**Exome Sequencing in Patients With Antiepileptic Drug Exposure And Complex Phenotypes**

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AJ wrote the manuscript and performed bioinformatic analysis on the DDD data. JCS conceived the idea for this study and supervised the project along with RB. HW provided microarray data from the local cohort. CD, PV, IS, JD, NS, JB, SH and DB provided further phenotypic data on DDD participants. All authors reviewed the final manuscript and were in agreement with submission for publication.

**Abstract**

**Introduction:** Fetal anticonvulsant syndrome (FACS) describes the pattern of physical and developmental problems seen in those children exposed to certain anti-epileptic drugs (AEDs) in utero. The diagnosis of FACS is a clinical one and so excluding alternative diagnoses such as genetic disorders is essential.

**Method:** We reviewed the pathogenicity of reported variants identified on exome sequencing in the Deciphering Developmental Disorders (DDD) Study in 42 children exposed to AEDs in utero, but where a diagnosis other than FACS was suspected. In addition, we analysed chromosome microarray data from 10 FACS patients seen in a Regional Genetics Service.

**Results:** Seven children (17%) from the DDD study had a copy number variant or pathogenic variant in a developmental disorder gene which was considered to explain or partially explain their phenotype. Across the AED exposure types, variants were found in 2/15 (13%) valproate exposed cases and 3/14 (21%) carbamazepine exposed cases. No pathogenic copy number variants were identified in our local sample (n=10).

**Conclusions:** This study is the first of its kind to analyse the exomes of children with developmental disorders who were exposed to AEDs in utero. Though we acknowledge that the results are subject to bias, a significant number of children were identified with alternate diagnoses which had an impact on counselling and management. We suggest that consideration is given to performing whole exome sequencing as part of the diagnostic work up for children exposed to AEDs in utero.

**What is known about this topic?**

* Children exposed to certain AEDs in utero can have physical and cognitive sequelae.
* Not all children exposed experience problems and there is a likely genetic predisposition.
* Fetal Anticonvulsant Syndrome (FACS) is a diagnosis of exclusion and current guidance is to perform chromosomal analysis as a baseline however genetic technologies have significantly advanced since these guidelines.

**What this study adds.**

* Whole exome sequencing, whilst not being able to exclude a genetic disorder completely in an individual has facilitated identification of pathogenic variants in several children exposed to AEDs in utero which may contribute to their phenotype
* The chance of identifying an underlying genetic condition is likely to be higher when children have features which are more severe than or atypical for FACS. Some of the genetic variants identified in patients diagnosed with FACS have counselling and clinical management implications, highlighting the importance of their identification
* FACS remains a diagnosis of exclusion and higher resolution analysis of patients’ genomes may be warranted to better understand FACS susceptibility and exclude other primary genetic causes.

**Background**

The term Fetal Anticonvulsant Syndrome (FACS) has been coined to describe children who have been exposed to AEDs in utero and have a characteristic pattern of physical and cognitive difficulties.[[1]](#endnote-1) Prior to women with epilepsy becoming pregnant it is essential to optimise AED therapy to achieve a low risk of fetal harm by avoiding AED polytherapy, achieving seizure control at the lowest possible dose and avoiding drugs which are highly teratogenic.

Certain AEDs have been demonstrated to be associated with elevated rates of major congenital malformations. Current evidence suggests significantly increased risks of major congenital malformations for valproate (VPA), carbamazepine (CBZ), phenytoin (PHT) and topiramate (TOP). Adverse outcomes associated with human teratogens are typically wider than major structural malformations and often include functional deficits such as reduced intellectual functioning, altered growth parameters and more subtle physical malformations, occurring in a recognisable and consistent pattern.[[2]](#endnote-2) To date, three anticonvulsant syndromes have been reported in the literature: Fetal Hydantoin Syndrome,[[3]](#endnote-3) Fetal Valproate Syndrome[[4]](#endnote-4) and Fetal Carbamazepine Syndrome.[[5]](#endnote-5) All three have distinct presentations and include major organ malformations, more minor or functional physical difficulties and neurodevelopmental deficits.

The diagnosis of FACS, which is a diagnosis of exclusion, depends upon the ruling out of other possible environmental and/or genetic causes of the presenting symptoms. In the past the diagnosis has been accepted if there are normal cytogenetic studies. However, even chromosomal microarray (CMA) with a resolution of around 180kb[[6]](#endnote-6) will not detect single gene disorders which occur with significant frequency in individuals presenting with structural and developmental abnormalities and could be enriched in families where epilepsy is a feature. Whole Exome Sequencing (WES) is a more detailed genetic test than CMA, and involves sequencing the entire genetic code, base-by-base, for the majority of protein-coding regions of the human genome (coverage depending on platform). The use of such genetic tests is likely to enhance the accuracy of the diagnosis of FACS by identifying additional or alternative diagnoses.

