Molecular analysis of 20 patients with 2q37.3 monosomy: definition of minimum deletion intervals for key phenotypes [research letter]

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Molecular analysis of 20 patients with 2q37.3 monosomy: definition of minimum deletion intervals for key phenotypes

M A Aldred, R O C Sanford, N S Thomas, M A Barrow, L C Wilson, L A Brueton, M C Bonaglia, R C M Hennekam, C Eng, N R Dennis, R C Trembath

METHODS
This study has been approved by the Leicestershire ethics committee. Seven patients have been described previously.1 4 7 16 20 26 Thirteen additional patients with known 2q37 rearrangements were ascertained through conventional cytogenetics departments in the UK and clinical details are provided as supplementary online information at http://jmg.bmj.com/ supplemental/. Informed consent was obtained from parents or guardians. The patient panel comprised 16 deletions, two inverted duplication/deletions, one ring chromosome and one unbalanced translocation. The ring chromosome (patient 53) has virtually no loss of 2p material, being heterozygous for microsatellite D2S2584, ~160 kb from the telomer, and retaining the 2p subtelomeric FISH probe 2052f6. The phenotype is therefore presumed to be due solely to the 2q37 deletion.

DNA was extracted from peripheral blood leukocytes or buccal cells using standard methods. MAPH was conducted essentially as described,14 15 except that probes were cloned into pCR2.1-TOPO using the TOPO-TA cloning kit (Invitrogen, Paisley, UK) and the sequence of the blocking material, being heterozygous for microsatellite D2S2584, ~160 kb from the telomer, and retaining the 2p subtelomeric FISH probe 2052f6. The phenotype is therefore presumed to be due solely to the 2q37 deletion.

Key points
- We have conducted detailed dosimetric analysis in 20 patients with monosomy 2q37.
- No common breakpoints were found, indicating that 2q37 rearrangements are likely not mediated by duplicated low copy repeats.
- The minimum deleted region in patients with characteristic facial dysmorphism and Albright hereditary osteodystrophy (AHO)-like brachymetaphalangism has been narrowed to approximately 3 Mb.
- For the first time, preliminary assignments of critical intervals for other features of the syndrome have now been made. All such intervals share a 1.5 Mb overlap.
- However, considerable clinical variability was apparent and no clear genotype-phenotype correlations could be drawn that would help predict clinical prognosis in a newly-diagnosed young proband.
screening of publicly-available BAC sequence using the Tandem Repeats Finder program.\textsuperscript{36} Primer sequences and annealing temperatures are shown in table 1. All new markers proved to be polymorphic. Existing microsatellite markers from the Genethon and Marshfield genetic maps were analysed using primers available from the public genome databases. Singleplex reactions were conducted for 40 cycles using HotStar PCR mastermix (Qiagen, Crawley, UK) supplemented with 1 x Q-solution. Singleplex reactions utilised the Multiplex PCR Mastermix (Qiagen, Crawley, UK) supplemented with 0.5 x Q-solution, also for 40 cycles following the manufacturer’s recommended thermocycle profile. All microsatellites were labelled with 6-FAM, HEX, or TET fluorophores and analysed on an ABI377 12 cm genotyping gel.

RESULTS

Clinical characteristics

Clinical features for all cases are summarised in table 2. Consistent with the literature, all except the very youngest patient had mild or moderate developmental delay and some degree of facial dysmorphism. Consent for publication of facial photographs was given in four cases (fig 1) and a further five were published previously (patients 75, 76, 10780, 419 and 622).\textsuperscript{24,71} Common features include round face with flattened nasal bridge, frontal bossing, deep-set eyes, up-slanting palpebral fissures, anteverted nares, and thin upper lip. In contrast, the facial dysmorphism in patient 63 was markedly different (see online supplementary information), consistent with her duplication for much of 2q37 and only a very small telomeric deletion (see molecular results below). AHO-like brachymetaphalangism was observed in 11 (55%) of our patients, autistic or repetitive, hyperkinetic behaviours in seven (35%), non-febrile seizures also in seven (35%), eczema in five (25%), and heart abnormalities in four (20%). These frequencies are in keeping with those in the wider literature, with the exception of patient 75 (AW, Fisher et al\textsuperscript{46}), who showed an interstitial deletion with the distal breakpoint localised between D2S140 (deleted) and AC005237CA (retained). Microsatellite analysis in patient 63 showed that the inverted duplication detected cytogenetically was accompanied by a previously undetected small terminal deletion. The duplicated and deleted regions were apparently separated by a small region of normal gene dosage, as judged by relative and approximately equal proportions of paternally and maternally-derived rearrangements were observed. A similar lack of bias in parental origin is seen in Williams-Beuren, DiGeorge, and 18p- syndromes,\textsuperscript{33,47} whereas Sotos, Wolf-Hirschhorn, Cri-du-chat, and 18q- syndromes are predominantly paternal in origin\textsuperscript{33,47} and 1p36 deletions show a slight maternal bias.\textsuperscript{33}

