Hutchinson-Gilford progeria syndrome (HGPS; MIM 176670) is an extremely rare genetic disorder displaying features reminiscent of premature senescence. Typically, affected children appear normal at birth, but begin to develop characteristic symptoms within the first years of life such as failure to thrive, alopecia, lipodystrophy, and scleroderma-like skin changes. Though the first HGPS cases were described more than 100 years ago, its extreme rarity (1:4–8 000 000) and mostly sporadic occurrence made it difficult to identify the underlying genetic cause. By means of homozygosity mapping as well as candidate gene analysis, two research groups recently reported that heterozygous, recurrent de novo point mutations in the lamin A/C gene (LMNA; MIM 150330), a component of the filamentous meshwork of the nuclear lamina, caused HGPS. LMNA encodes two A-type lamins, lamin A and C, which are the result of alternative splicing and share the first 566 amino acids. Together with B-type lamins, they represent the main components of the nuclear lamina. In contrast to B-type lamins, which are ubiquitously expressed in all cell types at all developmental stages, A-type lamins are absent in the cells of the early embryo, embryonic stem cells, stem cells of the immune and haematopoietic systems as well as in cells of the neuroendocrine system (reviewed in Goldman et al and Mounkes et al).

Besides HGPS, germline mutations in LMNA have been shown to cause seven phenotypically different disorders, inherited in an autosomal dominant and/or recessive manner. Considering the tissue(s) affected, they can be grouped into those involving mainly (i) striated and cardiac muscle, (ii) peripheral nerves, and (iii) white adipose tissue and bones. Together with HGPS, two of them belong to the so-called progeroid syndromes: an atypical form of Werner syndrome (WRN; MIM 277700) and mandibuloacral dysplasia (MAD; MIM 248370).

The observation of heterozygous de novo LMNA mutations in HGPS patients supports the prevailing hypothesis that HGPS essentially represents a sporadic autosomal dominant disorder. In this study, performing genome-wide linkage analysis and subsequent LMNA mutation screening in a consanguineous family, we provide molecular evidence for autosomal recessive inheritance of HGPS, which was already hinted at by a few clinical reports and a recent Lmna mouse knock-out model. Furthermore, the phenotypic features observed in this kindred raise the question whether autosomal recessive MAD and HGPS represent essentially the same, that is, allelic disorder albeit with varying degrees of disease severity.

METHODS

Subjects
The HGPS family originates from North India and the parents are first degree cousins (fig 1A). Of their seven children, the first child (IV:1) died of unknown causes shortly after birth. Child IV:2 had suffered from HGPS, based on photographic documentation, and had died of pneumonia at age 16. Four more affected sibs (IV:3, IV:4, IV:6, and IV:7) and one healthy (IV:5) sib were alive at the time of consultation (fig 2A–D). According to the family history, no further affected relatives are known.

After the death of the 10 year old girl (IV:6), skin biopsies from the lower right abdomen as well as biopsies from the liver, abdominal muscle (m. rectus abdominis), and the right Achilles tendon were taken and fixed in 4% formaldehyde...
For histopathological examination. Written informed consent was obtained for the clinical, histopathological, and molecular genetic investigation of the family.

**Genome-wide linkage analysis**

Genome-wide linkage analysis was performed on the seven members of the HGPS family, including the parents, four affected children and one healthy sib. DNA was extracted from peripheral blood leukocytes according to the manufacturer's protocol (QIAamp DNA Blood Maxi Kit, Qiagen). Genotyping of the polymorphic microsatellite markers was carried out using fluorescently-labelled primers from the ABI Prism Linkage Mapping Set-MD10 (Applied Biosystems), encompassing a total of 382 short tandem repeat markers with 10 cM resolution, and analysed on an ABI PRISM 3700 DNA Analyzer (Applied Biosystems). Statistical linkage analysis was performed using the MLINK program from the LINKAGE package. Based on the linkage results, ten additional microsatellite markers (fig 1A) from the candidate region 1p13.3–1q23.3 were analysed to verify and refine the locus of the HGPS gene (primer and marker information retrieved from UCSC genome browser: http://genome.ucsc.edu).