To date there has been no systematic review of the comorbid presence of genetic variants in children exposed to AEDs. This information may therefore be useful to outline its role in facilitating diagnosis and optimal clinical management and it has implications, also, for studies which aim to determine teratogenic status following in utero exposure to medications.

The Deciphering Developmental Disorders (DDD) study used WES in over 13,000 children, of whom ~8,000 also had exon resolution CMA, with a range of developmental disorders which were unexplained after clinical evaluation and baseline genetic tests including CMA in the majority of cases. Copy number variants were sought by analysis of the exome sequence in those not undergoing separate CMA analysis. After 1133 cases had been analysed the study had identified a causative variant in 40% of cases.[[7]](#endnote-7) As a significant number of patients recruited to the study had been exposed to AEDs in utero, this data set presented an opportunity through which the comorbid presence of effects of AED exposure and presence of potential pathogenic variants could be investigated.

**Method**

The study participants were a retrospective cohort of patients with developmental disorders exposed to AEDs in utero who have undergone WES as part of the DDD Study. Ethical approval was obtained for the study from the relevant bodies (REC 16/NW/0788). A detailed overview of the DDD study has been described previously[[8]](#endnote-8) but in brief, clinicians from UK genetic centres were invited to recruit patients with significant structural malformations and/or intellectual disability who, remained undiagnosed after routine paediatric and genetic assessment, to the study. Saliva samples were collected from the child and both parents and a stored DNA sample from the child and a trio of exomes sequenced. Patients were phenotyped by a Consultant Clinical Geneticist using Human Phenotype Ontology (HPO) terms and comprehensive data was supplied for each patient, including details of medical history, maternal illness and drug exposure during pregnancy and the main clinical features observed along with growth parameters and developmental milestones. Bioinformatic algorithms were used to identify variants within all genes known to cause developmental disorders at the time of the analysis. Re-analysis is undertaken periodically throughout the study as new bioinformatic algorithms and information about newly discovered genes became available. Variants considered to have contributed to the phenotype were fed back to the recruiting clinical geneticist and where appropriate were discussed with patients and validated in local NHS diagnostic laboratories. Clinicians from the regional centres were invited to study subsets of the data as Complementary Analysis Projects. The DDD study group in Cambridge approved a Complementary Analysis Study Request for this study in February 2016.

A list of variants for the 42 patients exposed to AEDs in utero was provided by the DDD study group. These were compared to the patient’s available phenotypic data to assess whether they explained the patient’s phenotype. In addition, we performed further analysis of these variants by searching online databases, interrogating evolutionary conservation and performing *in silico* analyses. All variants were reported and analysed on the GRCh37/hg19 genome build. These methods were used to give a pathogenicity score to each variant according to the American College of Medical Genetics (ACMG) guidelines.[[9]](#endnote-9) Furthermore, referring clinicians were approached for patients identified to have pathogenic variants.

In addition to the DDD cohort, and as a source of additional genetic data, parents of a series of FACS patients who had been referred to our Regional Genetics Centre were sent information about this study and invited to participate by allowing access to their previously obtained chromosomal microarray data. These results were reviewed for any pathogenic changes. The OGT ISCA v2 8x60k microarray was used in all cases.

**Results**

The DDD Study Group had completed WES on 46 eligible children-parent trios by the data freeze of 4293 trios on 05/07/2016 when the application for data was accepted. Figure 1 shows the breakdown of exposures. After exclusion of 4 trios due to no clear documentation of AED in utero exposure, 42 trios remained for analysis. This included 26 males and 16 females with a mean age at enrolment into DDD of 6 years 8 months.

In parallel, 20 patients with a clinical diagnosis of FVS were identified from our Regional Genetics Centre and were invited to participate in the study. A positive response was received in 10 cases (50%). These 10 cases included 4 males and 6 female cases, all of which had chromosomal microarray analysis but not WES.

