Further clinical and molecular delineation of the 15q24 microdeletion syndrome

Heather C Mefford,1,2 Jill A Rosenfeld,3 Natasha Shur,4 Anne M Slavotinek,5 Victoria A Cox,5 Raoul C Hennekam,6 Helen V Firth,7 Lionel Willatt,7 Patricia Wheeler,8 Eric M Morrow,9,10 Joseph Cook,1 Rachel Sullivan,11 Albert Oh,12 Marie T McDonald,13 Jonathan Zonana,14 Kory Keller,14 Mark C Hannibal,1,2 Susie Ball,15 Eric M Morrow,9,10 Joseph Cook,1 Rachel Sullivan,11 Albert Oh,12 Marie T McDonald,13 Jonathan Zonana,14 Kory Keller,14 Mark C Hannibal,1,2 Susie Ball,15 Jennifer Kussmann,16 Jerome Gorski,16 Susan Zelewski,17 Valerie Banks,18 Wendy Smith,18 Rosemarie Smith,18 Lindsay Paull,19 Kenneth N Rosenbaum,19 David J Amor,20 Joao Silva,21 Allen Lamb,3 Evan E Eichler22

ABSTRACT

Background Chromosome 15q24 microdeletion syndrome is a rare genomic disorder characterised by intellectual disability, growth retardation, unusual facial morphology and other anomalies. To date, 20 patients have been reported; 18 have had detailed breakpoint analysis.

Aim To further delineate the features of the 15q24 microdeletion syndrome, the clinical and molecular characterisation of fifteen patients with deletions in the 15q24 region was performed, nearly doubling the number of reported patients.

Methods Breakpoints were characterised using a custom, high-density array comparative hybridisation platform, and detailed phenotype information was collected for each patient.

Results Nine distinct deletions with different breakpoints ranging in size from 266 kb to 3.75 Mb were identified. The majority of breakpoints lie within segmental duplication (SD) blocks. Low sequence identity and large intervals of unique sequence between SD blocks likely contribute to the rarity of 15q24 deletions, which occur 8–10 times less frequently than 1q21 or 15q13 microdeletions in our series. Two small, atypical deletions were identified within the region that help delineate the critical region for the core phenotype in the 15q24 microdeletion syndrome.

Conclusion The molecular characterisation of these patients suggests that the core cognitive features of the 15q24 microdeletion syndrome, including developmental delays and severe speech problems, are largely due to deletion of genes in a 1.1–Mb critical region. However, genes just distal to the critical region also play an important role in cognition and in the development of characteristic facial features associated with 15q24 deletions. Clearly, deletions in the 15q24 region are variable in size and extent. Knowledge of the breakpoints and size of deletion combined with the natural history and medical problems of our patients provide insights that will inform management guidelines. Based on common phenotypic features, all patients with 15q24 microdeletions should receive a thorough neurodevelopmental evaluation, physical, occupational and speech therapies, and regular audiologic and ophthalmologic screening.

INTRODUCTION

The introduction of genome-wide approaches to identify deletions and duplications throughout the human genome has facilitated the discovery of numerous novel causes for intellectual disability (ID), autism, and other developmental disorders.1 2 In the clinical work-up of undiagnosed intellectual disability, array comparative genomic hybridisation (aCGH) has the ability to make a diagnosis in 10–30% of cases. Recently, an international consensus has been reached that chromosomal microarray should be a first-tier clinical diagnostic test for individuals with developmental disabilities or congenital anomalies.3 It has also been shown that in many patients abnormal chromosomal microarray testing influences medical care by precipitating specialty referral, diagnostic imaging, or specific laboratory testing.4 For patients with well known classical microdeletion syndromes such as 22q11.2 deletion syndrome, Prader-Willi syndrome and Williams syndrome, extensive data exist on clinical features observed in patients, and management guidelines have been developed. For newly discovered microdeletion/duplication syndromes, case reports and family support groups such as Unique, the Rare Chromosome Disorder Support Group (http://www.rarechromo.org), offer limited resources. Systematic characterisation of newly reported patients provides much needed information for clinicians and patients.

