Delineating the phenotypic spectrum of Bainbridge-Ropers syndrome: Twelve new patients with *de novo*, heterozygous, loss-of-function mutations in *ASXL3* and review of published literature

M. Balasubramanian\(^1\)\(^*,\) J. Willoughby\(^2\)\(^*,\) A. E. Fry\(^3\)\(^,\)\(^4\) A. Weber\(^5\)\(^,\) H. V. Firth\(^6\)\(^,\) C. Deshpande\(^7\)\(^,\) J. N. Berg\(^8\)\(^,\) K. Chandler\(^9\)\(^,\) K. A. Metcalfe\(^9\)\(^,\)\(^10\) W. Lam\(^11\)\(^,\) D. Pilz\(^12\)\(^,\) S. Tomkins\(^13\)\(^,\) DDD Study\(^14\)

\(^*\)Joint first authors

**Short Title:** Bainbridge-Ropers syndrome: twelve new cases and literature review

\(^1\)Sheffield Clinical Genetics Service, Sheffield Children’s NHS Foundation Trust, Sheffield, UK

\(^2\)Sheffield Diagnostic Genetics Service, Sheffield Children’s NHS Foundation Trust, Sheffield, UK

\(^3\)Institute of Medical Genetics, University Hospital of Wales, Cardiff, UK

\(^4\)Division of Cancer and Genetics, School of Medicine, Cardiff University, Cardiff, UK

\(^5\)Clinical Genetics Department, Alder Hey Children’s NHS Foundation Trust, Liverpool, UK

\(^6\)East Anglian Medical Genetics Service, Clinical Genetics, Addenbrooke’s Hospital, Cambridge, UK

\(^7\)Department of Clinical Genetics, Guy’s & St. Thomas’ Hospital NHS Trust, London, UK

\(^8\)Ninewells Hospital and Medical School, University of Dundee, UK

\(^9\)Manchester Centre for Genomic Medicine, Saint Mary’s Hospital, Manchester, UK

\(^10\)Division of Evolution and Genomic sciences, Faculty of Biology, Medicine and Health, University of Manchester, Manchester, UK

\(^11\)Clinical Genetics Unit, Western General Hospital, Edinburgh, UK

\(^12\)West of Scotland Genetics Service, Glasgow, UK

\(^13\)Clinical Genetics Service, University Hospitals of Bristol NHS Foundation Trust, Bristol, UK

\(^14\)DDD Study, Wellcome Trust Sanger Institute, Hinxton, Cambridge, UK

*Author to whom correspondence should be addressed*
ABSTRACT

Background: Bainbridge–Ropers syndrome (BRPS) is a recently described developmental disorder caused by de novo truncating mutations in the Additional sex combs-like 3 (ASXL3) gene. To date there have been fewer than ten reported patients.

Objectives: Here we delineate the BRPS phenotype further by describing a series of twelve previously unreported patients identified by the Deciphering Developmental Disorders (DDD) study.

Methods: Trio-based exome sequencing was performed on all twelve patients included in this study which found a de novo truncating mutation in ASXL3. Detailed phenotypic information and patient images were collected and summarised as part of this study.

Results: By obtaining genotype: phenotype data, we have been able to demonstrate a second mutations cluster region within ASXL3. This report expands the phenotype of older patients with BRPS; common emerging features include severe intellectual disability (12/12), poor/absent speech (12/12), autistic traits (9/12), distinct face (arched eyebrows, prominent
forehead, high-arched palate, hypertelorism and down-slanted palpebral fissures), (9/12), hypotonia (12/12) and significant feeding difficulties (12) when young.

**Discussion:** Similarities in the patients reported previously in comparison to this cohort included their distinctive cranio-facial features, feeding problems, absent/limited speech, and intellectual disability. Shared behavioural phenotypes include autistic traits, hand-flapping, rocking, aggressive behaviour, and sleep disturbance.

**Conclusions:** This series expands the phenotypic spectrum of this severe disorder and highlights its surprisingly high frequency. With the advent of advanced genomic screening, we are likely to identify more variants in this gene presenting with a variable phenotype which this study will explore.