**LMNA gene mutation analysis**

Coding regions and exon–intron boundaries of the LMNA gene (GenBank accession number NM_170707) were directly sequenced in forward and reverse direction using the BigDye Terminator Cycle Sequencing Kit (Applied Biosystems) and analysed on an automated sequencer (ABI PRISM 310 Genetic Analyser, Applied Biosystems). The mutation identified was further verified by Alu restriction enzyme digestion. The presence of the LMNA mutation K542N identified in the HGPS kindred was subsequently investigated in 50 healthy controls originating from North India.

**RESULTS**

**Clinical features**

The clinical examination of the four affected children revealed age-related features of HGPS (figs 1A and 2A–D), in particular early age of onset (18–24 months), failure to thrive (weight, height, and BMI below the third percentile of the Indian population), diffuse fronto-temporo-occipital alopecia with absent eyebrows and eyelashes, large open fontanelles, and impaired or absent sexual maturation (table 1). The patients' skin in general appeared to be dry, thin, and shiny. The fingers and toes showed scleroderma-like changes.
with the nails being short and dystrophic (fig 2A–D). In addition, skeletal abnormalities such as micrognathia, hypoplastic and absent clavicules as well as acro-osteolysis of the distal phalanges of the hands and feet were observed. The older children were also suffering from stiffness of their joints, which severely impaired their movements. Medical examination including dermatological, neurological, and cardiological assessment did not reveal any obvious pathological findings in the parents or the healthy daughter.

Three patients (IV:4, IV:6, and IV:7) were available for laboratory and radiological investigations. Besides the skeletal lesions mentioned above, no old or current fractures were present. Electrocardiogram and echocardiography showed no pathological findings. Abdominal ultrasound revealed that the size, shape, and position of the internal organs corresponded with the children’s age. Fasting blood glucose and cholesterol levels were within the normal range, as were neurodevelopment and intelligence. A few weeks after initial assessment of the family, patient IV:6 died of respiratory failure due to severe pneumonia.

Histopathological examination of the liver, abdominal muscle, and achilles tendon biopsies taken from the deceased 10 year old girl (IV:6) was unremarkable. The skin displayed several pathological features. The deep reticular dermis contained thickened and hyalinised, sclerotic collagen bundles with an obliteration of interbundle spaces (fig 3). In contrast to the sweat glands, which were very prominent because of the compact connective tissue, hair follicles and sebaceous glands were completely absent. The subcutaneous tissue was atrophic, without any sclerotic changes.

**Linkage analysis**

Preceding the recent identification of the gene responsible for HGPS, genome-wide linkage analysis encompassing 382 short tandem repeat markers with a 10 cM resolution was performed on the HGPS kindred displaying an autosomal recessive mode of inheritance (fig 1A). Because the parents were first degree cousins, affected children were expected to share the same (identical by descent) polymorphic marker alleles from the region of the HGPS gene and to harbour the
same HGPS mutation. Segregation analysis revealed identical alleles by descent exclusively for markers in the chromosomal region 1p13.3–1q23.3, which was further supported by linkage analysis, using the MLINK program, with a two-point LOD score of 2.83 at a recombination fraction $h = 0$.

Investigation of additional microsatellite markers from this region refined the borders of the HGPS locus between markers D1S2726 and D1S2635, an interval of 46 Mb (fig 1A).

**LMNA mutation analysis**  
At the same time, progeria mice carrying an autosomal recessive Lmna gene mutation as well as HGPS patients harbouring heterozygous de novo mutations in LMNA, located in the 1q22 region, were reported.451 5 In subsequent mutation analysis all four affected HGPS family members were found to be homozygous for a G to C transversion at nucleotide 1626 (1626G>C) in exon 10 (fig 1B). This mutation results in a non-conservative substitution of lysine (K) to asparagine (N) at codon 542 (K542N), an evolutionary highly conserved amino acid across species, including mouse (GenBank accession number P48678), rat (GenBank accession number P48679), chicken (GenBank accession number P13648), zebrafish (GenBank accession number NP_694503), and X. laevis (GenBank accession number P11048). The mutation was verified by AluI digests (fig 1C). K542N was not present in 100 chromosomes from healthy individuals originating from North India.