Recurrent microdeletion of chromosome 15q24 was described as a new genomic disorder after identification of patients with overlapping deletions, intellectual disability and similar clinical features.5 The 15q24 region is a complex genomic region with at least five segmental duplication (SD) blocks, also known as low copy repeats. These SD blocks, referred to as breakpoints A, B, C, D, and E, have varying amounts and degrees of sequence similarity to one another and can facilitate non-allelic homologous recombination (NAHR) at meiosis, leading to deletion of the intervening sequence. NAHR between different SD blocks can lead to deletions of various sizes and with different breakpoints. To date, 18 patients with 15q24 deletions and detailed breakpoint analysis have been described in the medical literature.6–15 A characteristic 15q24...
phenotype has been delineated with major features that include growth retardation, microcephaly, dysmorphic facial features, genital anomalies, and digital anomalies. Here we report clinical and molecular data for 15 patients with deletions in the 15q24 region, nearly doubling the number of reported patients. Among these, there are nine distinct deletions with different breakpoints, and two patients carry small, atypical deletions within the region that help delineate the critical region for core phenotypes in the 15q24 microdeletion syndrome. Finally, we offer recommendations for evaluation and management of patients with 15q24 deletion syndrome.

SUBJECTS AND METHODS
Study subjects
Fifteen individuals (10 males and five females) with a 15q24 deletion were included in this study. Fourteen cases were initially ascertained based on clinical aCGH or single nucleotide polymorphism microarray analysis. The deletion in patient 15 was initially identified using a custom bacterial artificial chromosome (BAC) array as previously described. Clinical information and facial photographs were obtained from the referring clinicians or families. Several of the patients met through the ‘Unique’ support group and shared information between themselves and their clinicians. This study was approved by institutional review boards at the University of Washington, Rhode Island Hospital, and Spokane.

Molecular studies
Refinement of the 15q24 deletion intervals in 13/15 cases for which DNA was available was conducted using a custom high density oligonucleotide array with 7450 probes in the 15q24 region (hg18, chr15: 69 000 000–77 000 000) with an average probe spacing of 1074 bp. When possible, parent-of-origin studies were performed using microsatellite markers within the deleted region.

RESULTS
Identification of novel 15q24 deletions
We report 15 patients with deletions in the 15q24 region (table 1, figure 1). Deletions range from 266 kb to 3.75 Mb in size. The majority of deletions have both breakpoints in one of the SD blocks in this region of chromosome 15. We have adopted the nomenclature put forth by El-Hattab and colleagues for the region (hg18, chr15: 69 000 000–77 000 000) with an average probe spacing of 1074 bp. When possible, parent-of-origin studies were performed using microsatellite markers within the deleted region.

Table 1 Frequency of 15q24 deletions with different breakpoints

<table>
<thead>
<tr>
<th>Breakpoints</th>
<th>Deletion size</th>
<th>N (this study)</th>
<th>N (literature)</th>
<th>Total N</th>
<th>Size, identity of flanking SDs *</th>
</tr>
</thead>
<tbody>
<tr>
<td>A–C</td>
<td>2.6 Mb</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>25 kb, &gt;98%</td>
</tr>
<tr>
<td>A–D</td>
<td>3.1 Mb</td>
<td>4</td>
<td>6</td>
<td>10</td>
<td>21 kb, 94%</td>
</tr>
<tr>
<td>B–D</td>
<td>1.7 Mb</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B–E</td>
<td>3.8 Mb</td>
<td>1</td>
<td>5</td>
<td>6</td>
<td>42 kb, &gt;95%</td>
</tr>
<tr>
<td>C–D</td>
<td>500 kb</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>27 kb, &gt;93%</td>
</tr>
<tr>
<td>Atypical</td>
<td>Varies</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>17</td>
<td>32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Based on NCBI Build 36/hg18, the size and percentage identity of the longest stretch of directly oriented, highly homologous sequence is listed.
Figure 1  High density array comparative genomic hybridisation (aCGH) data for the 15q24 region (NCBI Build 36, chr15:69,500,000—76,500,000 shown) for 13 new patients. Breakpoints are labelled as breakpoints A through E as described in the text. For each individual, deviations of probe log2 ratios from zero are depicted by vertical grey/black lines, with those exceeding a threshold of 1.5 standard deviations from the mean probe ratio coloured green and red to represent relative gains (duplications) and losses (deletions), respectively. Genes are depicted in blue below the aCGH data. The red bars represent the deletions for two patients (9 and 10) for which additional DNA was unavailable as well as previously published cases. The breakpoints are as described in clinical reports (patients 9 or 10) or within the publications noted.
Two patients had reported at least one seizure. Three patients were diagnosed with autism.