**INTRODUCTION**

Large scale whole exome sequencing projects such as the Deciphering Developmental Disorders (DDD) Project have led to the discovery of a number of new genes underlying developmental disorders [1,2]. A reverse-genetics approach has proven particularly important for the discovery of disorders like Bainbridge–Ropers syndrome (BRPS), whose main clinical features are non-specific, especially when looked at in isolation or with a small number of patients. *De novo* mutation status is the first clue to potential pathogenicity of a given variant and such mutations are known to constitute a significant proportion of the underlying causes of moderate and severe intellectual disability (ID) [3].

*ASXL1, ASXL2 and ASXL3* are human homologs of the Drosophila additional sex combs (asx) gene that encode putative polycomb proteins and are likely to act as histone
methyltransferases in complexes with other proteins [4]. Polycomb group proteins are implicated in embryogenesis and carcinogenesis through transcriptional regulation of target genes; the ASXL1 gene is thought to be one of the most frequently mutated genes in malignant myeloid diseases; ASXL is a scaffold protein interacting with methyltransferases and additional proteins of the epigenetic machinery [5,6]. Truncating mutations in ASXL1 have been reported in association with Bohring-Opitz syndrome (BOS) which has phenotypic overlap with BRPS [7]. More recently, truncating mutations in ASXL2 were reported in association with a newly recognisable clinical phenotype [8].

Srivastava et al., 2016 showed that ASXL3 interacts with BAP1, a hydrolase that removes mono-ubiquitin from histone H2A lysine 119 (H2AK119Ub1) as a component of the Polycomb repressive deubiquitination (PR-DUB) complex [9]. The authors observed a significant increase in H2AK119Ub1 in ASXL3 patient fibroblasts, highlighting an important functional role for ASXL3 in PR-DUB mediated deubiquitination. Transcriptome analysis revealed >500 genes differentially expressed in ASXL3 patient fibroblasts relative to controls, and these genes were enriched for those involved with molecular processes impacting transcriptional regulation, development and proliferation.

ASXL3 is expressed in similar tissues to ASXL1 including brain, spinal cord, kidney, liver, and bone marrow, but at a lower level [10]. The high correlation of expression patterns between ASXL1 and ASXL3 may account for some of the shared phenotypic features.

Heterozygous, de novo loss-of-function mutations in ASXL3, underlying the Bainbridge–Ropers syndrome (BRPS: OMIM #615485) have been described in 9 individuals to date [9,11-13]. The major phenotypic features described in the majority of patients so far include
failure to thrive, global developmental delay, feeding problems, hypotonia, dysmorphic features, profound speech delay and intellectual disability. Here we present genetic and phenotypic information on 12 previously unreported individuals with de novo truncating mutations in ASXL3, all of which were detected via the trio exome sequencing carried out by the DDD Project. Additional clinical features of BRPS are likely to emerge with identification of additional patients through such large scale exome sequencing projects as described here.

METHODS

EXOME SEQUENCING

In all twelve individuals identified via the DDD study, trio-based exome sequencing was performed on the affected individual and their parents, as previously described by Wright et al., 2014. Each affected individual has also had a high-resolution analysis for copy number abnormalities using array-based comparative genomic hybridization (aCGH). Putative de novo mutations were identified from exome data using DeNovoGear software as described by Ramu et al., 2013 and were validated using targeted Sanger sequencing [14,15].

All recruited patients had the following de novo heterozygous pathogenic mutations identified which confirmed the diagnosis of Bainbridge-Ropers syndrome (OMIM:615485):

Patient 1: c.4330C>T, p.(Arg1444*)

Patient 2: c.1201del, p.(Ala401GlnfsTer8)

Patient 3: c.1074T>A, p.(Tyr358*)

Patient 4: c.4144C>T, p.(Gln1382*)

Patient 5: c.1783C>T, p.(Gln595*)
Patient 6: c.3355dup, p.(His1119Profs*7)
Patient 7: c.1082dup, p.(Leu362AlafsTer23)
Patient 8: c.3635T>G, p.(Leu1212*)
Patient 9: c.3127_3128dup, p.(Gly1045Valfs*99)
Patient 10: c.3178dup, p.(Arg1060Profs*50)
Patient 11: c.1484insTGAA, p.(Asp497*)
Patient 12: c.1491dup, p.(Asn498*)

Mutation nomenclature is according to HGVS recommendations (http://varnomen.hgvs.org/), and is based on reference transcript NM_030632.2.

