Genetic screening of 202 individuals with congenital limb malformations and requiring reconstructive surgery

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ABSTRACT

Background: Congenital limb malformations (CLMs) are common and present to a variety of specialties, notably plastic and orthopaedic surgeons, and clinical geneticists. The authors aimed to characterise causative mutations in an unselected cohort of patients with CLMs requiring reconstructive surgery.

Methods: 202 patients presenting with CLM were recruited. The authors obtained G-banded karyotypes and screened EN1, GLI3, HAND2, HOXD13, ROR2, SALL1, SALL4, ZRS of SHH, SPRY4, TBX5, TWIST1 and WNT7A for point mutations using denaturing high performance liquid chromatography (DHPLC) and direct sequencing. Multiplex ligation dependent probe amplification (MLPA) kits were developed and used to measure copy number in GLI3, HOXD13, ROR2, SALL1, SALL4, TBX5 and the ZRS of SHH.

Results: Within the cohort, causative genetic alterations were identified in 23 patients (11%): mutations in GLI3 (n = 5), HOXD13 (n = 5), the ZRS of SHH (n = 4), and chromosome abnormalities (n = 4) were the most common lesions found. Clinical features that predicted the discovery of a genetic cause included a bilateral malformation, positive family history, and having increasing numbers of limbs affected (all p < 0.01). Additionally, specific patterns of malformation predicted mutations in specific genes.

Conclusions: Based on higher mutation prevalence the authors propose that GLI3, HOXD13 and the ZRS of SHH should be prioritised for introduction into molecular genetic testing programmes for CLM. The authors have developed simple criteria that can refine the selection of patients by surgeons for referral to clinical geneticists. The cohort also represents an excellent resource to test for mutations in novel candidate genes.

Congenital limb malformations (CLMs) affect approximately 1 in 500 live births1 and usually require surgical intervention to improve functional and aesthetic outcome. CLMs are very diverse in their epidemiology, aetiology and anatomy. In around half of cases, CLMs occur bilaterally, and in unilateral CLM the right and left sides are affected with approximately equal frequency. Up to 18% of children with a CLM die before the age of 6 years, usually because of associated malformations.1 Major causes of CLM include intrauterine disruptions (for example, caused by fetal haemorrhage, hypovolaemia or teratogenesis) and genetic abnormalities (chromosome abnormalities and single gene mutations). Major anatomical categories of CLM include limb hypoplasia reduction defects, brachydactyly, and the polydactyly–syndactyly–triphalangism group.2–5

Previous investigations into the genetics of human CLM have taken two approaches. First, positional candidate methods have been used to identify mutated genes in affected families following linkage analysis, or in individuals harbouring chromosome abnormalities.2–6 Second, genetic mutations causing CLM have been identified in model organisms such as the mouse, and the orthologous gene in humans has been screened for mutations in patients with a similar phenotype.5 Although these approaches have yielded many important gene discoveries, they also have inherent methodological problems. A suitable pedigree structure is required for linkage analysis, meaning that only a small proportion of patients will be suitable for study; similarly, chromosome abnormalities are a relatively uncommon cause of CLM. The model organism/candidate gene approach assumes a correlation between the phenotypes present in the model organism and in the human: this is not always the case. For example, heterozygous mutations in the mouse gene Acta2 cause polydactyly, whereas the limbs are normal when the exactly equivalent mutation occurs in the human orthologue.5–7

In this study we took a different approach to the genetic analysis of CLM. We recruited from a paediatric hand surgery clinic a large cohort of unselected patients with CLM, who underwent surgery; we then undertook mutation analysis of selected genes in the entire cohort, regardless of phenotype. This approach has three potential advantages. First, it makes no prior assumption about which patients will harbour mutations in which gene, allowing the discovery of novel phenotypes associated with mutations in genes already known to cause human CLM. Second, it allows unbiased estimation of the relative contribution of mutations in different genes to the total burden of human CLM; this has not been reported previously. Third, the cohort constitutes a large panel to search for mutations in novel candidate genes as they are discovered in model organisms, without assuming any specific phenotypic correlation in the pattern of CLM.