Of note, seven patients in this group had eye or vision abnormalities including strabismus (n = 3), blindness (n = 1), anisocoria (n = 2), and coloboma (n = 1). Four patients suffered from hearing loss, and six reported recurrent ear infections, ear effusions or ear tubes.

Cardiac evaluations were performed in seven patients. One patient had pulmonic stenosis, and another had a patent foramen ovale, patent ductus arteriosus, and peripheral pulmonic stenosis. Though genital abnormalities have been commonly reported in patients with 15q24 deletions, only 1/8 males with deletions involving region B–C had hypospadias. One female patient had an imperforate anus. A few of the patients had endocrine problems. One patient had delayed puberty and insulin dependent diabetes, and another patient had acanthosis nigricans. Two patients had obesity later in life.

Deletions involving only region C–D
Two patients were found to have small, previously unreported deletions between breakpoints C and D. As described above (Atypical deletions), patient 13 has a de novo 266 kb deletion that involves only five genes. Patient 14 has a de novo 500 kb deletion with breakpoints in the flanking SDs. Both of these patients have borderline to mild intellectual disability with IQ scores of 65 and 75, respectively. In addition, although patient 13 did not speak until age 4, both patients now have reasonable speech and communication skills. Interestingly, both patients have dysmorphic features similar to patients with deletions of the B–C region including large forehead, and both have short fifth fingers.

Patient 1: proximal deletion
Patient 1 has a 2.37 Mb deletion that begins proximal to BP-A and extends only 300 kb into the 1.1 Mb critical region. She presented with mild motor delays, an IQ of 47 at 15 years of age, dysmorphic features (figure 3), periventricular nodular heterotopia, and brachydactyly type E. The brachydactyly was not present in other family members, suggesting that one or more genes in the large, proximal deletion may be responsible.

Inheritance
In 11 cases, parents were available for analysis, and in each case the deletion was de novo. In four cases, we were unable to determine inheritance. In addition, we determined that the deletion originated on the maternal chromosome in three cases. We were unable to determine parent of origin for the remaining cases.

