported in the literature.

Other less well delineated subtypes

Halal and Azouz provisionally added three more subtypes to the Spranger classification including generalized enchondromatosis with irregular vertebral lesions (type VII), generalized enchondromatosis with mucopolysaccharides (type VIII) and enchondromatosis with concave vertebral bodies (type IX), all of which are non-hereditary [87]. Gabos and Bowen describe 8 patients with extensive unilateral involvement of epiphyseal and metaphyseal regions by enchondromas appearing before growth plate closure leading to severe deformity. It is however unclear whether this is a variant of Ollier disease, or that it should be classified separately as epiphy-

seal-metahyseal enchondromatosis as proposed by the authors [88]. In addition, metaphyseal chondrodysplasia, Vandraager-Pena type may also be considered an enchondromatosis subtype (MIM 250300) [89] although it is more often considered a subtype of metaphyseal dysplasia. It is an autosomal recessive disorder in which the metaphyses of the long bones have an extensive sponge-like appearance at radiographs while histologically numerous islands of cartilage reminiscent of enchondromatosis are seen [89].

Conclusions

Many different syndromes are present with multiple enchondromas, and most of them are extremely rare. None of these syndromes seem to be determined by a simple mendelian manner, and it is unclear whether they represent separate entities, or that they are manifestations of a single causal process. Since they all share the occurrence of multiple enchondromas, this may suggest that the same gene or gene family may be involved in at least a proportion of the different types of enchondromatosis. It can be expected that within the upcoming era of next generation sequencing approaches, elucidating the genes causing rare genetic disorders, also the gene(s) that causes the different enchondromatosis subtypes may be identified. Adequate classification of the different enchondromatosis subtypes as reviewed here is not only relevant for clinical management with regards to genetic counseling and the risk of malignant transformation, but also to allow future molecular studies to reveal whether (a proportion of) the different subtypes are different ends of a spectrum caused by a pleiotropic single gene, or that they truly represent separate disease entities.

Note added in proof

Sobreira et al recently reported mutations in the PTPN11 gene in two metachondromatosis families (PLOS Genet, 2010;6;6). Future studies should reveal whether this gene is also involved in other enchondromatosis subtypes.

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