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Exome Sequencing and the Management of Neurometabolic Disorders

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ORIGINAL ARTICLE

Exome Sequencing and the Management of Neurometabolic Disorders

M. Tarailo-Graovac, C. Shyr, C.J. Ross, G.A. Horvath, R. Salvarinova, X.C. Ye, L.-H. Zhang, A.P. Bhavsar, J.J.Y. Lee, B.I. Drögemöller, M. Abdelsayed, M. Alfadhel, L. Armstrong, M.R. Baumgartner, P. Burda, M.B. Connolly, J. Cameron, M. Demos, T. Dewan, J. Dionne, A.M. Evans, J.M. Friedman, I. Garber, S. Lewis, J. Ling, R. Mandal, A. Mattman, M. McKinnon, A. Michoulas, D. Metzger, O.A. Ogunbayo, B. Rakic, J. Rozmus, P. Ruben, B. Sayson, S. Santra, K.R. Schultz, K. Selby, P. Shekel, S. Sirrs, C. Skrypynyk, A. Superti-Furga, S.E. Turvey, M.I. Van Allen, D. Wishart, J. Wu, J. Wu, D. Zafeiriou, L. Kluijtmans, R.A. Wevers, P. Eydoux, A.M. Lehman, H. Vallance, S. Stockler-Ipsiroglu, G. Sinclair, W.W. Wasserman, and C.D. van Karnebeek

ABSTRACT

BACKGROUND

Whole-exome sequencing has transformed gene discovery and diagnosis in rare diseases. Translation into disease-modifying treatments is challenging, particularly for intellectual developmental disorder. However, the exception is inborn errors of metabolism, since many of these disorders are responsive to therapy that targets pathophysiological features at the molecular or cellular level.

METHODS

To uncover the genetic basis of potentially treatable inborn errors of metabolism, we combined deep clinical phenotyping (the comprehensive characterization of the discrete components of a patient's clinical and biochemical phenotype) with whole-exome sequencing analysis through a semiautomated bioinformatics pipeline in consecutively enrolled patients with intellectual developmental disorder and unexplained metabolic phenotypes.

RESULTS

We performed whole-exome sequencing on samples obtained from 47 probands. Of these patients, 6 were excluded, including 1 who withdrew from the study. The remaining 41 probands had been born to predominantly nonconsanguineous parents of European descent. In 37 probands, we identified variants in 2 genes newly implicated in disease, 9 candidate genes, 22 known genes with newly identified phenotypes, and 9 genes with expected phenotypes; in most of the genes, the variants were classified as either pathogenic or probably pathogenic. Complex phenotypes of patients in five families were explained by coexisting monogenic conditions. We obtained a diagnosis in 28 of 41 probands (68%) who were evaluated. A test of a targeted intervention was performed in 18 patients (44%).

CONCLUSIONS

Deep phenotyping and whole-exome sequencing in 41 probands with intellectual developmental disorder and unexplained metabolic abnormalities led to a diagnosis in 68%, the identification of 11 candidate genes newly implicated in neurometabolic disease, and a change in treatment beyond genetic counseling in 44%. (Funded by BC Children's Hospital Foundation and others.)

The authors' full names, academic degrees, and affiliations are listed in the Appendix. Address reprint requests to Dr. van Karnebeek at the Division of Biochemical Diseases, Rm. K3-201, Department of Pediatrics, BC Children's Hospital, Centre for Molecular Medicine and Therapeutics, University of British Columbia, 4480 Oak St., Vancouver, BC V6H 3V4, Canada, or at cvankarnebeek@cw.bc.ca.

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NEXT-GENERATION SEQUENCING HAS revolutionized the discovery of genes in which variants cause rare mendelian diseases.¹ A diagnostic yield of 16% (with most variants classified as de novo mutations) has been documented for whole exome sequencing among patients with unexplained intellectual developmental disorder,^{2,3} a condition that affects an estimated 3% of the population worldwide.⁴ Along with coexisting illnesses that include epilepsy, psychiatric or behavioral disturbances, movement disorders, sensory deficits, and other organ dysfunction, intellectual developmental disorder poses a substantial emotional, functional, and economic burden.⁵ Copy-number variants, methylation abnormalities, and single-gene defects are known to cause intellectual developmental disorder.^{2,3,6,7}

Diagnosis is essential for accurate genetic counseling, informed decision making by families and physicians, and access to appropriate medical support and services in the community but does not often translate into disease-modifying treatments. The exception is inborn errors of metabolism, the largest group of genetic intellectual developmental disorders that are amenable to causal therapy — in other words, interventions that directly target pathogenesis at the cellular and molecular level.⁸ For example, the discovery that pyridoxine-dependent epilepsy is caused by variants in *ALDH7A1*, which encodes an enzyme that catabolizes lysine, led to the implementation of a lysine-restricted diet and arginine supplementation, which improved neurodevelopmental outcomes.⁹ Approximately 90 treatable inborn errors of metabolism are known to cause intellectual developmental disorder,^{8,10,11} and it seems likely that more such neurometabolic disorders remain to be discovered. We therefore sequenced the exomes of consecutive patients with intellectual developmental disorder that had an unexplained metabolic phenotype and then used a semiautomated bioinformatics pipeline and a multidisciplinary approach to identify causal variants.