DISCUSSION
The 15q24 microdeletion syndrome is a newly characterised microdeletion syndrome. We performed an extensive clinical and molecular characterisation of 15 patients. In the majority of cases the microdeletion was initially identified by clinical aCGH performed because of multiple congenital anomalies and/or intellectual disability. Of these, eight patients were identified at Signature Genomic Laboratories between November 2007 and December 2009. During this period, 21820 patients were evaluated.
<table>
<thead>
<tr>
<th>Patient</th>
<th>Coord (Mb)</th>
<th>Breakpoints</th>
<th>Size (# genes)</th>
<th>Inheritance</th>
<th>Age at diagnosis</th>
<th>Growth</th>
<th>Motor development</th>
<th>Cognitive</th>
<th>Speech</th>
<th>Face</th>
<th>Eyes</th>
<th>Ears</th>
<th>Brain, neurologic exam</th>
<th>Psychiatric</th>
<th>Cardiac</th>
<th>GI/GU</th>
<th>Skeletal</th>
<th>Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.06—72.43</td>
<td>A-C</td>
<td>2.37 Mb (33 genes)</td>
<td>De novo (maternal)</td>
<td>29 years</td>
<td>Wt 90%</td>
<td>Mild delay</td>
<td>IQ 47 at 15 y</td>
<td>Significant expressive speech delay</td>
<td>Prominent philtrum, high palate, retrogнатia</td>
<td>Strabismus, R amblyopia, high hyperopia</td>
<td>Low-set, dysplastic</td>
<td>MRI —3 small lesions of periventricular nodular heterotopia, one seizure at 25 years, EEG with paroxysmal activity R central region</td>
<td>Impulsivity, ADHD</td>
<td>Normal echo</td>
<td>Normal abdominal, renal, pelvic US</td>
<td>Brachydactyly type E</td>
<td>Hypopigmented macules on abdomen and neck</td>
</tr>
<tr>
<td>2</td>
<td>70.73—73.33</td>
<td>A-C</td>
<td>2.60 Mb (45 genes)</td>
<td>De novo</td>
<td>7 years</td>
<td>Wt 50—75%</td>
<td>Receiving OT, PT</td>
<td>Mod to severe ID</td>
<td>2 words at 7 years</td>
<td>Broad mouth, broad nasal tip</td>
<td>Chorioretinal coloboma, microphthalmia</td>
<td>Normal</td>
<td>Normal</td>
<td>MRI at 34 m showed subtle closed lip schizencephaly or grey matter heterotopia in the frontal lobe</td>
<td>Autistic disorder; poor social awareness</td>
<td>Normal echo, ECG</td>
<td>Normal</td>
<td>Lumbar lordosis, pes planus</td>
</tr>
<tr>
<td>3</td>
<td>70.73—73.33</td>
<td>A-C</td>
<td>2.60 Mb (45 genes)</td>
<td>De novo</td>
<td>12 years</td>
<td>Wt 75%</td>
<td>Moderate delay</td>
<td>Moderate ID</td>
<td>20 words at 32 m</td>
<td>Narrow mandible, widely spaced eyes</td>
<td>Pseudo exotropia, L exotopia</td>
<td>PE tubes</td>
<td>MRI normal; hypotonic with brisk reflexes, normal strength, wide based gait</td>
<td>Autism, aggressive behaviours</td>
<td>PDA, PFO, PPS</td>
<td>Constipation</td>
<td>Lumbar lordosis, pes planus</td>
<td>Eczema, 3 CALs</td>
</tr>
<tr>
<td>4</td>
<td>70.73—73.33</td>
<td>A-C</td>
<td>2.60 Mb (45 genes)</td>
<td>De novo</td>