For this study we chose candidate genes falling into two broad groups. First, we selected genes in which mutations causing human CLMs had been described previously: GLI3, HOXD13, ROR2, SALL1, SALL4, ZRS of SHH, and TBX5.2–5,8–13 Here we aimed to quantify their contribution to human CLM and, potentially, to extend the phenotypic spectrum of mutations. Second, we selected genes either known to play critical roles in limb development or mutated...
in association with mouse CLMs, but for which mutations in the human orthologue causing isolated CLM had not at the time been reported: EN1, HAND2, SPRY4, TWIST1, and WNT7A. Here, the aim was to describe novel mutations and thereby provide further insight into the molecular genetics of human limb formation and CLM.

In this report, we describe this genetic analysis of the cohort. The results were also used to identify clinical characteristics that predict a genetic aetiology, and thereby define referral criteria for patients to clinical genetics services.

METHODS
Subjects
Approval for the work was obtained from the Oxford Research Ethics Committee C (C99.181: Molecular basis of congenital limb abnormalities). Consent was requested from all parents/guardians of patients presenting between 1999 and 2006 to the Department of Plastic and Reconstructive Surgery, Oxford, with a congenital CLM requiring reconstructive surgery. At operation, 3–10 ml of venous blood was collected, which was used for routine karyotype analysis and isolation of genomic DNA using phenol/chloroform extraction. A database containing detailed phenotypic information on each patient recruited to the study was created, and the clinical notes of all patients were individually reviewed.

The family history was obtained by the surgeon in clinic. For statistical comparisons, we utilised two definitions of a positive family history of CLM: (1) having any relative affected with an identical or very similar CLM; and (2) the more strict definition of having an affected first degree relative.

Mutation screening
Screening for point mutations was undertaken by WAVE denaturing high performance liquid chromatography (DHPLC) (Transgenomic, Omaha, Nebraska, USA), followed by direct sequencing of abnormally eluting fragments as previously described. All primer sequences and reaction conditions are available on request. Owing both to continuing recruitment while molecular analysis was ongoing, and mutations being discovered in some patients, each gene was screened in different numbers of patients as follows: EN1, 187; GLI3, 198; HAND2, 174; HOXD13, 175; ROR2, 159; SALL1, 197; SALL4, 185; ZRS of SHH, 187; SPRY4, 149; TBX5, 160; TWIST1, 188; WNT7A, 187.

In collaboration with MRC-Holland (Amsterdam, The Netherlands), we designed multiplex ligation dependent probe amplification (MLPA) probe sets to test for deletions of all exons of GLI3, HOXD13, ROR2, TBX5, SALL1 and SALL4 (MLPA probe sets P179 and P180, MRC-Holland). Details of the probe sequence at the ligation site are provided in supplemental tables S1 and S2. The probe sets P179 and P180 were used to screen 194 and 198 subjects, respectively. A subset of patients (n = 26), chosen because they had bilateral syndactyly and/or polydactyly, was screened for abnormal dosage of the ZRS of SHH using a previously described MLPA probe mix. Statistical comparisons between dichotomous variables were made using Fisher’s exact test.

RESULTS
Genetic abnormalities identified in the cohort
In total, 202 patients were recruited to the study; their clinical features are summarised in table 1. Of these, 98 (49%) had more than one limb affected; 51 (25%) had a family history of CLM including 42 (21%) with an affected first degree relative. Twenty-seven patients (13%) had non-limb malformations, which in 15 (6%) constituted a recognised syndrome or association. The most common CLM was polydactyly (56% of cases), with postaxial being about twice as common as preaxial polydactyly. Syndactyly, either isolated or combined with polydactyly, was the next most common malformation (21%), followed by longitudinal dysplasia (9%) and symbrachydactyly (6%).

The cohort includes five patients in whom a cytogenetic or molecular diagnosis (three chromosome abnormalities, and single mutations in ESCO2 and SALL1) was made independently as a result of routine clinical care. In a further 18 cases, a new cytogenetic or molecular diagnosis was obtained through our research protocol, giving a total of 23 subjects (11%) with a proven genetic lesion accounting for their malformation.