PATIENT ASCERTAINMENT

All twelve individuals were recruited via UK NHS Regional Genetics Services onto the Deciphering Developmental Disorders (DDD) Project (www.ddduk.org). As part of that study, patient and parental samples receive array CGH and exome sequencing analysis and findings of potential clinical significance are reported back to recruiting clinical geneticists. Any significant findings are usually validated by an accredited UK NHS diagnostic genetics laboratory before being reported to patients and their families; mutations described in this paper have been validated as such. Patient phenotype information was provided to the authors via Clinical Geneticists from several UK NHS genetics services. See Table 1 for a summary of the clinical and molecular findings.

RESULTS

ASXL3 MUTATIONS
Previously reported truncating ASXL3 mutations cluster mainly within the 5’ end of exon 11 between codons 404 and 659. This region lies in-between the N-terminal protein scaffolding functional domains of the gene and the C-terminal chromatin/DNA-targeting functional domain. Srivastava et al., 2016 reported two mutations significantly 3’ to this main cluster region, at codons 1122 and 1444 [9]. One of the patients (Patient 1) within our cohort carries the same c.4330C>T p.(Arg1444*) mutation as the patient reported by Srivastava et al, 2016 suggesting it as a possible recurrent mutation.

Among our cohort, 5/12 (Patients 2, 3, 7, 11, 12) of the mutations could be described as occurring within the originally reported mutation cluster region, 1/12 (Patient 5); c.1783C>T, p.(Gln595*), maps more 3’, and the remaining 6 (Patients 1, 4, 6, 8, 9, 10) lie further downstream within the more 3’ region, reported by Srivastava et al, 2016, which could be considered as a distinct mutation cluster region, extending between codons 1045 and 1444 [9]. All these mutations are publicly available on www.ddduk.org.

**PATIENT PHENOTYPES**

**Antenatal history and birth:** Polyhydramnios and concerns regarding poor growth were noted in 1/12 but otherwise unremarkable. For 9/12 patients, a caesarean section was performed, mostly due to breech presentation. All 12 patients had an average birth weight and apart from 4/12 patients who were admitted to the Neonatal unit for respiratory difficulties/apnoea, the remainder neonatal period was uneventful.
Feeding problems: Consistent with previous reports, 9/12 patients were reported to have significant feeding problems, often including gastro-oesophageal reflux and requiring intervention in the form of nasogastric tube feeding, fundoplication. The majority were described as having failure to gain weight with poor appetite.

Growth: Patients reported here had consistent poor growth with weight and height below the 0.4th centile and relative microcephaly (7/12). This is in keeping with previously reported literature.

Craniofacial features: 9/12 have a high-arched palate, distinctive facial dysmorphism as described below (Figure 1).

Dysmorphic features: 10/12 had down-slanting palpebral fissures and 2 had up-slanting palpebral fissures; both have previously been reported but down-slanting seems to be more common. A long, tubular nose with a prominent nasal bridge is apparent in most. Most of the individuals have a broad nasal tip with low columella. The mouth is wide with full (everted) lower lip. Hypertelorism, a narrow head shape with prominent forehead, ‘pencilled’ and/or high-arched eyebrows and crowded teeth were also common features.

Other significant features: 12/12 had significant hypotonia, 7/12 had strabismus of varying severity. 3 patients had seizures, previously reported in 2 other ASXL3 patients. Patient 2 had scoliosis requiring surgery. 3 patients had arachnodactyly, not previously reported in any ASXL3 patients. 3/12 appears to have a Marfanoid habitus with arachnodactyly, tall stature, pes planus and scoliosis.
**Intellectual Disability:** The level of intellectual disability ranged from moderate to profound but more likely at the severe end of the spectrum. All patients had ID of varying degree; generally severe. Most were very delayed in walking unassisted and 2 remained entirely non-ambulant. 9/12 patients were entirely non-verbal, including Patient 2 at 22 years of age. 9/12 patients had either formally diagnosed autism or autism spectrum disorder, or were described as having autistic features. 3 patients exhibited hand-flapping, rocking. All the patients were in a special needs school requiring significant help.