As suggested by the original cytogenetic analyses, all patients were found to have terminal deletions with the exception of patient 75 (AW, Fisher et al\textsuperscript{46}), who showed an interstitial deletion with the distal breakpoint localised between D2S140 (deleted) and AC005237CA (retained). Microsatellite analysis in patient 63 showed that the inverted duplication detected cytogenetically was accompanied by a previously undetected small terminal deletion. The duplicated and deleted regions were apparently separated by a small region of normal gene dosage, as judged by relative

Molecular characteristics

Molecular results are summarised in fig 2. Parental samples were available in 16 of the 19 non-familial cases. All 16 were shown to be de novo rearrangements, none showed co-existence with the known 2q subtelomeric polymorphism.\textsuperscript{37,38}
<table>
<thead>
<tr>
<th>ID</th>
<th>Karyotype</th>
<th>Sex</th>
<th>Age</th>
<th>Facial dysmorphism</th>
<th>Developmental delay</th>
<th>Skeletal anomalies</th>
<th>Behaviour</th>
<th>Eczema</th>
<th>Seizures</th>
<th>Congenital heart anomalies</th>
<th>Other</th>
<th>Previous reference</th>
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<tr>
<td>74</td>
<td>46,XX,del(2)(q37.1)</td>
<td>F</td>
<td>20 months</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Hypotonia, lumbar lordosis</td>
<td>LM (Fisher et al 16)</td>
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<td>76</td>
<td>46,XX,del(2)(q37.1)</td>
<td>F</td>
<td>18 years</td>
<td>++</td>
<td>B, L</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Obesity, lymphoedema of legs</td>
<td>Power et al 4 e</td>
</tr>
<tr>
<td>78</td>
<td>46,XX,del(2)(q37.1)</td>
<td>F</td>
<td>7 years</td>
<td>++</td>
<td>B, S</td>
<td>R</td>
<td>--</td>
<td>I</td>
<td>--</td>
<td>--</td>
<td>Umbilical hernia</td>
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</tr>
<tr>
<td>8490</td>
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<td>F</td>
<td>10 years</td>
<td>++</td>
<td>B, S</td>
<td>R</td>
<td>--</td>
<td>I</td>
<td>--</td>
<td>--</td>
<td>Umbilical hernia</td>
<td></td>
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<tr>
<td>12410</td>
<td>46,XY,del(2)(q37.1)</td>
<td>M</td>
<td>32 years</td>
<td>++</td>
<td>Rs</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Oedema and ulceration of legs</td>
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<tr>
<td>315</td>
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<td>++</td>
<td>--</td>
<td>H</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Myopia</td>
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<td>8491</td>
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<td>F</td>
<td>16 years</td>
<td>++</td>
<td>B, D, P</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Hydrocephalus</td>
<td>Bonaglia et al 26</td>
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<tr>
<td>8493</td>
<td>46,XX,invdup(2)(q33q37)</td>
<td>F</td>
<td>7 years</td>
<td>+</td>
<td>S, Cl</td>
<td>H, Ag, M</td>
<td>--</td>
<td>GA</td>
<td>PDA, PAD</td>
<td>Myopia, arachnodactyly</td>
<td>Bonaglia et al 26</td>
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<tr>
<td>63</td>
<td>46,XX,invdup(2)(q36.2q37.3)</td>
<td>F</td>
<td>9 years</td>
<td>+</td>
<td>Cl</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Squint, glaucoma, recurrent infections</td>
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</tr>
<tr>
<td>75</td>
<td>46,XX,del(2)(q37.2)</td>
<td>F</td>
<td>10 years</td>
<td>++</td>
<td>--</td>
<td>Aut</td>
<td>+</td>