METHODS

PATIENTS

Patients of all ages were consecutively enrolled if they had confirmed or potential intellectual developmental disorder (i.e., the presence of toxic metabolites that are known to cause brain dam-

age in the neonatal period) along with a metabolic phenotype of unknown cause after comprehensive clinical phenotyping with extensive previous metabolic or genetic testing. A metabolic phenotype was defined as one or more of the following: a pattern of abnormal metabolites in urine, blood, or cerebrospinal fluid; abnormal results on functional studies at a biochemical or cellular level (e.g., a deficiency in the mitochondrial-respiratory-chain complex); or abnormalities on clinical history (e.g., developmental or cognitive regression), physical examination (e.g., organomegaly), neuroimaging or physiological analysis (e.g., leukodystrophy), or pathological analysis (e.g., storage vacuoles) suggestive of a neurometabolic disorder.

The study was approved by the ethics committee of the Faculty of Medicine at the University of British Columbia. Each patient or designated guardian provided written informed consent for participation in the study and publication of the results. During the informed-consent process, investigators explained the risks and benefits of research-based whole-exome sequencing analysis to patients and their families, and an option for disclosure of medically actionable incidental findings was provided.

SEQUENCING AND BIOINFORMATICS ANALYSIS

We isolated genomic DNA, using standard techniques, from either peripheral blood or saliva obtained from the proband and from both parents and all affected and unaffected siblings (if available). We performed whole-exome sequencing analysis on samples obtained from the probands, the parents, and any affected siblings using either the SureSelect targeted capture kit (Agilent) on the Illumina HiSeq 2000 sequencer or the Ion AmpliSeq Exome Kit and Ion Proton System (ThermoFisher).

We developed and applied a semiautomated gene-discovery pipeline, which involves manual inspection of data quality and collaborative interactions between clinicians and bioinformaticians (Fig. 1). (Details are provided in the Supplementary Appendix, available with the full text of this article at NEJM.org.) After the completion of whole-exome sequencing, we provided a clinician-referral form containing data on phenotype, family history with pedigree, ancestry, and previous results of diagnostic testing for variant interpretation. We classified the pathogenicity of the variants according to recent standards and guide-