Using three different splice site recognition software tools (NetGene2, NNSplice, and SpliceView) there was no evidence that the 1626G>C mutation would generate a cryptic splicing site (data not shown). Functional significance of the K542N mutation could not be further assessed since no cultured cells or mRNA were available for investigation.

**Table 1 Phenotypic features in affected HGPS family members**

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>IV:7</th>
<th>IV:6</th>
<th>IV:4</th>
<th>IV:3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>Age at presentation (years)</td>
<td>4½</td>
<td>10</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>10.5 (± 6.6 SD)</td>
<td>8* (± 11 SD)</td>
<td>13* (± 11.8 SD)</td>
<td>13* (± 18 SD)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>96* (± 3 SD)</td>
<td>95* (± 7.7 SD)</td>
<td>124* (± 5.1 SD)</td>
<td>120* (± 12 SD)</td>
</tr>
<tr>
<td>Body mass index (kg/cm²)</td>
<td>11.4* (± 2.4 SD)</td>
<td>8.8* (± 6 SD)</td>
<td>8.5* (± 10 SD)</td>
<td>9* (± 2.3 SD)</td>
</tr>
<tr>
<td>Alopecia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Eyebrows and eyelashes</td>
<td>Present</td>
<td>Absent</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>Scleroderma-like skin atrophy</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Mottled pigmentation of the skin</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>Generalised lipodystrophy</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Sexual maturation</td>
<td>Prepubertal</td>
<td>Absent</td>
<td>Impaired</td>
<td>Absent</td>
</tr>
<tr>
<td>Prominent eyes/proptosis</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Pinched nose/beaked profile</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Open fontanelles</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>Micrognathia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Crowded teeth</td>
<td>Milk teeth</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>Clavicles</td>
<td>Hypoplastic</td>
<td>Absent</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>Acro-osteolysis</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Joint stiffness/arthritis</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Number of “+” denotes degree of severity (also see fig 2). *Denotes below the third percentile, with z-score in parentheses (Indian population).

**Table 2 Clinical differences between classical HGPS, the reported HGPS kindred, and LMNA mutation positive MAD patients**

<table>
<thead>
<tr>
<th>LMNA germline mutation</th>
<th>Classical HGPS</th>
<th>Reported HGPS kindred</th>
<th>MAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of onset</td>
<td>1</td>
<td>1–2</td>
<td>3–5</td>
</tr>
<tr>
<td>Age of death</td>
<td>12–15</td>
<td>10 and 16</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Alopecia</td>
<td>Present</td>
<td>Present</td>
<td>Mostly absent</td>
</tr>
<tr>
<td>Eyebrows and eyelashes</td>
<td>Absent</td>
<td>Absent</td>
<td>Mostly absent</td>
</tr>
<tr>
<td>Scleroderma-like skin atrophy</td>
<td>Present</td>
<td>Present</td>
<td>Mostly absent</td>
</tr>
<tr>
<td>Generalised lipodystrophy</td>
<td>Present</td>
<td>Present</td>
<td>Mostly absent</td>
</tr>
<tr>
<td>Open fontanelles</td>
<td>Present</td>
<td>Present</td>
<td>Mostly absent</td>
</tr>
<tr>
<td>Premature loss of teeth</td>
<td>Absent</td>
<td>Absent</td>
<td>Present</td>
</tr>
<tr>
<td>Sexual maturation</td>
<td>Absent/impaired</td>
<td>Absent/impaired</td>
<td>Present</td>
</tr>
</tbody>
</table>