<td>GM</td>
<td>ASD, GA</td>
<td>Neonatal hypercalcaemia</td>
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<tr>
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<td>F</td>
<td>9 years</td>
<td>++</td>
<td>B, Cl</td>
<td>Ag</td>
<td>--</td>
<td>Ab</td>
<td>--</td>
<td>--</td>
<td>2–3 toe syndactyly, joint laxity, squint, horseshoe kidney</td>
<td>Wilson et al 44</td>
</tr>
<tr>
<td>213</td>
<td>46,XX,del(2)(q37.3)</td>
<td>F</td>
<td>15 years</td>
<td>+</td>
<td>B, D, L, S</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Joint laxity, myopia, squint</td>
<td>RA (Wilson et al 44)</td>
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<tr>
<td>106</td>
<td>46,XX,del(2)(q37.3)</td>
<td>F</td>
<td>15 months</td>
<td>Mild</td>
<td>Mild</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Inginal hernias, recurrent infections</td>
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</tr>
<tr>
<td>127</td>
<td>46,XX,del(2)(q37.3)</td>
<td>M</td>
<td>5 years</td>
<td>+</td>
<td>--</td>
<td>B</td>
<td>H, Ob</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Obesity, inguinal hernia, squint</td>
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<tr>
<td>128</td>
<td>46,XX,del(2)(q37.3)</td>
<td>F</td>
<td>11 years</td>
<td>+</td>
<td>--</td>
<td>B</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Obesity, inguinal hernia, squint</td>
<td></td>
</tr>
<tr>
<td>389</td>
<td>46,XX,del(2)(q37.3)</td>
<td>F</td>
<td>22 years</td>
<td>Mild</td>
<td>Mild</td>
<td>B</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
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<tr>
<td>419/622*</td>
<td>t(2;8)(q37.3;q24.3)</td>
<td>N/A</td>
<td>N/A</td>
<td>--</td>
<td>--</td>
<td>B</td>
<td>H, Ag, M</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>Hynons, recurrent infections</td>
<td>Bijlma et al 7</td>
</tr>
<tr>
<td>10780</td>
<td>46,XX,del(2)(q37.3)</td>
<td>F</td>
<td>12 years</td>
<td>++</td>
<td>B, Cr</td>
<td>--</td>
<td>--</td>
<td>GM</td>
<td>--</td>
<td>--</td>
<td>Squint, short stature, obesity</td>
<td>KW (Wilson et al 44)</td>
</tr>
<tr>
<td>122</td>
<td>46,XX,del(2)(q37.3)</td>
<td>F</td>
<td>6 years</td>
<td>++</td>
<td>B</td>
<td>SCD</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Joint laxity, 2–3 toe syndactyly</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>46,XY,r(2)(p25.3q37.3)</td>
<td>M</td>
<td>5 months</td>
<td>--</td>
<td>Cl</td>
<td>--</td>
<td>--</td>
<td>Ab</td>
<td>--</td>
<td>--</td>
<td>Microcephaly</td>
<td></td>
</tr>
</tbody>
</table>

*Familial translocation—data represent a composite for all family members with an unbalanced der(2) karyotype.

Ab, absences; Ag, aggression; AS, atrial stenosis; ASD, atrial septal defect; Aut, autism; B, brachymetaphalangism; CA, coarctation of the aorta; CAS, controlling, attention-seeking; Cl, fifth finger clinodactyly; Cr, craniosynostosis; D, bilateral dislocation of the hips; F, fabric; GA, generalised atonic; GM, grand mal; H, hypertonia; I, post-immunisations; L, abnormalities of the long bones; M, self-mutilating; Ob, obsessional; Os, osteoporosis; P, Perthes disease of the hip; PAD, pulmonary artery dilatation with left ventricular hypertrophy; PDA, patent ductus arteriosus; R, routine bound; S, scoliosis; SCD, receptive language and social communication disorders; VSD, ventricular septal defect.
peak heights of the microsatellites. This has not yet been verified by alternative methods, but would be in keeping with the mechanism proposed by Bonaglia et al. for the causation of inverted duplications.