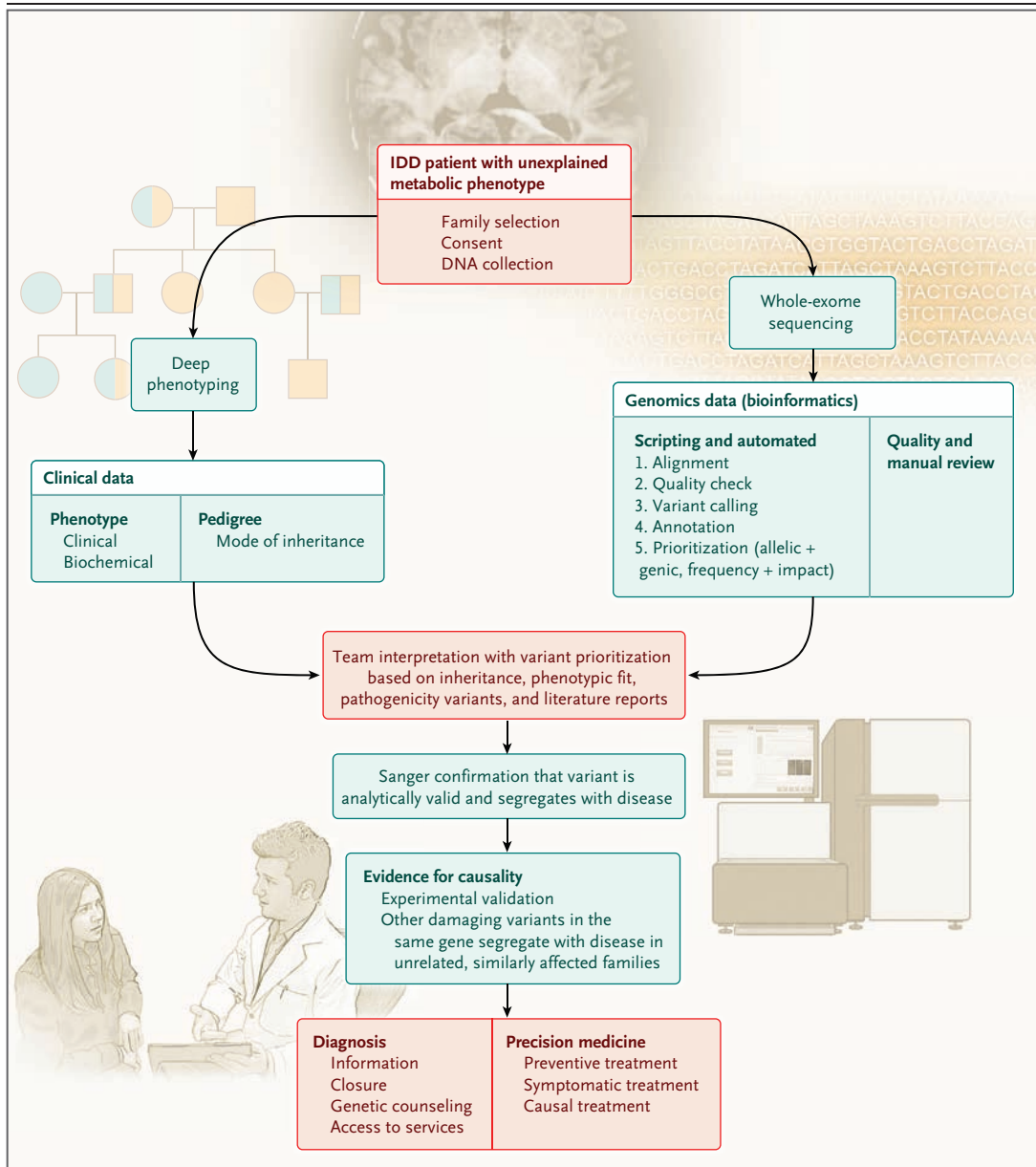


Figure 1. Flow Chart Showing Gene-Discovery Approach with the Use of Collaborative Phenomics and Semiautomated Genomics.

This research process of uncovering the genetic basis of potentially treatable neurometabolic conditions in patients with an intellectual developmental disorder (IDD) involves a combination of deep clinical phenotyping (the comprehensive characterization of the discrete components of a patient’s clinical and biochemical phenotype), whole-exome sequencing analysis, team interpretation, validation, and translation to the clinical setting. Whole-exome sequencing analysis is performed on DNA samples obtained from the proband and on available samples from parents and any affected siblings. The semiautomated gene-discovery pipeline involves manual inspection of data quality and collaborative interactions among clinicians, laboratory scientists, and bioinformaticians for interpretation, candidate-gene selection, and subsequent experimental and clinical validations. The benefits of a diagnosis for patients and their families are shown; in some cases, the diagnosis enables a targeted treatment strategy. Details are provided in the Supplementary Appendix.

lines of the American College of Medical Genetics and Genomics (ACMG).¹² Variant genes were described as newly identified (novel), candidate, or known to cause disease.² Genes that were described as newly identified had not been implicated in human disease previously and harbored distinct damaging variants in at least two affected patients with striking phenotypic overlap from unrelated families. When such a variant was observed in only a single family, it was described as a candidate gene.

RESULTS

PATIENTS

From October 2012 through January 2015, we recruited and completed whole-exome sequencing on samples obtained from 47 probands who met the eligibility criteria. All the patients were referred by local medical specialists in Vancouver, Canada, except for 3 patients, who were referred by clinicians in Greece, the United Kingdom, and Saudi Arabia. Negative results on whole-exome sequencing that ruled out a monogenic cause and details regarding the clinical course at the time of the study helped to confirm previously suspected diagnoses of teratogen exposure (in 1 patient), congenital infection (in 1 patient), and an autoimmune disorder (in 2 patients). In one patient, a chromosomal copy-number variant that was classified as having unknown significance before the study was determined to be pathogenic on the basis of a new entry in the ClinVar database (www.ncbi.nlm.nih.gov/clinvar/), which describes the same copy-number variant in an unrelated person with a similar phenotype. None of the remaining patients were identified as having a copy-number variant (either pathogenic or of unknown significance). In addition, one family, for whom whole-exome sequencing identified a *de novo* pathogenic variant in a known syndromic gene associated with intellectual developmental disorder, withdrew from the study.

Of the 41 remaining probands, 37 (90%) were children. The age at the time of enrollment ranged from 8 months to 31 years (median, 5.9 years); 15 of the probands were female (37%), and 26 were male (63%). Among these patients with intellectual developmental disorder, 19 had

mild disease, 14 had moderate disease, and 8 had profound disease, with a spectrum of additional clinical and biochemical manifestations (Table 1). A total of 26 of the probands (63%) were of European descent and had been born to non-consanguineous parents without a family history of intellectual developmental disorder. In all the probands, diagnostic investigations for intellectual developmental disorder had been initiated during early childhood (in the 1990s through 2014) with regular follow-up for additional testing. All the patients had undergone biochemical testing according to a published diagnostic algorithm for treatable intellectual developmental disorder¹⁰ and a combination of clinical genetics testing (including mitochondrial DNA sequencing) without receiving a diagnosis. Nine probands had affected siblings who also underwent whole-exome sequencing analyses. A summary of the results for all 50 patients (41 probands and 9 siblings) is provided in Table S1 in the Supplementary Appendix.