**Relevant negative findings:** Seizures does not appear to be a major feature, seen in only 3/12 patients and generally well-controlled absence seizures; MRI-brain imaging only showed non-specific features with white matter changes (3/12) and vermis hypoplasia (1/12) which is relevant given the significance of intellectual disability in this cohort of patients.

**DISCUSSION**

The recently described Bainbridge–Ropers syndrome (BRS; OMIM # 615485), associated with *de novo* truncating mutations in the *Additional sex combs-like 3 (ASXL3)* gene (OMIM * 615115), shows phenotypic overlap with Bohring-Opitz syndrome, which is associated with *de novo* truncating mutations in *ASXL1* (OMIM * 612990). Bohring-Opitz syndrome (BOS; OMIM # 605039) is characterised by distinct craniofacial features and posture, severe intellectual disability, feeding problems, small size at birth, and failure to thrive.

Bainbridge *et al.* 2013 reported a series of four unrelated probands with *de novo*, heterozygous, truncating mutations in *ASXL3*, sharing similar phenotypes, including severe feeding difficulties, failure to thrive, and neurologic abnormalities with significant
developmental delay [11]. More recently, truncating mutations in ASXL2 were reported as being associated with a newly recognisable syndrome with overlapping features to BOS and BRPS [8]. In this report, the authors described six unrelated patients with de novo truncating mutations in ASXL2 with shared clinical features including intellectual disability, macrocephaly, distinct facies, facial nevi, feeding difficulties and hypotonia. Comparison of patients reported in this with BRPS shows the facial dysmorphism to be more similar to BOS with macrocephaly, arched eyebrows, synophrys and facial nevi rather than with BRPS. Other distinguishing features included macrocephaly, congenital heart disease, structural brain malformations and seizures in these patients, which differs to the BRPS cohort. However, there are emerging similarities within this group of conditions, including hypotonia, feeding difficulties and ID, which will become more apparent as more patients are reported with ASXL2 mutations.

To date there have been fewer than ten reported patients with de novo truncating ASXL3 mutations. Emerging similarities include, distinctive cranio-facial features with arched eyebrows, prominent forehead, high-arched palate, hypertelorism with down-slanted palpebral fissures; significant feeding difficulties needing support; profound/ severe intellectual disability; emerging behavioural phenotype consisting of autistic traits, hand-flapping, rocking, aggressive behaviour, sleep issues with absent/ poor speech. Table 1 provides a comprehensive summary of reported features in this cohort: predominant features in the phenotype are normal pregnancy, higher incidence of caesarean section due to breech presentation, relative microcephaly, significant feeding difficulties, facial dysmorphism, high-arched palate, strabismus, hypotonia, skeletal features including a Marfanoid habitus (especially in the older patients), severe intellectual disability with poor/ absent speech, autistic traits, need for special education. Seizures, structural malformations of internal
organisms including the brain, kidneys do not appear to be a predominant part of their phenotype. However, this is likely to be revised/expanded as more patients are described with BRPS.

There is a wide age range (4-22 years), this being the first report of older patients with BRPS. The older patients in this cohort all have moderate to severe ID, autistic features, attended a special needs school and are in assisted living. Seizures are a component but not a predominant part of their phenotype and they do not appear to have any major structural associations with this diagnosis as they have grown older. The behavioural phenotype appears to be in keeping with other severe developmental disorders with absent/poor speech, periods of agitation, frustration and poor sleep.

Though Bainbridge-Ropers syndrome (BRPS) is likely to remain a challenging syndrome to recognise clinically, however this cohort of patients has enabled further delineation and expansion of the phenotype. Results of analysis of the first several thousand patient trios within the DDD Project suggests that de novo ASXL3 mutations are among the more common underlying causes of disease within the DDD cohort (at time of writing, ASXL3 ranks number 12 out of the top 20 genes in which a pathogenic de novo mutation has been found), and therefore it is expected that there will be many more BRPS patients diagnosed in the near future, further defining the associated clinical spectrum.