Several of the mutations in GLI3, HOXD13, SALL1, and ZRS of SHH discovered in this cohort have been reported in previous publications; selected data for unpublished mutations are shown in supplemental fig S1.

The molecular/cytogenetic and clinical details of this “genetic diagnosis” cohort are summarised in table 2. Of the 19 molecular alterations listed in table 2, 15 were considered obviously pathogenic because they represented deletions, duplications or nonsense mutations involving known disease genes. Of the remaining nucleotide substitutions, supporting
evidence for pathogenicity of the 940A>C (I514L) substitution encoded by HOXD13 and the 295T>C substitution in the ZRS of SHH is discussed elsewhere.\(^{16,17}\) The 266T>A mutation in TBX5, encoding V93E, affects a conserved residue in the DNA binding T-box and was not identified in 265 controls.

The most common causative genetic alterations that we identified in our CLM cohort were heterozygous mutations in GLI3 (n = 5), HOXD13 (n = 5), ZRS of SHH (n = 4), and miscellaneous microscopically visible chromosome abnormalities (n = 4). More unusual were mutations in SALL1 (n = 2), SALL4 (n = 1) and TBX5 (n = 1). We did not find any pathogenic mutations in the remaining genes screened, including all those genes not yet associated with defined human CLM syndromes (EN1, HAND2, SPRY4 and TWIST1), as well as ROR2 and WNT7A. After this study was initiated, recessive mutations of WNT7A were reported in Al-Awadi/Raas-Rothschild/Schnizel phocomelia and Fuhrmann syndromes (MIM 228930)\(^{24}\); however, our cohort did not include any individuals with these disorders.

In addition to the above pathogenic mutations, we identified 33 additional non-synonymous variants that were considered either non-pathogenic or where the evidence was inconclusive, as itemised in supplemental table S3. A further 80 synonymous variants either non-pathogenic or where the evidence was inconclusive, as itemised in supplemental table S4–S6. Our sample size is too small to exclude the possibility that they created cryptic splice sites using a known single nucleotide polymorphisms (SNPs), we checked and non-coding variants were identified: where these were not as itemised in supplemental table S3. A further 80 synonymous and non-coding variants were identified: where these were not known single nucleotide polymorphisms (SNPs), we checked the possibility that they created cryptic splice sites using a neural network splice site prediction program (supplemental tables S4–S6). Our sample size is too small to exclude the possibility that some of these variants act as susceptibility alleles for particular CLMs.

Factors predicting the discovery of a genetic cause for the CLM

We examined both the general clinical features of the 23 subjects in the genetic diagnosis group and the specific clinical features that might have led to the correct genetic diagnosis independently of our research protocol. Twenty-one of the 23 patients had a bilateral malformation (96%), compared to 76/179 (42%) without a confirmed genetic diagnosis (p<5x10^-6). There was a positive family history of CLM in 12/23 (52%) with a genetic diagnosis, compared to 39/179 (22%) without (p = 0.004). Using the stricter criterion of having a first degree relative affected with an identical or very similar malformation, 12/23 (52%) with a genetic diagnosis had a positive family history of CLM, compared to 30/179 (17%) without (p = 0.0004). Having increasing numbers of limbs affected also predicted the discovery of a molecular genetic cause for the malformation: 6/23 (26%) of those with a molecular genetic diagnosis had all four limbs affected, compared to 12/179 (7%) without (p = 0.008), and 21/23 (91%) of patients with a molecular genetic diagnosis had more than one limb affected, compared to 77/179 (45%) without (p = 6x10^-6).

Specific patterns of malformation were also associated with the discovery of a mutation. Four out of five patients (80%) with mutations in GLI3 had a combination of bilateral preaxial polydactyly of the feet and a hand malformation. In contrast, only two other patients had preaxial polydactyly of the foot, in both cases it was unilateral, and in only one case was it associated with a hand malformation. Thus, the presence of bilateral preaxial polydactyly of the feet, especially if combined with a hand malformation, is strongly associated with mutation in GLI3.