**Copy Number Variants (CNVs)**

There was one patient with a reported CNV (DECIPHER ID 263311) from the DDD cohort, which was felt to be contributory to the child’s phenotype. This was a 7Mb gain at the 1q21.1 locus (chr1:142540048- 149765695)x3 encompassing the recurrent 1q21.1 microdeletion region and including at least 128 genes. This CNV was maternally inherited although little phenotypic data was available for the mother. The mother in this case was taking 1200mg VPA and 400mg CBZ for post-traumatic seizures suggesting she was not affected by a genetic seizure disorder. The child’s features included undescended testes, hypospadias repair, overlapping toes, thin upper lip and downturned mouth. He did not have a typical facial phenotype for Fetal Valproate Syndrome.

The 1q21.1 recurrent microduplication syndrome (OMIM 612475) is well-described in the literature and predisposes to learning disability, ASD, macrocephaly, hypospadias, hypertelorism, and schizophrenia but is rarely associated with seizures.[[10]](#endnote-10) The patient had global developmental delay, ventriculomegaly, plagiocephaly, long palpebral fissures, hypospadias, and thoracic scoliosis. The opinion from the referring clinician was that this child’s developmental delay was severe and a further explanation was sought from the 100,000 genomes project, although both the 1q21.1 microduplication and VPA exposure were thought to be contributory.

Analysis of the microarray data of 10 patients (Supplementary Table 1) with a FACS diagnosis known to our centre did not find any known pathogenic variants. All patients were exposed to VPA with 7 exposures in monotherapy and 3 polytherapy (VPA+LVT, VPA+Vigabatrin and VPA+LTG). There was one patient exposed to both VPA and LVT who had a 327Kb gain at 15q21.1 which does not contain any genes and is of uncertain significance (chr15: 46,334,812-46,661,995)x3. This patient had moderate to severe learning difficulties, ventricular septal defect, hypermobility, left hip dysplasia, mild low frequency hearing loss and repetitive autistic traits, which could all be attributed to VPA exposure and the phenotype was therefore considered to be consistent with the original Fetal Valproate Syndrome diagnosis.

**Single nucleotide variants(SNVs)**

There were 19/42 (45%) patients with reported SNVs from the DDD Study WES data. Six of these variants occurring in the 42 patients (14%) were classified as pathogenic or likely pathogenic as per ACMG guidelines and thought to explain the participant’s phenotype either in full or partially, alongside the AED exposure (Table 1). Across the AED exposure types variants were found in 2/15 (13%) VPA exposure cases and 3/14 (21%) CBZ exposed cases. Two further variants were initially thought to be pathogenic on bioinformatic grounds however did not appear to be contributory to the patients’ phenotypes.

**Clinical Evaluation of Identified Variants**

**A summary of the patients in whom variants were identified, their clinical and genetic findings and the details of their AED medication are summarised in Table 1. Further details of ACGM pathogenicity scores can be found in Supplementary Table 2.**

*Patient 1 NF1*

This child had clinical appearances consistent with a diagnosis of Soto's syndrome, although NSD1 testing was negative and bone age was normal. His OFC was on the 97th centile and he had a long chin with a thin upper lip. He did not have any other features suggestive of FACS and consensus opinion was a Sotos-like phenotype. He, and his mother, had a few faint cafe-au-lait spots but would not fulfil criteria for neurofibromatosis. This variant was considered contributory to phenotype.

*Patients 2 & 3 EEF1A2*

This variant was considered contributory but the phenotype was less severe than expected. Neither of these siblings had typical FVS facial features.

*Patient 4 NEXMIF*

This patient had previously been investigated for Angelman syndrome due to severe developmental delay, hand flapping and repetitive mannerisms. The phenotype was felt to be consistent with other patients previously described to have NEXMIF variants. He had a tented upper lip and short upturned nose but no facial features of FACS. He had autistic features and an alternative diagnosis was considered early on. His behavioural phenotype was thought to be in keeping with others with NEXMIF variants however a contribution of VPA to his learning difficulties cannot be excluded.

*Patient 5 DCX*

It was very difficult to separate the effects of prenatal CBZ exposure from the effects of the DCX variant. The grandmother of the index case had the DCX variant but did not have epilepsy. Three of her daughters inherited the DCX variant, had epilepsy and a variable degree of developmental disorder, and were on CBZ during their pregnancies. One of her daughters did not inherit the DCX variant and had normal development and no epilepsy. Of the three children in the third generation, who had prenatal exposure to CBZ, all have speech delay, two have inherited the DCX variant and also have epilepsy, one did not and has no epilepsy (Supplementary figure.). This DCX variant has previously been reported as likely pathogenic (rs587783577) causing white matter heterotopia. There was also a maternally inherited VUS in SRCAP (ENST00000262518.4:c.3212T>C, (p.Leu1071Pro)) in the index patient. Pathogenic variants of this gene cause Floating-Harbour syndrome (FHS) (OMIM 136140). A blended phenotype is possible, but neither the patient, nor her mother, have short stature, a key feature of FHS.