Our cohort has also firmly established a second, 3’ mutational cluster region within ASXL3 which may be of significance to disease mechanism. In regards to this, an ASXL3 mRNA transcript carrying the c.1448dupT truncating mutation has previously been shown to be prone to nonsense-mediated decay, with resultant reduction in expression of ASXL3 [6].
Consistent with previous reports and consistent with this disease mechanism, the cohort of patients described here do not show a correlation between phenotypic features or severity and mutation position. It has previously been noted that several truncating mutations in \textit{ASXL3} are described in databases composed of sequence variants from phenotypically normal individuals (see Figure 2). To date there are 4 such mutations within the ExAC dataset, each identified within only one individual within the dataset, and they occur both 5’ to the original 5’ mutational cluster region (MCR) and 3’ to the new 3’ cluster region, and also in between the two cluster regions. The explanation for these mutations is as yet uncertain.

We have also been able to collect phenotypic data from several patients with previously unreported missense variants in \textit{ASXL3} (including p.Ser86Ala, p.Lys1026Asn, p.Arg933Trp and p.Ser720Cys). However, in each case the variants were inherited from clinically unaffected parents and the patients had very dissimilar presentations in comparison to the clinical presentation associated with \textit{ASXL3} loss-of-function mutations. Without further investigation it cannot be ruled out that these variants are of clinical significance, however it is unlikely that they are the sole cause of the phenotypes observed in these patients and it is possible that they represent rare polymorphisms. In support of this, all of these variants are found, albeit at low frequency, within healthy control populations (Exome Aggregation Consortium, Cambridge, MA, URL: http://exac.broadinstitute.org).

\textit{Ropers et al.}, 2015 previously highlighted the presence of truncating mutations in \textit{ASXL3} and several other dominant genes for intellectual disability or related disorders, within healthy control populations, suggesting the possibility of incomplete penetrance for truncating
mutations within these genes [14]. This included \textit{ASXL1}, for which 56 such mutations were found within the ExAC dataset.

Whilst it cannot be entirely ruled out that truncating \textit{ASXL3} mutations exhibit incomplete penetrance, the number of such mutations (four) found within the ExAC data is still relatively small compared to \textit{ASXL1} and the other genes examined, and the list of reported patients with \textit{ASXL3} truncating mutations that have a Bainbridge-Ropers syndrome consistent phenotype is growing.

Therefore, it seems reasonable that all four of these \textit{ASXL3} mutations may be accounted for by the various other explanations that Ropers put forward, for example, two of the mutations occur at the extreme 3’ end of the gene, and may therefore escape nonsense mediated decay (NMD), retaining protein activity. Bainbridge \textit{et al.}, 2013 suggested that mutations may arise post-zygotically or during later embryogenesis and thus the phenotypic variability or incomplete penetrance may be explained by mosaicism [11]. With the increasingly wider access of high read-depth exome sequencing for genetic diagnosis of children with developmental disorders it seems likely that this question will eventually be answered as more data emerges.

\textbf{CONCLUSIONS}

In this series, we report 12 patients with \textit{ASXL3} loss-of-function \textit{de novo} variant and expand the phenotype of Bainbridge-Ropers syndrome. New specific associated clinical features have become apparent, such as hypotonia, Marfanoid habitus, and arachnodactyly. This
cohort is consistent with previously reported patients with regards to the facial features and also confirms pertinent negative features such as lack of significant findings on brain imaging, and lack of seizures. This research further reiterates the power of whole exome studies in conjunction with a detailed clinical phenotype in providing an explanation for our patient’s difficulties and a unifying diagnosis for their concerns.

STATEMENTS:

A. Funding:

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B. Acknowledgements:

We would like to thank all these families for consenting to publication.

C. Contributorship Statement:
All authors recruited their respective patients to the DDD study and provided data regarding their patients; DDD study provided trio exome sequencing data. MB and JB planned the study; recruited Patient 1 to DDD; wrote manuscript; all authors reviewed and contributed to the manuscript.

D. Competing Interest: None to declare for all authors.

FIGURE AND TABLE LEGENDS

Figure 1: Facies of individuals with ASXL3 loss-of-function mutations reported herein demonstrating down-slanted palpebral fissures, a long, tubular nose with a prominent nasal bridge is apparent in most. Most individuals have a broad nasal tip with low columella. The mouth is wide with full (everted) lower lip; hypertelorism, a narrow head shape with prominent forehead, ‘pencilled’ and/or high-arched eyebrows.

Figure 2. Map of ASXL3 mutations reported to date. Mutation nomenclature according to HGVS guidelines (http://varnomen.hgvs.org/) using NCBI reference Transcript NM_030632.3).