Two other examples of specific patterns of malformation are provided by triphalangeal thumb and ring finger duplication. All three patients with bilateral triphalangeal thumb harboured an identical substitution in the ZRS of SHH.\(^{24}\) Only two other patients in the cohort had triphalangeal thumb, and in neither case was the malformation bilateral; one patient had unilateral triphalangeal thumb associated with ipsilateral preaxial polydactyly and a mutation in SALL1,\(^{22}\) the other had triphalangeal thumb associated with tetralogy of Fallot, and no identified mutation. Thus, the presence of triphalangeal thumbs (especially if bilateral) is strongly suggestive of a mutation in the ZRS of SHH. Both patients with partial duplication of the ring finger had HOXD13 mutations, but this criterion would miss three of the HOXD13 mutations. Broadening the diagnostic criterion to syndactyly of the third web space of the hand would yield two additional cases with HOXD13 mutation, at the expense of including a further 18 subjects negative for HOXD13 mutation.

Estimation of the overall genetic contribution to CLM

In addition to the 25 probands in whom a genetic diagnosis was made, 39 other patients (25 with isolated postaxial polydactyly) had a family history of similar CLM, suggesting a contribution by either single gene mutations or polygenic variants. Two further sporadic patients had clinical diagnoses of Fanconi anaemia but did not have a specific mutation identified. Therefore, a minimum of 64/202 (32%) of patients with a CLM requiring reconstructive surgery have a genetic contribution to their malformation.

DISCUSSION

To our knowledge, this study is the first to screen systematically for mutations in an unselected cohort of individuals with CLMs requiring reconstructive surgery. We discovered mutations in GLI3, HOXD13, SALL1, SALL4, the ZRS of SHH and TBX5 in 17 patients, karyotyping revealed a pathological rearrangement in a single patient, and the clinical genetics service independently obtained a cytogenetic or molecular genetic diagnosis in five patients, making a total of 25/202 (11%) patients in the cohort with a defined genetic diagnosis.

It may appear surprising that only 5/23 (22%) of these genetic diagnoses were achieved through routine clinical genetics services. This appears to reflect two factors. First, despite sometimes extensive family histories, most patients with genetic diagnoses (16/23) had not been referred by their medical carers for genetic counselling. It is possible that the relative lack of availability of genetic testing services for CLM, and a subjective lack of concern on the part of some parents about the nature and genetic implications of the CLM, may have contributed to this under-referral. Second, in the two additional cases previously referred to clinical geneticists, the retrospectively correct clinical diagnosis had not been confirmed molecularly. In one instance (OX2084, TBX5 mutation) a tentative diagnosis of Holt–Oram syndrome (MIM 142900) had been made, but an electrocardiogram (ECG) and echocardiogram were normal, and genetic testing was not arranged. In another (OX3424, ZRS triplication), the correct clinical diagnosis of syndactyly type IV (Haas) (MIM 186200) was suggested, but the role of rearrangements of the ZRS of SHH in the aetiology of this disorder was not known at the time. In none of the probands with GLI3 mutations had the diagnosis of Greig cephalopolysyndactyly (GCP, MIM 175700) been suggested previously, even though this was clinically apparent retrospectively in four of the five subjects.

It is interesting to analyse the extent to which the universal screening approach that we adopted in this study fulfilled the three anticipated advantages that we identified in the introduction. Certainly we could estimate, in an unbiased fashion, the relative mutation frequencies of genes for which mutations have a well established role in CLM.
Table 2  Clinical characteristics of patients with a confirmed molecular genetic diagnosis