*Patient 6 EHMT1*

This patient was felt to have a phenotype entirely consistent with the *EHMT1* variant identified. She did not have typical features of FACS and an alternative diagnosis was considered early on. In this case, CBZ was taken for management of Bipolar Affective Disorder. Interestingly, Kleefstra syndrome has recently been reported as a phenocopy in a patient presumed to have Fetal Valproate Syndrome highlighting that FACS should remain a diagnosis of exclusion.[[11]](#endnote-11)

**Variants not contributory to phenotype**

*Patient 7 KIF5C*

A 41-bp deletion in KIF5C (ENST00000435030.1:c.2679\_2719del) identified by WES causes frameshift and hence was thought likely to be pathogenic however did not correlate with clinical findings. This patient was known to have a maternally inherited 16p12.2 deletion, which was pathogenic. This microdeletion syndrome is known to cause developmental delay, cognitive impairment and seizures, although a variable phenotype.[[12]](#endnote-12) He also has a paternally inherited 20q13.33 duplication of uncertain significance. Both of these CNVs were identified by CMA prior to referral to DDD study as neither variant was thought completely explanatory to the phenotype. WES also found a VUS in KMT2D (ENST00000301067.7:c.5980G>A (p.Asp1994Asn)), a gene associated with Kabuki syndrome. He did not have typical features of either of these conditions so the SNVs in KIF5C and KMT2D were felt unlikely to be clinically significant.

*Patient 8 FOXP1*

This patient’s facial and behavioural phenotype was not typical for FACS. The FOXP1 variant (ENST00000491238.1:c.1372C>T (p.Gln458Ter)), although a nonsense variant, was felt not adequate to explain entire the phenotype and FACS was felt to possibly have contributed. Variants in this gene cause intellectual disability with language impairment (OMIM 613670) however she did not completely demonstrate this phenotype. She had occasional bouts of aggressive behaviour and dysmorphic features not consistent with FACS nor any obvious alternative diagnosis.

**Discussion**

This study is the first to investigate potential underlying genetic diagnoses using CMA or WES to identify a potential explanatory, or contributory causes, for the clinical phenotypes in children exposed to AEDs in utero who have developmental disorders. Clinically relevant SNVs (and one CNV) were identified in 17% (7/42) individuals.

This high yield might be expected, given that these individuals were recruited into the DDD study because clinicians felt that their symptoms remained unexplained by the diagnosis of FACS alone, However, this study demonstrates well that children exposed to AEDs in utero can, in some cases, have underlying genetic causes for their symptoms and therefore the prenatal AED exposure may be of no or of limited relevance. These results also emphasise that FACS should be a diagnosis of exclusion following clinical assessment and appropriate investigation, which should include WES where available.

The clinical diagnosis of children with developmental disorders is often difficult and the added complication of AED exposure in utero may make the task even more challenging. The diagnostic guidelines for FACS were published by Dean et al1 and have yet to be updated in the light of ever more sensitive newer genetic investigations (such as CMA and WES). These criteria stress that FACS is a diagnosis of exclusion citing normal karyotype and 22q11 studies as a prerequisite to diagnosis. It is reasonable to suggest, based on our findings here that those children diagnosed with FACS some time ago based on the Dean criteria could potentially be found to have an alternate genetic diagnosis if further investigation was undertaken with CMA or WES. Consistent with our work published here, in 2012, Douzgou et al[[13]](#endnote-13) reported on 80 children referred for a possible diagnosis of Foetal Alcohol Syndrome. Using a combination of FISH and CMA, 9% of these children were found to have an alternative genetic diagnosis.

As well as the implications for clinical diagnosis of the FACS these results also have implications for research aimed at delineating the risks associated with in utero exposure to medications. This has comprised of case reports and series but also cohort studies or population studies. Whilst the inclusion of a control group from the same source and excluding children with a known genetic diagnosis may assist in ensuring the results of such studies are not biased by the inclusion of children with physical and neurodevelopmental difficulties which are in fact not linked to the teratogenic exposure, the data presented here suggest that genetic testing should also be considered in future studies if completely reliable risk estimates are to be generated.