Table 1: Clinical features of twelve previously-unreported patients with ASXL3 loss-of-function mutations reported herein in comparison to previously reported patients with Bainbridge-Ropers syndrome.

Supplementary section containing a detailed clinical summary of all patients reported here.
REFERENCES


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<td>Absent</td>
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<td>Absent</td>
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<td>Few words</td>
<td>Absent</td>
<td>Delayed, few words</td>
<td>Delayed, needed speech therapy</td>
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<td>Behaviour</td>
<td>NA</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Poor sleep; aggressive</td>
<td>NR</td>
<td>Aggressive</td>
<td>NR</td>
<td>Moderate autism, poor sleep</td>
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<td>Hand flapping</td>
<td>NA</td>
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<td>Educational support</td>
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<td>NR</td>
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<td>Patient</td>
<td>Decipher ID</td>
<td>ASXL3 Variant</td>
<td>Sex</td>
<td>Age</td>
<td>Height</td>
<td>Weight</td>
<td>OFC</td>
<td>Gestation</td>
<td>Feeding Difficulties</td>
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<td>2</td>
<td>275026</td>
<td>c.1210delA</td>
<td>M</td>
<td>2yrs</td>
<td>&lt;0.4&quot;</td>
<td>40th</td>
<td>25/40</td>
<td>Term</td>
<td>Yes: Poor suck/swallow, GOR, fundoplication at 4yrs</td>
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<td>3</td>
<td>274593</td>
<td>c.(10747&gt;A)T</td>
<td>F</td>
<td>6yrs</td>
<td>28th</td>
<td>50th</td>
<td>42/42</td>
<td>Term</td>
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<td>4</td>
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<td>c.4144C&gt;T</td>
<td>F</td>
<td>9yrs</td>
<td>&lt;0.4&quot;</td>
<td>25th</td>
<td>25/40</td>
<td>Term</td>
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<td>5</td>
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<td>c.1783C&gt;T</td>
<td>M</td>
<td>6yrs</td>
<td>25th</td>
<td>50th</td>
<td>41 weeks</td>
<td>Term</td>
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<tr>
<td>6</td>
<td>265854</td>
<td>c.335dupA</td>
<td>M</td>
<td>10yrs</td>
<td>&lt;0.4&quot;</td>
<td>40th</td>
<td>38/40</td>
<td>Term</td>
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<td>7</td>
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<td>c.1082dupG</td>
<td>F</td>
<td>20yrs</td>
<td>&lt;0.4&quot;</td>
<td>&lt;25th</td>
<td>25/40</td>
<td>Term</td>
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<td>8</td>
<td>257860</td>
<td>c.3637T&gt;G</td>
<td>F</td>
<td>50th</td>
<td>40th</td>
<td>50th</td>
<td>25/40</td>
<td>Term</td>
<td>Yes: Yes: Stopped breast feeding at 4mths due to poor weight gain</td>
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<td>9</td>
<td>265908</td>
<td>c.3127_123dupG</td>
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<td>Female</td>
<td>9yrs</td>
<td>No</td>
<td>38/40</td>
<td>Term</td>
<td>No</td>
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<tr>
<td>10</td>
<td>259420</td>
<td>c.(11217&gt;G)T</td>
<td>F</td>
<td>25th</td>
<td>20th</td>
<td>40th</td>
<td>38/40</td>
<td>Term</td>
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<td>11</td>
<td>272591</td>
<td>c.1484insTGA, p.(Asp494Tyr)</td>
<td>M</td>
<td>Male</td>
<td>19yrs</td>
<td>No</td>
<td>38/40</td>
<td>Term</td>
<td>No</td>
</tr>
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</table>

M: Male; F: Female; NR: Not reported; NA: Not applicable; PD: Palpebral fissures; ASD: Autism spectrum disorder; ID: Intellectual disability; Dx: Diagnosis; NAD: No abnormality detected; BW: Birth weight; Em CS: Emergency caesarean section; El CS: Elective caesarean section; SEN: Special educational needs; GOR: gastro-esophageal reflux; FTT: Failure to thrive; GTCS: generalized tonic-clonic seizure; PESCS: Picture exchange communication system; - Not known; R/V: review summary.