DIAGNOSTIC YIELD

We established a genetic diagnosis in 28 of the 41 probands (68%), which included the identification of variants in 2 genes newly implicated in disease, 22 known genes with newly identified phenotypes, and 9 genes with expected phenotypes. In most of the genes, the variants were classified as either pathogenic or probably pathogenic. In 9 additional probands, we identified 9 candidate genes (Table 2). Our group generated experimental data providing evidence for the effect of variants on protein function for 14 of these genes (2 newly implicated genes, 6 candidate genes, and 6 known genes with newly identified phenotypes) (Section C in the Supplementary Appendix).

We performed whole-exome sequencing on samples obtained from the proband and from both parents in 28 of the cases (68%). In total, we identified 58 diagnostic variants in 42 genes; all except the previously reported somatic *KRAS* variant were germ-line variants.^{13,14} Of the 58 variants, 24 (41%) were classified as pathogenic and 17 (29%) as probably pathogenic, according to recently published ACMG standards and guidelines (Table S2 in the Supplementary Appendix).¹² Most of these variants (78%) were not

Table 1. Clinical Characteristics of the 41 Probands.*

| Characteristic | Proband no. (%) |
|--|--------------------|
| Sex | |
| Male | 26 (63) |
| Female | 15 (37) |
| Age | |
| <19 yr | 37 (90) |
| ≥19 yr | 4 (10) |
| Family structure | |
| Nonconsanguineous | |
| One affected child | 30 (73) |
| Two affected children | 7 (17) |
| Consanguineous | |
| One affected child | 2 (5) |
| Two affected children | 2 (5) |
| Population† | |
| White European | 26 (63) |
| East Asian | 3 (7) |
| West Asian | 7 (17) |
| South Asian | 3 (7) |
| Latino | 2 (5) |
| Phenotype | |
| Intellectual developmental disorder | 41 (100) |
| Unexplained metabolic phenotype | 39 (95) |
| Abnormal neuroimaging | 26 (63) |
| Abnormal muscle tone | 18 (44) |
| Seizure | 13 (32) |
| Abnormal movement | 11 (27) |
| Epilepsy | 11 (27) |
| Psychiatric symptoms | 8 (20) |
| Dysmorphic features | 8 (20) |
| Cardiac defect | 7 (17) |
| Short stature | 4 (10) |
| Immune dysfunction | 4 (10) |
| Clinical, genetic, and biochemical analyses | |
| Chromosomal microarray analysis | 36 (88) |
| Targeted gene sequencing | 34 (83) |
| Mitochondrial DNA sequencing | 18 (44) |
| Biochemical testing | 41 (100) |

* Percentages may not total 100 because of rounding.

† The population group was determined by self-report and a detailed family history.

present in either our database (which consists of 350 individual exomes or genomes) or the database of single-nucleotide polymorphisms of the National Center for Biotechnology Information (dbSNP, version 138), whereas 13 variants were present but rare (average allele frequency, 0.006) in the dbSNP. Seven diagnostic variants (12%) had been previously identified as pathogenic (Table S3 in the Supplementary Appendix), a prevalence that is similar to that in a previous study.¹⁵ As compared with variants in the Exome Aggregation Consortium (ExAC), a database of 61,486 unrelated persons, 31 of the 58 variants (53%) were newly identified and 27 (47%) were rare, with an average allele frequency of 0.004. The ExAC data set includes patients with mental illnesses, so the presence of a rare variant in this data set does not exclude the possibility that it is pathogenic.

Of the 58 variants, 51 (88%) were single-nucleotide variants; these included 43 missense variants (74%), 4 nonsense variants (7%), and 4 splice-site variants (7%); 4 in-frame omissions of conserved amino acids (7%) and 3 frameshift variants (5%) were also identified (Table 2). The mode of inheritance was recessive in 30 of the 42 genes (71%), including compound heterozygous variants in 16 genes (38%), homozygous variants in 8 genes (19%), and X-linked recessive variants in 6 genes (14%) (Table 3). Dominant variants were identified in 12 patients (29%), including 11 de novo variants (10 heterozygous and 1 mosaic) and a single familial autosomal dominant variant with variable penetrance. For the nine families with pathogenic variants in known human disease genes and expected phenotypes, pedigrees with electropherograms are provided in Figure S1 in the Supplementary Appendix.

EFFECT ON CLINICAL MANAGEMENT

Genetic diagnosis affected the clinical treatment of 18 probands (44%) in whom a pathogenic or probably pathogenic variant was identified (Table S4 in the Supplementary Appendix). These changes consisted of preventive measures, such as regular screening for cancer and avoidance of disease triggers in 4 probands (with a variant in *CBL*,¹⁶ *SMAD4*, *MTOR*, or *PRSS1*); immune-modulating therapies, such as chemotherapy or stem-cell transplantation in 3 probands (with a vari-

ant in *SENPI*, *SYTL2*, or *KRAS*); more precise symptomatic treatment, such as supplementation with 5-hydroxytryptophan, levodopa, carbidopa, serine, or folinic acid supplementation in 5 probands (with a variant in *CNKSR2*, *SCN2A*, *ANO3*, *ATP2B3*, or *MECP2*); and treatments targeting the identified abnormality at a cellular or molecular level in 7 probands (with a variant in *CA5A*, *ACACB*, *GOT2*, *PCK1*, *NANS*, *MTO1*, or *QARS*). The diagnosis of *MTO1* deficiency in a female sibling pair enabled both preventive and targeted therapy. Although it is possible that these changes in clinical treatment may have improved health outcomes in all cases, it must also be acknowledged that different degrees of stabilization or improvement in patients with intellectual developmental disorder (or related outcomes) can be expected in different groups.

