A mutation in the gene encoding the α2 chain of the fibril-associated collagen IX, COL9A2, causes multiple epiphyseal dysplasia (EDM2)


Multiple epiphyseal dysplasia, an autosomal dominant disease, is among the more common inherited osteochondrodysplasias. Symptoms range from stiffness and pain in large joints to frank osteoarthritis associated with short stature and stubby fingers1-4. Linkage analyses of multiple epiphyseal dysplasia families suggest at least three loci. One locus, EDM1, maps to chromosome 19 (ref. 4), and is caused by mutations in cartilage oligomeric matrix protein (COMP). Mutations in COMP have also been identified in patients with pseudoachondrodysplasia (PSACH)5, consistent with previous analyses which suggested that EDM1 and PSACH could be allelic disorders6. A second locus, EDM2, maps to chromosome 1 in the vicinity of the COL9A2 gene6. Finally, exclusion of EDM1 and EDM2 in other families suggests the existence of at least one additional locus7. We now show that affected members of a large kindred with multiple epiphyseal dysplasia linked to the EDM2 locus are heterozygous for a splice site mutation within COL9A2, causing exon skipping during RNA splicing and an in-frame loss of 12 amino acid residues within the α2(IX) collagen chain. The results provide the first in vivo evidence for the role of collagen IX in human articular cartilage.

Clinical features in part of the present family have been previously reported2,13. Affected individuals typically presented during childhood and adolescence with waddling gait and stiffness and/or pain in the knees. Few patients experienced involvement of other joints such as the elbow, wrist, or ankle. No one complained of hip or shoulder pain. Some patients were mildly short statured and/or had stubby hands. Several patients never sought medical advice because of the mildness of their complaints. There were no spine abnormalities. X-rays revealed flattened, irregular epiphyses (Fig. 1), varus/valgus deformity of the knees, and gradually appearing osteoarthritis with or without loose bodies. Since family members did not have complaints about their hips, X-rays of hips are limited to only a few cases. In these cases (including the patient whose knees are shown in Fig. 1) a variable phenotype is seen, ranging from almost normal for age to slight irregularity of epiphyseal surface and acetabulum.

Linkage analysis was performed with microsatellite markers from the EDM1 (D19S199, D19S212, D19S215, D19S222) and EDM2 (D1S186 and MYCL) regions6. The EDM1 locus was excluded (data not shown), whereas significant linkage was observed between the disorder and the EDM2 locus. The maximal lod score z = 15.31 was obtained with the marker MYCL at θ = 0.016, based upon one recombination event occurring in an affected individual.

To look for the causative mutation we first used the reverse transcription-polymerase chain reaction (RT-PCR). The RNA source was either total RNA from short term cultured chondrocytes (obtained during arthroscopic surgery) or Epstein-Barr virus (EBV) transformed lymphoblasts from an affected patient. An unaffected individual's lymphoblasts were used as control. Nested PCR reactions amplified overlapping cDNA fragments encoding the NC2, COL2, NC3, and COL3 domains and the carboxyl half of the signal peptide of the α2(IX) collagen chain. Fig. 2 shows a schematic representation of the collagen components in cartilage collagen fibrils. Fragments of cDNA encoding the NC1 and COL1 domains were amplified without nesting. Electrophoretic separation of the RT-PCR products of the COL3 domain (obtained with nested primers 7/9 and the more closely spaced primers, 7/13) showed migration as a single appropriately sized fragment in the control individual, whereas the affected individual had two fragments of equal intensity (Fig. 3e). The abnormally sized fragment was eluted from the gel and subjected to cycle sequence analysis. This revealed an in-frame deletion of 36 nucleotides when compared to the wild-type sequence (data not shown).

The sequence of the 36 nucleotide deletion corresponds to a single exon encoding the N-terminal region of the COL3 domain of the α2(IX) collagen polypeptide (Fig. 3b). Amplification of genomic DNA with PCR primers that represented exons flanking the deleted sequence showed identified sized genomic PCR products in both

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Once of both uncleaved and cleaved products.

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**Figure 4.** Agarose gel electrophoresis of COL9A3 genomic frag.
endochondral ossification process. Pupal to adult transition involves a dramatic tissue remodelling process by which the larval tissues undergo considerable alteration and transformation. The tissue remodelling may be due to their delayed development. The body and limb buds in the adult are not fully differentiated and, in contrast to the EDW1 (ref. 4) individuals with the EDW2-linker deletion, EDW1 (ref. 4) individuals with a direct deletion of the CO1A2 gene. Similar to patients with a disorder linked to runt-related transcription factor 2 (Runt-related transcription factor 2) (refs 7, 8), the process of endochondral ossification is affected by the CO1A2 gene. The process of endochondral ossification is affected by the CO1A2 gene and by the appearance of cartilage-specific (cartilage-specific) (cartilage-specific) matrix proteins. These factors suggest a contribution of other modifying factors (modifying factors) to the process of endochondral ossification. In patients with multiple epiphyseal dysplasia, the characteristic changes in the cartilage are not observed in the CO1A2 gene and the EDW2 linker deletion. In patients with multiple epiphyseal dysplasia, the characteristic changes in the cartilage are not observed in the CO1A2 gene and the EDW2 linker deletion. In patients with multiple epiphyseal dysplasia, the characteristic changes in the cartilage are not observed in the CO1A2 gene and the EDW2 linker deletion. In patients with multiple epiphyseal dysplasia, the characteristic changes in the cartilage are not observed in the CO1A2 gene and the EDW2 linker deletion. In patients with multiple epiphyseal dysplasia, the characteristic changes in the cartilage are not observed. In patients with multiple epiphyseal dysplasia, the characteristic changes in the cartilage are not observed.
The product obtained with the pair 5/2 was amplified further by using primer pairs 7/9, 1/6, and 10/4 for second round PCR. All PCR reactions were done in a total volume of 10 μl containing 1 μl PCR buffer, 0.2 μM dATP, 0.5 μM (each) primer and 1 U of Taq polymerase. The PCR products were analysed on 2% agarose gels.

All primer pairs yielded the expected PCR products. DNA from the relevant family members were electrophoresed on agarose gels and digested with Hph1. The samples were then electrophoresed on sequencing gels.

Analysis of the COL9A2 gene. RNA was extracted from EBV-transformed lymphoblasts and cultured chondrocytes by the acid guanidinium thiocyanate/phenol/chloroform method25. First strand cDNAs were synthesized using the Superscript Preamplification System (GIBCO BRL). First strand cDNAs were synthesized with oligo(dT) primers and extracted DNA of 79 members of the family were digested with the pair 5/2 was amplified further by PCR. The conditions were heating at 95 °C for 0.5 min, 64 °C for 1 min, and at 72 °C for 2 min, with a final extension step at 72 °C for 10 min. These amplification products were also cycle sequenced with primers 16/13 from genomic DNA of 79 members of the family were digested with Hph1 and analysed on 4% agarose gels. The primers were synthetized on the basis of both published sequences.

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