<table>
<thead>
<tr>
<th>Gene</th>
<th>Patient number</th>
<th>Mutation (heterozygous unless stated otherwise)</th>
<th>Clinical features*</th>
<th>Hands</th>
<th>Feet</th>
<th>Other</th>
<th>Bilateral</th>
<th>Family history</th>
<th>Number of limbs affected</th>
<th>Final diagnosis</th>
<th>Reference</th>
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<tbody>
<tr>
<td>GLI3</td>
<td>OX1746</td>
<td>366C&gt; G, Y122X</td>
<td>Synd 3rd web L</td>
<td>PrP, Synd 1st 2nd 3rd webs</td>
<td>Macrocephaly</td>
<td>Yes</td>
<td>Yes</td>
<td>3</td>
<td>GCPS</td>
<td></td>
<td>–</td>
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<td>GLI3</td>
<td>OX2979</td>
<td>1320dupT, E441X</td>
<td>PrP, PoP type B</td>
<td>PrP, Synd 1st 2nd webs</td>
<td>Macrocephaly, undescended testicle</td>
<td>Yes</td>
<td>No</td>
<td>4</td>
<td>GCPS</td>
<td></td>
<td>22</td>
</tr>
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<td>GLI3</td>
<td>OX1277†</td>
<td>2372delC, P791RfsX3</td>
<td>PoP type B</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>2</td>
<td>PoP type A1</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>GLI3</td>
<td>OX3536</td>
<td>2374C&gt;T, R792X</td>
<td>PoP type B</td>
<td>PrP</td>
<td>Hypertelorism</td>
<td>Yes</td>
<td>Yes</td>
<td>4</td>
<td>GCPS</td>
<td></td>
<td>22</td>
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<tr>
<td>HOXD13</td>
<td>OX2137</td>
<td>165_185dup, A59_61dup</td>
<td>Synd 3rd web</td>
<td>PoP, Synd 4th web</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>4</td>
<td>SPD1</td>
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<td>18</td>
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<tr>
<td>HOXD13</td>
<td>OX1238</td>
<td>752-2delA</td>
<td>Synd 3rd web R hand, clinodactyly little fingers</td>
<td>Extra bony element in 1st web space</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>3</td>
<td>SPD1 with foot anomaly</td>
<td></td>
<td>23</td>
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<tr>
<td>HOXD13</td>
<td>OX1749</td>
<td>940A&gt;C, I314L</td>
<td>Lateral duplication of ring finger phalanges, Synd 3rd webs</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
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<td>SPD1/brachydactyly E overlap</td>
<td></td>
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<tr>
<td>HOXD13</td>
<td>OX1752</td>
<td>940A&gt;C, I314L</td>
<td>Little finger hypoplasia, lateral duplication of ring finger phalanges</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>2</td>
<td>SPD1/brachydactyly E overlap</td>
<td></td>
<td>18</td>
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<tr>
<td>HOXD13</td>
<td>OX3015†</td>
<td>955C&gt;T, R319X</td>
<td>Clindactyly little fingers</td>
<td>PoP</td>
<td>Imperforate anus, rectal atresia, hypospadias, overfolded helices</td>
<td>Yes</td>
<td>No</td>
<td>2</td>
<td>Townes-Brocks syndrome</td>
<td></td>
<td>22, 30</td>
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<tr>
<td>SALL1</td>
<td>OX3355†</td>
<td>995delC, P332Hlsx10</td>
<td>PrP, R side Wassel type 6, L side type 3</td>
<td>–</td>
<td>–</td>
<td>No</td>
<td>No</td>
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<td>CLM with SALL1 mutation</td>
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<td>22</td>
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<tr>
<td>SALL4</td>
<td>OX2948†</td>
<td>3414_3415delAT,C1139WfsX14</td>
<td>PrP R, TpT R</td>
<td>–</td>
<td>–</td>
<td>No</td>
<td>No</td>
<td>1</td>
<td>CLM with SALL1 mutation</td>
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<td>22</td>
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<tr>
<td>SALL4</td>
<td>OX3701</td>
<td>293C&gt;T, R885X</td>
<td>Hypoplastic thumbs, L side Blauth type 3a, R side type 3b</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>No</td>
<td>2</td>
<td>Okihiro syndrome</td>
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<tr>
<td>TBX5</td>
<td>OX2084†</td>
<td>266T&gt;A, V89E</td>
<td>Grade 1 radial dysplasia with hypoplastic thumbs, Blauth type 4 R hand and type 5 L hand</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>No</td>
<td>2</td>
<td>Holt-Oram syndrome</td>
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<td>ZRS</td>
<td>OX1925</td>
<td>295T&gt;C</td>
<td>TpT</td>
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<td>–</td>
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<td>No</td>
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<td>TpT with ZRS mutation</td>
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<td>ZRS</td>
<td>OX3159</td>
<td>295T&gt;C</td>
<td>TpT, PrP</td>
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<td>–</td>
<td>Yes</td>
<td>Yes</td>
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<td>PrP type II</td>
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<td>ZRS</td>
<td>OX3601</td>
<td>295T&gt;C</td>
<td>TpT</td>
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<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>2</td>
<td>TpT with ZRS mutation</td>
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<td>ZRS</td>
<td>OX3424</td>
<td>Triplication</td>
<td>Complex polysyndactyly, fixed laxion at wrists</td>
<td>Complex polysyndactyly, severe talipes, mirror L foot, dislocated patella, talipes equinovarus, long bone deficiency, single digit</td>
<td>–</td>
<td>Yes</td>
<td>No</td>
<td>4</td>
<td>Synd type IV (Haas)</td>
<td></td>
<td>–</td>
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<tr>
<td></td>
<td>OX26125</td>
<td>t(2;18)(p14.2;p11.12)</td>
<td>Oligodactyly, more severe radially</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>No</td>
<td>4</td>
<td>Split-hand/foot malformation</td>
<td></td>
<td>26</td>
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<td></td>
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<tr>
<td></td>
<td>OX3689††</td>
<td>dup(6)(p22.2p23)</td>
<td>PrP</td>
<td>–</td>
<td>Low birthweight, microcephaly, developmental delay</td>
<td>No</td>
<td>No</td>
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<td>CLM with chromosome abnormality</td>
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<td></td>
<td>OX30845</td>
<td>del(22)(q11.2q11.2)</td>
<td>PrP</td>
<td>–</td>
<td>Cardiac malformation</td>
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<tr>
<td>ESCO2</td>
<td>OX3689††</td>
<td>del(9)(p22.1)</td>
<td>Camptodactyly, thumb hypoplasia</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
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<td>9p deletion syndrome</td>
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<td>ESCO2</td>
<td>OX3705</td>
<td>Homozygous, 955i2_5delTAAG</td>
<td>Radial dysplasia Talipes equinovarus</td>
<td>Microgastria, long columna, hypoplastic alae, nasal haemangioma, microcephaly</td>
<td>Yes</td>
<td>No</td>
<td>2</td>
<td>Roberts syndrome</td>
<td></td>
<td>31</td>
<td></td>
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</table>