<td>30 months</td>
<td>Wt 75%</td>
<td>Moderate delay</td>
<td>Minimal eye contact</td>
<td>2 words at 7 years</td>
<td>Prominent nasal bridge, full nasal tip, wide mouth, upslanting palpebral fissures</td>
<td>Strabismus</td>
<td>Large fleshy earlobes, PE tubes</td>
<td>MRI normal; hypotonic with brisk reflexes, normal strength, wide based gait</td>
<td>Minimal eye contact</td>
<td>PDA, PFO, PPS</td>
<td>Constipation</td>
<td>Lumbar lordosis, pes planus</td>
<td>Eczema, 3 CALs</td>
</tr>
<tr>
<td>5</td>
<td>70.73—73.33</td>
<td>A-D</td>
<td>3.16 Mb (&gt;50 genes)</td>
<td>Unknown</td>
<td>33 months</td>
<td>Ofc &gt;95%</td>
<td>Moderate delay</td>
<td>Minimal eye contact</td>
<td>2 words at 7 years</td>
<td>Non-dysmorphic</td>
<td>Exotropia</td>
<td>Conductive hearing loss</td>
<td>MRI normal; hypotonic with brisk reflexes, normal strength, wide based gait</td>
<td>Minimal eye contact</td>
<td>PDA, PFO, PPS</td>
<td>Constipation</td>
<td>Lumbar lordosis, pes planus</td>
<td>Eczema, 3 CALs</td>
</tr>
<tr>
<td>6</td>
<td>70.73—73.89</td>
<td>A-D</td>
<td>3.16 Mb (&gt;50 genes)</td>
<td>De novo (maternal)</td>
<td>5 years</td>
<td>Ofc &gt;95%</td>
<td>Moderate delay</td>
<td>Global developmental delay</td>
<td>2 words at 7 years</td>
<td>Pierre Robin sequence, prominent forehead, small mouth</td>
<td>Legally blind, L 20/540, R 20/80</td>
<td>Moderate SNHL</td>
<td>MRI at 34 m showed subtle closed lip schizencephaly or grey matter heterotopia in the frontal lobe</td>
<td>Non-dysmorphic</td>
<td>PDA, PFO, PPS</td>
<td>Constipation</td>
<td>Lumbar lordosis, pes planus</td>
<td>Eczema, 3 CALs</td>
</tr>
<tr>
<td>7</td>
<td>70.73—73.89</td>
<td>A-D</td>
<td>3.16 Mb (&gt;50 genes)</td>
<td>De novo</td>
<td>30 months</td>
<td>Ofc &gt;95%</td>
<td>Moderate delay</td>
<td>Global developmental delay</td>
<td>2 words at 7 years</td>
<td>Non-dysmorphic</td>
<td>Anisocoria with L pupil &gt; R pupil</td>
<td>Prone to ear infections, PE tubes</td>
<td>MRI at 34 m showed subtle closed lip schizencephaly or grey matter heterotopia in the frontal lobe</td>
<td>Non-dysmorphic</td>
<td>PDA, PFO, PPS</td>
<td>Constipation</td>
<td>Lumbar lordosis, pes planus</td>
<td>Eczema, 3 CALs</td>
</tr>
<tr>
<td>8</td>
<td>70.73—73.89</td>
<td>A-D</td>
<td>3.16 Mb (&gt;50 genes)</td>
<td>De novo</td>
<td>30 months</td>
<td>Ofc &gt;95%</td>
<td>Moderate delay</td>
<td>Global developmental delay</td>
<td>2 words at 7 years</td>
<td>Non-dysmorphic</td>
<td>Hypotonia, normal brain MRI</td>
<td>Conductive hearing loss, PE tubes</td>
<td>MRI at 34 m showed subtle closed lip schizencephaly or grey matter heterotopia in the frontal lobe</td>
<td>Non-dysmorphic</td>
<td>PDA, PFO, PPS</td>
<td>Constipation</td>
<td>Lumbar lordosis, pes planus</td>
<td>Eczema, 3 CALs</td>
</tr>
</tbody>
</table>