ILLUSTRATIVE CASES

New and Candidate Causes of Intellectual Developmental Disorder and Therapy

We describe two newly identified forms of inborn errors of metabolism that are potentially amenable to dietary restriction, supplementation, or pharmacologic interventions (see Case Reports and Table S4 in the Supplementary Appendix). The first discovery was a homozygous missense variant in *CA5A* (Mendelian Inheritance in Man [MIM] number 114761), encoding mitochondrial carbonic anhydrase VA, which is pivotal to the function of mitochondrial enzymes.¹⁷ Our group reported that a deficiency in this enzyme causes neonatal hyperammonemia, hyperlactatemia, and hypoglycemia.¹⁷ Such a deficiency is amenable to treatment with carnitine and an emergency protocol, which can prevent irreversible neurologic sequelae. We added this condition to the two-tiered diagnostic algorithm and interactive tool at Treatable ID.org (freely available as native and Web applications at www.treatable-id.org) to support clinicians in early identification.^{9,10}

The second newly identified inborn error of metabolism was caused by compound heterozygous variants in *NANS*, encoding N-acetylneuraminic acid phosphate synthase (MIM number 605202), in a 4-year-old presenting with epileptic encephalopathy and dysmorphic features. We detected increased levels of N-acetylated mannamine, the substrate of *NANS*, in his urine, plasma, and cerebrospinal fluid. Other recessive

Table 2. Diagnostic Yield and Summary of Whole-Exome Sequencing Analysis in 41 Probands.

| Variable | Value |
|--|--|
| Diagnosis by means of whole-exome sequencing — no. of probands | |
| Positive diagnosis (single contributing gene) | 32 |
| Positive diagnosis (two contributing genes) | 5 |
| No diagnosis | 4 |
| Extent of whole-exome sequencing — no. of probands | |
| Proband only | 3 |
| Proband and affected sibling | 1 |
| Proband and unaffected parent | 1 |
| Proband and both unaffected parents | 28 |
| Proband, affected sibling, and unaffected parents | 5 |
| Proband, unaffected sibling, and unaffected parents | 3 |
| Gene category — no. of genes (gene name) | |
| Not previously implicated in human disease* | 11 |
| Newly identified gene | 2 (<i>NANS</i> , <i>CA5A</i>) |
| Candidate gene | 9 (<i>ACACB</i> , <i>RBSN</i> , <i>GOT2</i> , <i>FAAH2</i> , <i>SENPI</i> , <i>SYTL2</i> , <i>RYR3</i> , <i>MFNG</i> , <i>NPL</i>) |
| Known gene with a new phenotype | 22 |
| Known gene with a known phenotype | 9 |
| Type of variant — no. | |
| All variants | 58 |
| Single-nucleotide variant | 51 |
| Missense | 43 |
| Nonsense | 4 |
| Splice-site | 4 |
| Insertion or deletion | 7 |
| In-frame | 4 |
| Frameshift | 3 |

* The classification by de Ligt et al.² was used for genes that had not been implicated in human disease previously. Genes were described as newly identified (novel) if additional unrelated families with striking phenotypic overlap and variants affecting the same gene were identified. Otherwise, a candidate classification was used.

NANS variants have been identified in a cohort of eight other patients with similar phenotypes in five unrelated families. Models of the mutated organisms recapitulated the phenotype, which is amenable to treatment with early supplementation of N-acetylneuraminic acid.

In addition, we identified two candidate genes that led us to conclude that the phenotypes for

Table 3. Inheritance Patterns of the 42 Genes Identified in the Study.

| Inheritance | No. of Genes Affected | Gene ID |
|-------------------------------|-----------------------|---|
| Autosomal recessive | | |
| Compound heterozygous | 16 | ACACB, RMND1, QARS, MTO1, RYR3, H6PD, MFNG, SCN4A, NDST1, ANO3, NPL, NANS, TMEM67, SYTL2, GOT2, MAT1A |
| Homozygous | 8 | CA5A, RBSN, AIMP1, GALC, GJB2, PCK1, SENP1, OSMR |
| X-linked | | |
| Recessive | 6 | CNKSR2, PIGA, FAAH2, MED12, PLP1, ATP2B3 |
| Dominant de novo heterozygous | 1 | MECP2 |
| Autosomal dominant | | |
| De novo heterozygous | 9 | SCN2A, CBL, DYRK1A, SMAD4, KMT2A, KCNQ2, EHMT1, PACS1, PUF60 |
| De novo mosaic | 1 | KRAS |
| Inherited | 1 | PRSS1 |