The current study is limited by a small sample size and almost certain recruitment bias as patients will probably have been entered into DDD study due to clinical suspicion that their phenotype was not completely in keeping with FACS. Many less complex or more mildly affected FACS patients would not have been entered into study as clinicians would be confident with the FACS diagnosis. This most likely explains why some DDD patients had complex phenotypes which didn’t specifically fit with current knowledge of FACS. The additional cases from the Regional Genetics Centre had more extensive phenotypic data available and were not selected on the basis of an unclear diagnosis, but rather were sequential patients attending a genetic clinic however WES data was not available for them.

Reverse phenotyping has been established as a useful tool in variant calling from exome data and describes clinical evaluation of a patient once again after the variant has been found.[[14]](#endnote-14) We feel this technique may be useful in rare disorders such as FACS although we must consider that a ‘negative’ exome does not completely rule out a contributing genetic cause in our patients. Further study using genome sequencing or epigenetic techniques may play a role in elucidating the complex genetics behind a FACS diagnosis.

**Conclusion**

This study is the first of its kind to analyse the exomes of a series of individuals with developmental disorders who were exposed to AEDs in utero. Using WES in those children with severe phenotypes or who were exposed to relatively low doses of AED (below 800mg daily of VPA for instance) would be useful in identifying alternative diagnoses. This will also be important in establishing if there are any FACS ‘genocopies’ suggesting that a child may have a purely genetic disorder which mimics FACS. This would have both significant implications for genetic counselling in future pregnancies and potentially for the processes currently used to determine teratogenic status of medications.

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Table 1

| Pat. N0 | Exposure DECIPHER ID | Variant | Inheritance | Patient Phenotype | OMIM Phenotype | ACGM Classification for Pathogenicity |
| --- | --- | --- | --- | --- | --- | --- |
| 1 | VPAMale263768 | NF1 ENST00000358273.4:c.5488C>T (p.Arg1830Cys) | Mat. | Pectus excavatum, GDD, Dysmorphism, Speech articulation difficulties, Abnormal aggressive, impulsive or violent behaviour, Poor motor coordination | Neurofibromatosis-Noonan Syndrome (601321) | Likely pathogenic |
| 2 & 3 | VPA, LVTMale, Siblings x2270782270783 | EEF1A2 ENST00000217182.3:c.505G>A (p.Glu169Lys) | Mat. | Cognitive impairment, Generalized seizures, IUGR. | Epileptic Encephalopathy (616409) | Likely Pathogenic |
| 4 | CBZMale260205 | NEWXMIF ENST00000055682.6:c.2096C>A (p.Ser699Ter) | Mat. | Intellectual disability, Ataxia, Wide mouth. | X-linked Mental Retardation (300912) | Pathogenic |
| 5 | CBZFemale269952 | DCX ENST00000338081.3:c.910G>A (p.Gly304Arg) | Mat. | GDD, Joint hypermobility, High palate, Delayed speech and language development, Abnormal aggressive impulsive or violent behaviour, White matter neuronal heterotopia | X-linked Lissencephaly (300067) | Likely pathogenic |
| 6 | CBZFemale270822 | EHMT1ENST00000460843.1:c.3310G>A (p.Glu1104Lys) | De novo | GDD, Periventricular leukomalacia, Seizures, Thoracolumbar scoliosis, Dysmorphism.  | Kleefstra Syndrome (610253) | Likely pathogenic |
| 7 | VPA, CBZMale263311 | (Chr1:142540048- 149765695)x3 | Mat. | GDD, ventriculomegaly, plagiocephaly, long palpebral fissures, hypospadias, thoracic scoliosis. | 1q21.1 duplication syndrome 612475 | Documented as clinically significant in multiple peer-reviewed publications.\* |

Table 1: Pathogenic variants in DDD patients exposed to AEDs in utero. VPA = valproate, LVT = levetiracetam, LTG = lamotrigine, CBZ = carbamazepine, PHT = phenytoin, GDD = global developmental delay, IUGR = intrauterine growth restriction, Mat. = maternal. \*CNV unable to classify with ACGM criteria for sequence variants.

Figure legends

Figure 1: Breakdown of AED exposures returned from the DDD Study Group. VPA = valproate, CBZ = carbamazepine, LVT = levetiracetam, LTG = lamotrigine, PHT = phenytoin, TOP = topiramate. Others = diazepam, ethosuximide, clonazepam, clobazam and trihexylphenidyl.

Supplementary Figure: Family pedigree showing segregation of DCX c.667G>A variant with epilepsy and learning difficulties (LD). The SRCAP variant was not tested in the extended family. CBZ = carbamazepine.

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