Continued
<table>
<thead>
<tr>
<th>Patient</th>
<th>Coord (Mb)</th>
<th>Breakpoints</th>
<th>Size (# genes)</th>
<th>Inheritance</th>
<th>Age at diagnosis</th>
<th>Growth</th>
<th>Motor development</th>
<th>Cognitive</th>
<th>Speech</th>
<th>Face</th>
<th>Eyes</th>
<th>Ears</th>
<th>Brain, neurologic exam</th>
<th>Psychiatric</th>
<th>Cardiac</th>
<th>GI/GU</th>
<th>Skeletal</th>
<th>Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>70.73–73.74*</td>
<td>A–D</td>
<td>3.01 Mb (&gt;50 genes)</td>
<td>De novo</td>
<td>6 years</td>
<td>Wt 75%</td>
<td>Moderate delay; walked at 24 m</td>
<td>Mild to moderate ID</td>
<td>Non-verbal</td>
<td>High anterior hairline, full lips, epicanthi, flared medial eyebrows</td>
<td>Normal exam</td>
<td>Low-set ears, PE tubes</td>
<td>MRI brain normal; hypotonic</td>
<td>Autism</td>
<td>Normal ECG</td>
<td>Normal renal US, mild hypospadias</td>
<td>Thinner hypoplasia</td>
<td>Acanthosis nigricans</td>
</tr>
<tr>
<td>10</td>
<td>72.22–73.81*</td>
<td>B–D</td>
<td>1.59 Mb (36 genes)</td>
<td>Unknown</td>
<td>18 years</td>
<td>Wt 50–75%</td>
<td>Moderate delay; walked at 24 m</td>
<td>Mild delay; walked at 24 m</td>
<td>Speaks in sentences</td>
<td>Thick medial eyebrows, bilateral epicanthi, retracted thumb</td>
<td>Normal vision</td>
<td>Thick anteverted lobes, R profound and L progressive SNHL</td>
<td>MRI normal; mild dilatation of lateral ventricles</td>
<td>Food seeking behaviour</td>
<td>Normal ECG</td>
<td>Normal renal US, mild hypospadias</td>
<td>Mild kyphoscoliosis, camptodactyly of 4th fingers, pronounced 5th finger brachydactyly with bilateral shortening of 5th middle phalanges, absent epiphyses, broad great toes with I halluc valgus</td>
<td>2 CALs</td>
</tr>
<tr>
<td>11†</td>
<td>72.20–74.04</td>
<td>B-unique</td>
<td>1.84 Mb (40 genes)</td>
<td>De novo (maternal)</td>
<td>6 years</td>
<td>Wt &lt;95%</td>
<td>Moderate delay; walked at 24 m</td>
<td>Moderate global developmental delay</td>
<td>&lt;12 words at 6 years</td>
<td>Thick medial eyebrows, bilateral epicanthi, rotoglosus</td>
<td>Cup-shaped ears, PE tubes</td>
<td>MRI normal; mild dilatation of lateral ventricles</td>
<td>MRI normal; hypotonic</td>
<td>Obsessive compulsive behaviours</td>
<td>Gastro-oesophageal reflux disease</td>
<td>Small fingers, pes planus</td>
<td>Acanthosis nigricans</td>
<td>2 CALs</td>
</tr>
<tr>
<td>12</td>
<td>72.20–75.95</td>
<td>B–E</td>
<td>3.75 Mb (&gt;50 genes)</td>
<td>De novo</td>
<td>30 months</td>
<td>Wt &lt;3%</td>
<td>Mild delay; walked at 24 m</td>
<td>Moderate global developmental delay</td>
<td>Some sounds, signs</td>
<td>Bisphosphonate, broad forehead, flared medial eyebrows</td>
<td>Moderate HL in one twin</td>
<td>MRI normal; mild dilatation of lateral ventricles</td>
<td>Normal exam aside from delays</td>
<td>First words at 4 years, reasonable speech after</td>
<td>Normal exam</td>
<td>Gastro-oesophageal reflex disease</td>
<td>Mild kyphoscoliosis, camptodactyly of 4th fingers, pronounced 5th finger brachydactyly with bilateral shortening of 5th middle phalanges, absent epiphyses, broad great toes with I halluc valgus</td>
<td>2 CALs</td>
</tr>
<tr>
<td>13</td>
<td>73.32–73.59</td>
<td>Atypical</td>
<td>266 kb (5 genes)</td>
<td>De novo</td>
<td>20 years</td>
<td>Wt &gt;95%</td>
<td>Mild delay; walked at 24 m</td>
<td>Mild delay</td>
<td>First words at 1 year</td>
<td>Round face, flared medial eyebrows</td>
<td>High anterior hairline, full lips, epicanthi</td>
<td>Moderate HL in one twin</td>
<td>MRI normal; mild dilatation of lateral ventricles</td>
<td>MRI—encephalophy, mild dilatation of lateral ventricles, hypoplastic CC; normal EEG</td>
<td>Normal exam aside from delays</td>
<td>Gastro-oesophageal reflex disease</td>
<td>Mild kyphoscoliosis, camptodactyly of 4th fingers, pronounced 5th finger brachydactyly with bilateral shortening of 5th middle phalanges, absent epiphyses, broad great toes with I halluc valgus</td>
<td>2 CALs</td>
</tr>
<tr>
<td>14</td>
<td>73.38–73.88</td>
<td>C–D</td>
<td>500 kb (11 genes)</td>
<td>De novo</td>
<td>9.5 years</td>
<td>Wt 7%</td>
<td>Atypical</td>
<td>Mild delay; walked at 24 m</td>
<td>First words at 6 years</td>
<td>Telecanthus, bilateral epicanthi</td>
<td>Normal vision</td>
<td>MRI normal; hypotonic</td>
<td>MRI—encephalophy, mild dilatation of lateral ventricles</td>
<td>Normal exam aside from delays</td>
<td>Normal exam aside from delays</td>
<td>Gastro-oesophageal reflex disease</td>
<td>Mild kyphoscoliosis, camptodactyly of 4th fingers, pronounced 5th finger brachydactyly with bilateral shortening of 5th middle phalanges, absent epiphyses, broad great toes with I halluc valgus</td>
<td>2 CALs</td>
</tr>
<tr>
<td>15</td>
<td>75.12–75.60</td>
<td>Atypical</td>
<td>480 kb (4 genes)</td>
<td>Unknown</td>
<td>24 years</td>
<td>Wt 7%</td>
<td>Atypical</td>
<td>Moderate delay; walked at 24 m</td>
<td>Normal exam</td>
<td>Low anterior hairline, broad nasal tip, smooth philtrum, narrow palpebral fissures, bilateral epicanthi, flat zygomatic arches</td>
<td>Anisocoria, normal vision</td>
<td>MRI normal; mild dilatation of lateral ventricles</td>
<td>MRI normal; mild dilatation of lateral ventricles</td>
<td>Obsessive compulsive behaviours</td>
<td>Anisocoria, normal vision</td>
<td>Low anterior hairline, broad nasal tip, smooth philtrum, narrow palpebral fissures, bilateral epicanthi, flat zygomatic arches</td>
<td>2 CALs</td>
<td></td>
</tr>
</tbody>
</table>