intellectual developmental disorder were potentially treatable. In a 6-year-old boy with acquired microcephaly, severe seizure disorder, spasticity, sleep disturbances, abdominal spasms, and low levels of serine in plasma and cerebrospinal fluid, we identified compound heterozygous variants in *GOT2* (MIM number 138150), encoding mitochondrial glutamate oxaloacetate transaminase.¹⁸ After receiving oral serine and pyridoxine supplements, the patient showed improved head growth, psychomotor development, and seizure control. Finally, we are evaluating whether a deficiency in acetyl-coenzyme A carboxylase beta associated with compound heterozygous variants in *ACACB* (MIM number 601557) is a potentially treatable inborn error of metabolism.

Expansion of the Phenotypic Spectrum

We identified variants in 22 genes that have previously been reported to cause monogenic conditions¹⁹⁻²⁵ (Table S4 in the Supplementary Appendix). In all these conditions, we observed previously unreported clinical symptoms.

The delineation of phenotype can point to new treatment targets. An example from this study was an 8-year-old boy with intellectual developmental disorder, autism, movement disorder, intractable epileptic encephalopathy, and persistently abnormal neurotransmitter profiles (low levels of homovanillic acid, 5-hydroxyindoleacetic acid, and neopterin in cerebrospinal fluid)

in whom we identified a de novo pathogenic splice-site variant. This mutation resulted in the deletion of exon 14 in *SCN2A*,²⁴ encoding voltage-gated sodium channel type II. Voltage-gated sodium channels are heteromeric complexes that generate and propagate action potentials. The known phenotype of *SCN2A* deficiency varies and includes benign forms of epilepsy, severe epileptic encephalopathy, autism, and intellectual developmental disorder without seizures, as well as rare cases of dystonia, hypotonia, and hypersomnia.²⁶ Neurotransmitter deficiencies have not been described in this disorder previously. We hypothesized that this channelopathy causes abnormal synaptic secretion and uptake of monoamine metabolites through impaired vesicular release and imbalance in electrochemical ion gradients, which in turn aggravate the seizures. Treatment with oral 5-hydroxytryptophan, levodopa, carbidopa, and a dopa agonist normalized the child's levels of neurotransmitters in the cerebrospinal fluid and was associated with improvements in attention, communication, and seizure control.

Combined Phenotypes from Two Coexisting Monogenic Defects

Multiple genetic events leading to complex phenotypes may be mistaken for new disorders or newly identified phenotypes of a known disorder. This reminds us that a layer of unbiased and

systematic interpretation of data from next-generation sequencing is necessary in any clinical pipeline. Recent reports regarding next-generation sequencing support the hypothesis that blended phenotypes are an appreciable cause of disease.^{1,27} This concept was shown in our study group, in which 5 of 37 probands (14%) for whom diagnoses had been established harbored variants at two distinct disease loci associated with the phenotype (Table S5 in the Supplementary Appendix). For instance, in a 19-year-old male patient who was born to nonconsanguineous Filipino parents and who had progressive dilated cardiomyopathy, sensorineural hearing loss, and unexplained sialic aciduria, whole-exome sequencing revealed compound heterozygous damaging missense variants in *NPL* (MIM number 611412) encoding N-acetylneuraminase pyruvate lyase (which controls the final step of sialic acid metabolism) and a known homozygous missense variant in *GJB2* (connexin 26) reported to cause deafness.

Medically Actionable Incidental Findings

In the families of the 41 probands, we identified only one medically actionable incidental finding in *CFTR* (MIM number 602421). Both alleles (rs78655421 and rs121908745) had been previously reported to be pathogenic. These alleles were found to be in trans on Sanger sequencing. The clinical phenotype did not include symptoms of cystic fibrosis. The family chose not to be informed of incidental findings, so we did not disclose this result to them.

DISCUSSION

Our approach, which involved phenotyping and whole-exome sequencing of samples obtained from 41 consecutively enrolled probands with intellectual developmental disorder who had an unexplained metabolic phenotype, provided a diagnostic yield of 68%, including variants in two newly implicated genes. We also identified nine candidate genes. Although the study was designed to evaluate the numerical yield of whole-exome sequencing in probands, affected siblings also benefited from a diagnosis in nine families (Table S1 in the Supplementary Appendix). Studies to validate or rule out causality of the candidate genes are ongoing. We have pro-

vided information on variants that were possibly pathogenic in these genes using more stringent weighting of available genetic evidence according to ACMG guidelines¹² and taking into account existing experimental data (Tables S2 and S4 and the Experimental Data section in the Supplementary Appendix). Our diagnostic rate exceeds that of most published studies applying next-generation sequencing in rare diseases.^{2,3,15,28-31}

In one of four families with negative results on whole-exome sequencing, subsequent whole-genome sequencing identified a causal homozygous variant in *CSTB* (in a region of low coverage on whole-exome sequencing) in two siblings with neurodegenerative epilepsy who had a response to carbidopa–levodopa and 5-hydroxytryptophan. In another family, whole-exome sequencing of samples obtained from parents established a pathogenic de novo mutation (*MYLK*); previously, only the proband had undergone whole-exome sequencing analysis (see the Discussion section in the Supplementary Appendix). However, the most important outcome of our genomics study was the effect of diagnosis by means of whole-exome sequencing on the clinical treatment of 44% of the probands who were analyzed.