Breakpoint mapping and minimum deletion intervals
Since we wished to focus on the critical interval for AHO-like phenotype, distal to D2S338, breakpoints in the larger deletions were not characterised in detail. Breakpoints in the nine smallest terminal deletions, the translocation, and one duplication/deletion all localised within a 3.8 Mb region bounded by D2S338 proximally and AC0153469CA distally. Two of these breakpoints, patients 10780 and 122, were precisely localised to non-overlapping intervals of 169 and 33.8 kb, respectively, within the HDAC4 gene. Taken as a whole, these data define the most distal breakpoints so far characterised for both interstitial and terminal 2q37 deletions.

We then attempted to define the minimal deleted interval for each of the major features of the syndrome (fig 2). Due to the apparent reduced penetrance, this was done on an inclusion-only basis, that is, the absence of a clinical characteristic was not used as a criterion for excluding that genomic region. The critical interval for the AHO-like brachymetaphalangism extends from HDAC4 to the telomere, a region of approximately 3 Mb, as defined by patients 10780 and 122. These patients also both show the characteristic facial dysmorphism. The interstitial nature of the deletion in patient 75, who clinically showed an atrial septal defect, eczema, epilepsy, and autism, potentially excludes a number of the most telomeric 2q genes as candidates for these phenotypes. Thus, the minimum deleted region amongst our patients with autistic or hyperkinetic behaviour and/or epilepsy is ~2.1 Mb between HDAC4 and AC005237CA. An overlapping 1.5 Mb region is deleted in patients with eczema, while RAMP1 and AC005237CA bound a ~3.4 Mb region common to patients with cardiac septal defects (fig 2).

**DISCUSSION**
Genotype–phenotype correlations have been instructive in a number of other deletion syndromes to define discrete clinical subgroups, leading to more accurate prognostication and identification of candidate genes for specific phenotypes. In conducting this detailed analysis of 20 patients with 2q37 rearrangements, our aims were threefold: (a) to refine the minimal deleted region for the AHO-like brachymetaphalangism; (b) to determine whether genotype–phenotype correlations could be drawn for other features of the syndrome; and (c) to precisely map the breakpoints as possible clues to the rearrangement mechanism.

**Brachymetaphalangism**
The critical interval for the AHO-like brachymetaphalangism is unequivocally assigned to the 3 Mb region from HDAC4 to
the telomere. This represents a refinement of approximately 2 Mb compared to the previous minimum interval.\textsuperscript{15} It has previously been suggested that much of this interval could be excluded due to arachnodactyly in patient 8493.\textsuperscript{26} However, the duplicated region in this patient extends just proximal of the Indian hedgehog gene (\textit{IHH}). Mutations of \textit{IHH} are now known to cause brachyactly type A.\textsuperscript{51} Therefore, duplication of the gene might result in the reverse phenotype, unusually long fingers, which would account for the arachnodactyly phenotype in this patient and would likely override any subtle abnormality due to the terminal 2q deletion. Three genes previously proposed as candidates for the brachymetaphalangism phenotype, \textit{GPC1}, \textit{HDLBP}, and \textit{STK25},\textsuperscript{10,12,15} are localised within the 3 Mb minimal region and remain candidates. Conversely, \textit{TWIST2}, which we considered a candidate gene on the basis of its proposed role in regulating osteoblast development,\textsuperscript{55} is not deleted in patient 10780 and can therefore be excluded. Brachymetaphalangism is partially penetrant and is present in approximately half of the patients deleted for this minimal region. Some patients show additional, more serious, skeletal abnormalities but, due to the small number characterised to date, it is unclear whether these represent pleiotropic effects of the same underlying gene.