*From clinical report—DNA unavailable for high-density array.
†One of monozygotic twins who both have the same 15q24 deletion and share the majority of clinical features listed.
ADHD, attention deficit hyperactivity disorder; CAL, café-au-lait macule; CC, corpus callosum; EEG, electroencephalogram; GI, gastrointestinal; GU, genitourinary; Ht, height; ID, intellectual disability; L, left; OFC, occipitofrontal circumference; OT, occupational therapy; PDA, patent ductus arteriosus; PE, pressure equalisation; PFO, patent foramen ovale; PPS, peripheral pulmonic stenosis; PT, physical therapy; R, right; SNHL, sensorineural hearing loss; US, ultrasound; Wt, weight.
This suggests that, despite a genomic architecture that predicts recurrent rearrangement, deletions in the region account for only 3–4/10 000 cases that are sent for clinical aCGH studies. In comparison, the rate at which recurrent deletions of 15q13 or 1q21 were identified during the same time period was eightfold to 10-fold higher. The larger interval of unique sequence between SD blocks (2.6–3.8 Mb compared to 1.3–1.5 Mb for 1q21 and 15q13) and the lower sequence identity between SD blocks in direct orientation likely contribute to the lower frequency of 15q24 deletion events.

The 15q24 region contains several clusters of segmental duplications that are thought to facilitate non-allelic homologous recombination resulting in recurrent deletion. The deletions in our series of patients, which ranged from 266 kb to 3.75 Mb, support this assertion. Eleven of the 15 deletions had both breakpoints in segmental duplications flanking the deleted region. Three patients had deletions with both breakpoints in unique sequence. One deletion had one breakpoint in unique sequence and the other in a segmental duplication. The most common deletions in our series, found in four patients each, were the 2.6 Mb deletion between breakpoints A and C and the 3.1 Mb deletion between breakpoints A and D (table 1, figure 1).

Evaluation of previously reported deletions suggest that the deletion between breakpoints A and D occurs most frequently and accounts for about one third of deletions in the region (10/32 reported; table 1). Deletions between A and C and between B and E occur with approximately equal frequency, accounting for 15–20% of deletions. The breakpoint combinations are consistent with an NAHR mechanism between directly oriented segmental duplications. Breakpoints A and C share a \( \sim 25 \) kb directly oriented sequence block with \( >98\% \) sequence identity. Similarly, breakpoints A and D share a \( \sim 21 \) kb directly oriented sequence block with \( >94\% \) identity. Breakpoints B and E share a 42 kb stretch of \( >95\% \) identity, and C and D share a 27 kb stretch of \( >93\% \) identity. Conversely, there are no large stretches of highly homologous and directly oriented repeats between blocks A and B, A and E, B and C, or B and D, suggesting the deletions are much less likely to occur via NAHR between these blocks.

Our analysis of the clinical features in our series of patients with 15q24 deletions is largely consistent with previous reports. Common features, present in more than 50% of the patients and that should prompt consideration of this diagnosis, include dysmorphic facial features, including...
a prominent forehead, high anterior hairline, prominent nasal bridge, and microphtalmia. Other features include deep-set eyes, strabismus, or other ocular anomalies. Short metacarpals and proximally placed thumbs may also be a clue to diagnosis. A history of failure to thrive and developmental delay is typical. Severe speech delay or absence of speech is a consistent feature in patients with typical deletions. Diaphragmatic hernia has been reported in some patients with the deletion, but no patients in our series reported this. Similarly, we found only 1/8 males with hypospadias.