Figure 3 Haematoxylin-eosin stained section of skin biopsy taken from the 10 year old female patient IV:6. Note the tightly packed, sclerotic collagen fibre bundles in the dermis, and, in contrast to the sweat glands (arrowheads), the absence of hair follicles and sebaceous glands.
DISCUSSION

To date, 29 sporadic HGPS cases with LMNA germline mutations have been described.4–17 Twenty-five (86%) of them carry a heterozygous G608G splicing mutation which occurred de novo (that is, not detected in parents) and is presumed to act in a dominant negative fashion. In this study, we present molecular evidence that HGPS is also transmitted in an autosomal recessive mode of inheritance as previously hinted at by consanguineous families with more than one affected sib.11–14

The homozygous K542N LMNA germline mutation identified in our consanguineous HGPS kindred is most likely pathogenic given that it changes an evolutionary highly conserved, charged residue to an uncharged residue and that it is absent in 100 chromosomes from a North Indian control population. Further, indirect evidence stems from genome-wide linkage analysis performed in this family, which significantly excluded all chromosomal loci except the 1p13.3–1q23.3 region.

The fact that the heterozygous mutation carriers (parents, child IV:5) were phenotypically normal strongly argues against a dominant negative effect of the K542N mutation in this family as well as against the hypothesis of recessive HGPS being the result of germline mosaicism.1 In contrast to the most prevalent LMNA mutation G608G impinging only on the lamin A protein, the K542N mutation alters the coding sequence shared by both LMNA splice variants and thus affects lamin A and C. Based on the results from our in silico analysis, 1626G→C (K542N) is unlikely to affect LMNA splicing as observed in the de novo G608G mutation.4,5 Since K542 is localised in the globular C-terminal portion of the lamin A/C molecule, within the emerin and LAP2α interaction, as well as the DNA binding domains, substitution of a charged lysine to an uncharged asparagine is likely to affect both the organisation of the internal nuclear envelope structure and the lamin–DNA interaction.18–21 The functional consequence(s) of this missense mutation, though, remain to be established in future molecular and immunocytochemical investigations on cell cultures from affected family members.

In this HGPS kindred, affected members display remarkably uniform phenotypic features, albeit with age-related expressivity (table 1, figure 2A–D). All patients exhibited marked failure to thrive (well below the third percentile), large fontanelles, scleroderma-like skin alterations, generalised lipodystrophy as well as diffuse to almost total alopecia, loss of eyebrows and eyelashes. Besides the hallmark features of HGPS, patients also showed uniform skeletal malformations such as acro-osteolysis of the digits, micrognathia, and clavicular aplasia/hypoplasia, as previously reported.22–24 These characteristics are shared with MAD, a rare, autosomal recessively inherited disorder.22 Intriguingly, HGPS also shares clinical characteristics with MAD, a rare, autosomal recessively inherited disorder.11 Intriguingly, heterozygous LMNA mutations located in the vicinity of K542N, like R527P and L530P, have been shown to give rise to different, predominantly muscular phenotypes.25

In conclusion, this is the first report of a consanguineous HGPS family providing molecular evidence for autosomal recessive inheritance of HGPS. Thus, in addition to Emery-Dreifuss muscular dystrophy (EDMD2, MIM181350; EDMD3, MIM604929), HGPS represents the second laminopathy where germline mutations in the LMNA gene can cause disease in both a dominant and recessive mode of inheritance. Furthermore, the extent of skeletal lesions observed in this kindred raises the question whether autosomal recessive MAD and HGPS represent essentially the same, that is, allelic disorder albeit with varying degrees of disease severity.

Acknowledgements

We thank the family for participating in this study. We appreciate the care given to the patients by Sckhar Chatterjee and his team at S.B. Devi Charity Home. We are very grateful to Dr I Verma for kindly providing control DNA samples, Dr L Terraciano for expert histopathological advice on the liver and muscle specimens, Professor B Fowler for review of the manuscript and A Wanner for help with capillary electrophoresis. We also thank N Boesch, B Glinz, and F Wenzel for excellent technical support.

Electronic-database information


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