CLM, congenital limb malformation; GCPS, Greig cephalopolysyndactyly syndrome; L, left sided; PoP, postaxial polydactyly; PrP, preaxial polydactyly; R, right sided; Synd, syndactyly; SPD1, synpolydactyly 1; TpT, triphalangeal thumb.

*Limbs were bilaterally affected unless otherwise stated.
†Genetic abnormality that would not have been discovered by a clinically focused approach to mutation screening (see Discussion).
‡Cytogenetic diagnosis made as part of the study protocol.
§Clinical diagnosis made after consultation with clinical genetics service. Molecular genetic or cytogenetic diagnosis was made outside of this study.
Importantly, we did not identify any gene that is very commonly mutated in CLM; those genes most frequently mutated (GLI3 and HOXD13, five cases each) demonstrated an overall prevalence of only 2.5-2.8%. Although the difference between identifying one and five cases in this series is not statistically significant, these data do support prioritisation of the introduction of testing for GLI3, HOXD13 and the ZRS of SHH in clinical diagnostic services, on the basis that multiple mutations were identified: indeed, testing of the first two of these genes is now available through the Genetics Laboratories in Oxford (http://www.oxfordradcliffe.nhs.uk/forpatients/departments/labs/geneticslab/documents/diseaseservices.pdf (accessed 7 September 2009)). In many cases, careful evaluation of the phenotype would substantially enhance the specificity of genetic testing. For example, if the presence of bilateral preaxial polydactyly of the feet was made an essential criterion for testing GLI3, this would result in a sensitivity of 80% (four of five GLI3 mutations identified) and a positive predictive value (PPV) of 100% (four of four individuals with specified phenotype have a GLI3 mutation). A high sensitivity and PPV could also be achieved for the association of ZRS mutations and triphalangeal thumb (sensitivity 75%, PPV 60%). Mutations of HOXD13 would be more difficult to pick out: although symphalangism 1 (SPD1; MIM 113500),22 and a specific alteration of the phenotype associated with polyalanine tract expansion mutations (such as that identified in case OX2157), different molecular categories of HOXD13 mutation present with variant phenotypes as illustrated by the other cases discovered in our series (table 2 and discussed below). Use of ring finger duplication or third web space syndactyly as the diagnostic criterion for HOXD13 mutation in our series would have had good sensitivity (80%) but relatively poor PPV (18%).