It is important to note that we identified nine distinct deletions with different breakpoints in 15 patients. In fact, the deletions in patients 1–5 have no overlap with the deletions in patients 13, 14, and 15. Combining the deletions in our series with those in the literature, 28% of reported deletions are ‘private’ mutations seen in a single patient. The vast majority of reported deletions include the region between breakpoints B and C and most also include the C–D region. We identified two patients with small, atypical deletions that lie within the region between breakpoints C and D. Notably, both of these patients had only mild or borderline ID, with IQ scores of 65 and 75. Unlike the majority of patients with larger deletions, both have developed reasonable speech. This suggests that the severity of the core cognitive deficits of the 15q24 microdeletion syndrome are due to deletion of one or more genes with the 1.1 Mb critical region between breakpoints B and C containing 24 RefSeq genes. However, given the delays and dysmorphic features in our two atypical cases, some or all of the eight genes between C and D, and indeed the five genes deleted in case 15, must be important for normal development and behaviour. Furthermore, review of photographs for patients with deletions that do not include the region between C and D (patients 13 and 14 from this study, patient 5 in Andrieux et al and McInnes et al) suggests that their facial features are slightly less striking. This would suggest that some of the genes in the C–D region are important for the syndromic facies described for 15q24 deletions. On the other hand, we found that patients with deletions including the BP B–C region were more likely to have eye abnormalities. In addition, cardiac features and seizures were noted in several patients with deletions including the B–C region, but not in patients 1, 15 or 14, whose deletions do not include the critical region.

Based on common features of our patients, we feel that certain management recommendations can be made. Since there is a high incidence of eye and ear anomalies, ophthalmological evaluation and audiology evaluation should be routine referrals. Additional screening for genitourinary and cardiac anomalies should be considered. A formal developmental evaluation and careful screening for autism and related entities could help diagnose these potential problems early and initiate targeted services. Families should be counselled to observe closely for seizures, since there appears to be an increased risk in these patients. The families of our patients have reported that support group information is especially helpful to them.

In conclusion, the molecular and clinical characterisation of 15 individuals with the 15q24 microdeletion syndrome further defines the phenotypic features associated with this novel syndrome and provides further insight into the critical region for core features of this syndrome.

Author affiliations
1Department of Pediatrics, Division of Genetic Medicine, University of Washington, Seattle, Washington, USA
2Seattle Children’s Hospital, Seattle, Washington, USA
3Signature Genomics, Spokane, Washington, USA
4Department of Pediatrics, Division of Genetics, Rhode Island Hospital, Providence, Rhode Island, USA
5Department of Pediatrics, University of California, San Francisco, San Francisco, California, USA
6Department of Pediatrics, AMC, University of Amsterdam, Amsterdam, The Netherlands
7Department of Medical Genetics, Cambridge University Hospitals Foundation Trust, Cambridge, UK
8Division of Genetics, Nemours Children’s Clinic, Orlando, Florida, USA
9Department of Molecular Biology, Cellular Biology and Biochemistry, Brown University, Rhode Island, USA
10Laboratory for Molecular Medicine, Brown University, Rhode Island, USA
11Division of Plastic Surgery, Rhode Island Hospital, Rhode Island, Providence, USA
12Children’s National Medical Center, Department of Plastic and Reconstructive Surgery, Washington DC, USA
13Division of Medical Genetics, Department of Pediatrics, Duke University Medical Center, Durham, North Carolina, USA
14Oregon Health & Sciences University, Portland, Oregon, USA
15Children’s Village, Yakima, Washington, USA
16University of Missouri Healthcare System, Columbia, Missouri, USA
17Altru Health System, Grand Forks, North Dakota, USA
18Maine Medical Partners, Portland, Maine, USA
19Department of Genetics and Metabolism, Children’s National Medical Center, Washington DC, USA
20Drexel Children’s Research Institute, Royal Children’s Hospital, Victoria, Australia
21Unidade de Genética Médica, Centro de Genética Médica Jacinto Magalhães, Instituto Nacional Saúde Dr Ricardo Jorge, Porto, Portugal
22Department of Genome Sciences and Howard Hughes Medical Institute, University of Washington, Seattle, Washington, USA

Acknowledgements We thank all the patients and families who have participated in this study, with special thanks to Jason and Marissa Campbell, the Sjostrods, Samantha and Jerry Torres, and Carol Smith.

Funding This work was supported by a Burroughs Wellcome Fund Career Award for Medical Scientists, grant number 1007607 (HCM); by the Howard Hughes Medical Institute (EEE); and by the NIH Cambrige Biomedical Research Centre (HF).

Competing interests JAR and AL are employees of Signature Genomics, a subsidiary of PerkinElmer.

Ethics approval University of Washington, Rhode Island Hospital, Spokane.

Contributors Wrote the manuscript: HCM, JAR, NS; edited the manuscript: AL, EEE;
Contributors (certain roles): VF, JS, MS, DH, LS, AS, RS, LP, KNR, SJA, JS.

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement Custom array information is available upon request.

REFERENCES