\textbf{Additional clinical features}

Several other features of 2q37 deletions, such as congenital heart anomalies, eczema, autism, and epilepsy, have potentially greater morbidity and thus are clinically more significant. We therefore sought to make genotype–phenotype correlations and investigate whether these are discrete features of a contiguous gene deletion syndrome or pleiotropic effects of haplo-insufficiency for a single gene. Minimum intervals, ranging from 1.5 to 3.4 Mb, could be defined for each of these features. However, these phenotypes are less specific than brachymetaphalangism and, being more common in the general population, phenocopies will also exist. Thus, our assignment of critical intervals for these phenotypes, which is based on a small number of patients, should be regarded as preliminary and requires verification in a larger panel of patients. Some additional support for an autism susceptibility locus at 2q37.3 is already available from a small terminal deletion in a patient with isolated autism\textsuperscript{52} and from a weak suggestion of linkage in one genome scan.\textsuperscript{53} As presently defined, all minimum intervals share a 1.5 Mb region of overlap. Thus it remains to be determined whether the 2q37 deletion phenotype represents a contiguous gene deletion syndrome and it is possible that developmental abnormalities of several organ systems might result from haplo-insufficiency of a single gene.

\textbf{Genotype–phenotype correlations}

Amongst this panel of 2q37 deletion patients, we found no clear relationship between clinical features and the size or position of the monosomic region. Patients with very similar deletion breakpoints showed markedly different phenotypes, for example 10780 and 122, or 127 and 389. The same is true in translocation families, where individuals with identical 2q37 deletions have been reported with discordant phenotypes.\textsuperscript{14,15} This represents a significant challenge in predicting phenotype for this deletion, since the likely clinical outcome in a young proband cannot be determined from the deletion breakpoints. Variable expressivity is common in deletion syndromes and may be due to reduced penetrance of the haplo-insufficient genes, epigenetic factors, modifying effects of other genes, as recently proposed for \textit{VEGF} and cardiovascular defects in DiGeorge (del22q11) syndrome,\textsuperscript{55} or multigenic inheritance.\textsuperscript{56} An additional factor might be recessive phenotypes that are only uncovered in a minority of deletion patients.

\textbf{Mechanism of rearrangement}

Elucidating chromosomal breakpoints can provide clues as to the underlying mechanism of rearrangement. Several interstitial deletion syndromes, including Williams-Beuren (7q), Smith-Magenis (17p) and DiGeorge (22q), show clustered breakpoints and are commonly mediated by low copy repeat sequences and inversion polymorphisms.\textsuperscript{57–59} Clusters of olfactory receptor (OR) genes have also been implicated in recurrent rearrangements involving chromosomes 4p and 8p.\textsuperscript{60–62} OR-like genes have also been mapped to 2q37.3, but they do not co-localise with the deletion breakpoints in our patients. Furthermore, a recent study suggests that duplicated segments are not involved in mediating the majority of terminal deletions and translocations.\textsuperscript{63} Our data, which show a lack of identical breakpoint locations, support this finding.

\textbf{Summary}

This detailed analysis of 20 patients with 2q37.3 monosomy has, for the first time, allowed minimal deletion intervals to be defined for all the major phenotypes of the syndrome. However, there is striking phenotypic variability and it is clear that the size and extent of the deleted region cannot be used as a predictor of the likely phenotype in the patient. As increasing numbers of small deletions are detected by more widespread use of subtelomeric FISH, this presents a challenge for clinicians in trying to determine the likely prognosis for a young proband. Ultimately, therefore, the real challenge is to identify not only the gene(s) on 2q37 responsible for the phenotypes in these patients, but also the modifiers, be they genetic, epigenetic, or environmental, that contribute to the phenotypic variability between patients with similar breakpoints. Only then can we begin to give more precise prognostic information to the parents of a child newly-diagnosed with a 2q37.3 deletion.

\textbf{ACKNOWLEDGEMENTS}

We are indebted to Patricia Jacobs for forging this collaboration and to the families for their cooperation in this study. We thank Sue Price and Sheila Youings for additional clinical input and sample collection. John Armour for advice in setting up MAPH, the clinical cytogenetics staff in Salisbury, Leicester, Birmingham, and Manchester for their expertise, and Berendine van Zyl for additional mapping work. CE is a Doris Duke Distinguished Clinical Scientist.

\begin{center}
\textbf{An appendix showing clinical descriptions of previously unpublished patients is available online at http://jmg.bmjournals.com/supplemental/}
\end{center}
REFERENCES