A further benefit from our screening strategy is that we identified two new associations between CLMs and particular mutant alleles, both of which we have reported elsewhere: we found a novel HOXD13 mutation encoding I314 L in two independent families segregating a specific disorder with features combining SPD1 and brachydactyly type E (MIM 113500),22 and a specific alteration of the ZRS of SHH, 295 T>C, as a common cause (three independent cases) of triphalangeal thumb, representing the mild end of a phenotypic spectrum including preaxial polydactyly type II (MIM 174500).23 In addition we found mutations or cytogenetic abnormalities in a further five cases that were not readily predictable from the phenotype (footnote $^+$ to table 2). Three of these (isolated postaxial polydactyly and GLI3 mutation, unilateral preaxial polydactyly with triphalangeal thumb and SALL1 mutation, limb reduction defect and t(2;18) chromosome translocation) have been reported in detail elsewhere.22 26 The other two cases were preaxial polydactyly of the hands in a child with dup(6)(p22.3p23); and postaxial polydactyly of one foot with marked bilateral clinodactyly of the little fingers, associated with a heterozygous nonsense mutation (R319X) in HOXD13 (supplemental fig S1D). Although we were not successful in identifying a novel role for any of the more speculative candidate human genes in isolated CLM, our DNA panel provides a resource for further genetic studies as new candidates are identified.

As part of this project we designed new MLPA kits for the identification of deletions in the GLI3, HOXD13, ROR2, SALL1, SALL4 and TBX5 genes. The diagnostic yield from MLPA analysis of the cohort was low, with only a single partial GLI3 deletion being identified; however, the probe sets have subsequently been implemented in diagnostic laboratories, where additional deletions or duplications in GLI3, HOXD13, and SALL1 have been identified in patients previously without a molecular diagnosis (M Oldridge, G Cross, personal communication, 2008).

Clearly the list of known CLM genes included in our screen was not exhaustive:22 we focused on genes associated with variable CLM phenotypes in the better recognised, mostly dominantly inherited syndromes. Indeed some members of the cohort had clinical diagnoses (for example, Fanconi anaemia, ectrodactyly, and brachydactyly type C), that are associated with known genetic changes that we did not investigate, as this was outside the purpose of the study. These subjects were all included in the “genetic component” group in table 1. The minimum figure of 32% of patients from the cohort having a genetic aetiology for their malformation represents the first estimate of the genetic contribution to CLM. Previous epidemiological studies have focused on the incidence and type of malformation to aid in medical workforce planning have focused on CLM diagnosed prenatally,24 or have looked for an association between environmental, maternal or teratogenic factors and specific types of CLM.25 Clinical features that predicted the discovery of a genetic cause for the CLM were the presence of a bilateral malformation, a positive family history of CLM, and an increasing number of limbs being affected. Furthermore, specific patterns of CLM predicted a genetic aetiology. Based on these data, we propose some simple guidelines (table 3) that should trigger the referral of patients by surgeons to clinical genetics services for diagnosis and investigation. All the suggested criteria at least double the likelihood of a specific molecular or cytogenetic abnormality being identified.

Acknowledgements: We thank all the participants in this study, Mr Kevin Clarke for help with DNA sequencing, Mike Oldridge for information on GLI3, HOXD13 and ROR2 screening, Gareth Cross for information on SALL1 screening, and Dr Jan Schouten and his team at MRC Holland for help with the design and production of the MLPA probe sets used in this study.

Funding: Wellcome Trust (074457 to DF, 078666 to AOMW).

Competing interests: None.

Patient consent: Not required.

Provenance and peer review: Not commissioned; externally peer reviewed.

REFERENCES