Knowledge of the precise genetic or biochemical defect in a metabolic pathway provides the opportunity to modify disease by means of nutritional manipulation, which does not require the expensive and time-consuming preclinical development that is typical in drug manufacturing. This advantage is illustrated by the discovery of GOT2 deficiency in a child with severe neurologic symptoms that was amenable to oral serine and pyridoxine supplements (the product and cofactor, respectively, of GOT2), both of which are affordable and have been deemed to be safe for other inborn errors of metabolism.^{9,32} However, the diagnosis of NANS deficiency in another patient underscores a challenge presented by very rare diseases: how to test new treatments and obtain evidence of effect or lack thereof with a small number of patients.

The relatively high diagnostic yield that we report here may stem from the inclusion criterion of a metabolic abnormality, the prevalence of recessive conditions in metabolic disorders, or the close consultation with clinical specialists in our bioinformatics pipeline. We observed a higher portion of patients (14%) with variants at

two distinct disease loci (leading to blended phenotypes) than has been observed in other studies,^{1,27} perhaps because we specified the inclusion of two phenotypes (metabolic and intellectual developmental disorder) in the patient-selection criteria.

Translational genomics requires collaborations among patients, their families, subspecialist clinicians for careful phenotyping, bioinformaticians for accurate data analysis, and basic scientists engaged in specific research involving genes, pathways, or model organisms.³³ Difficult decisions with respect to invasive and costly procedures such as hematopoietic stem-cell transplantation or chemotherapy (e.g., in a patient with SYTL2 deficiency³⁴) are facilitated and supported by a genetic diagnosis. Outcome reports of such cases in the literature may help to guide other clinicians who are facing similar decisions. Data sharing and open communication are key to maximizing the diagnostic potential

of next-generation sequencing and its clinical benefit in rare diseases.

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Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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APPENDIX

The authors' full names and academic degrees are as follows: Maja Tarailo-Graovac, Ph.D., Casper Shyr, Ph.D., Colin J. Ross, Ph.D., Gabriella A. Horvath, M.D., Ph.D., Ramona Salvarinova, M.D., Xin C. Ye, M.Sc., Lin-Hua Zhang, Ph.D., Amit P. Bhavsar, Ph.D., Jessica J.Y. Lee, B.Sc., Britt I. Drögemöller, Ph.D., Mena Abdelsayed, Ph.D., Majid Alfadhel, M.D., Linlea Armstrong, M.D., Matthias R. Baumgartner, M.D., Ph.D., Patricie Burda, Ph.D., Mary B. Connolly, M.D., Jessie Cameron, Ph.D., Michelle Demos, M.D., Tammie Dewan, M.D., Janis Dionne, M.D., A. Mark Evans, Ph.D., Jan M. Friedman, M.D., Ph.D., Ian Garber, M.D., Suzanne Lewis, M.D., Ph.D., Jiqiang Ling, Ph.D., Rupasri Mandal, Ph.D., Andre Mattman, M.D., Margaret McKinnon, M.D., Aspasia Michoulas, M.D., Daniel Metzger, M.D., Oluseye A. Ogunbayo, Ph.D., Bojana Rkic, Ph.D., Jacob Rozmus, M.D., Peter Ruben, Ph.D., Bryan Sayson, B.Sc., Saikat Santra, M.D., Kirk R. Schultz, M.D., Kathryn Selby, M.D., Paul Shekel, Ph.D., Sandra Sirrs, M.D., Cristina Skrypnik, M.D., Andrea Superti-Furga, M.D., Ph.D., Stuart E. Turvey, M.D., Ph.D., Margot I. Van Allen, M.D., David Wishart, Ph.D., Jiang Wu, Ph.D., John Wu, M.D., Dimitrios Zafeiriou, M.D., Ph.D., Leo Kluijtmans, Ph.D., Ron A. Wevers, Ph.D., Patrice Eydoux, Ph.D., Anna M. Lehman, M.D., Hilary Vallance, M.D., Sylvia Stockler-Ipsiroglu, M.D., Ph.D., Graham Sinclair, Ph.D., Wyeth W. Wasserman, Ph.D., and Clara D. van Karnebeek, M.D., Ph.D.

The authors' affiliations are as follows: the Centre for Molecular Medicine and Therapeutics (M.T.-G., C. Shyr, X.C.Y., L.-H.Z., J.J.Y.L., B.I.D., I.G., W.W.W., C.D.K.), the Departments of Medical Genetics (M.T.-G., C. Shyr, C.J.R., X.C.Y., J.J.Y.L., L.A., J.M.F., S.L., M.M., M.I.V.A., A.M.L., W.W.W.), Pediatrics (C.J.R., G.A.H., R.S., L.-H.Z., A.P.B., B.I.D., M.B.C., M.D., T.D., J.D., A. Michoulas, D.M., J.R., K.R.S., K.S., S.E.T., John Wu, S.S.-I., C.D.K.), and Pathology and Laboratory Medicine (B.R., P.E., H.V., G.S.), the Child and Family Research Institute (M.T.-G., C. Shyr, C.J.R., G.A.H., X.C.Y., A.P.B., J.J.Y.L., B.I.D., L.A., M.B.C., M.D., J.D., J.M.F., I.G., S.L., M.M., D.M., J.R., K.R.S., K.S., S.E.T., M.I.V.A., John Wu, P.E., A.M.L., H.V., S.S.-I., G.S., W.W.W., C.D.K.), and the Division of Endocrinology, Adult Metabolic Diseases Clinic (A. Mattman, S. Sirrs), University of British Columbia, and the Divisions of Biochemical Diseases (G.A.H., R.S., B.S., S.S.-I., C.D.K.), Pediatric Neurology (M.B.C., M.D., A. Michoulas, K.S.), Pediatric Nephrology (J.D.), Pediatric Endocrinology (D.M.), and Immunology (S.E.T.) and the Division of Hematology, Oncology and Transplantation, Michael Cuccione Childhood Cancer Research Program (J.R., K.R.S., John Wu), BC Children's Hospital, Vancouver, the Department of Pathology and Laboratory Medicine, Hospital for Sick Children, University of Toronto, Toronto (J.C.), the Department of Biological and Computing Sciences, University of Alberta (R.M., D.W.), and the National Institute for Nanotechnology (D.W.), Edmonton, AB, and the Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, BC (M. Abdelsayed, P.R.) — all in Canada; the Division of Genetics, Department of Pediatrics, King Saud Bin Abdulaziz University for Health Sciences, King Abdulaziz Medical City, Riyadh, Saudi Arabia (M. Alfadhel); the Division of Metabolism and Children's Research Center, University Children's Hospital Zurich, Zurich (M.R.B., P.B.), and the Department of Pediatrics, University of Lausanne, Lausanne (A.S.-F.) — both in Switzerland; the Centre for Integrative Physiology, University of Edinburgh, Edinburgh (A.M.E., O.A.O., P.S.), and Birmingham Children's Hospital, Birmingham (S. Santra) — both in the United Kingdom; the Department of Microbiology and Molecular Genetics, University of Texas Health Science Center, Houston (J.L., Jiang Wu); Al Jawahra Center for Molecular Medicine and Inherited Disorders, Arabian Gulf University, Bahrain (C. Skrypnik); the Department of Pediatrics, Aristotle University of Thessaloniki, Thessaloniki, Greece (D.Z.); and the Department of Laboratory Medicine, Radboud University Medical Center, Nijmegen, the Netherlands (L.K., R.A.W.).

REFERENCES

1. Yang Y, Muzny DM, Xia F, et al. Molecular findings among patients referred for clinical whole-exome sequencing. *JAMA* 2014;312:1870-9.
2. de Ligt J, Willemssen MH, van Bon BWM, et al. Diagnostic exome sequencing in persons with severe intellectual disability. *N Engl J Med* 2012;367:1921-9.
3. Rauch A, Wiczorek D, Graf E, et al. Range of genetic mutations associated with severe non-syndromic sporadic intellectual disability: an exome sequencing study. *Lancet* 2012;380:1674-82.
4. Salvador-Carulla L, Reed GM, Vaez-Azizi LM, et al. Intellectual developmental disorders: towards a new name, definition and framework for "mental retardation/intellectual disability" in ICD-11. *World Psychiatry* 2011;10:175-80.
5. Meerding WJ, Bonneux L, Polder JJ, Koopmanschap MA, van der Maas PJ. Demographic and epidemiological determinants of healthcare costs in Netherlands: cost of illness study. *BMJ* 1998;317:111-5.
6. van Bokhoven H. Genetic and epigenetic networks in intellectual disabilities. *Annu Rev Genet* 2011;45:81-104.
7. Ellison JW, Rosenfeld JA, Shaffer LG. Genetic basis of intellectual disability. *Annu Rev Med* 2013;64:441-50.
8. van Karnebeek CDM, Stockler S. Treatable inborn errors of metabolism causing intellectual disability: a systematic literature review. *Mol Genet Metab* 2012;105:368-81.
9. Coughlin CR II, van Karnebeek CD, Al-Hertani W, et al. Triple therapy with pyridoxine, arginine supplementation and dietary lysine restriction in pyridoxine-dependent epilepsy: neurodevelopmental outcome. *Mol Genet Metab* 2015;116:35-43.
10. van Karnebeek CDM, Shevell M, Zschocke J, Moeschler JB, Stockler S. The metabolic evaluation of the child with an intellectual developmental disorder: diagnostic algorithm for identification of treatable causes and new digital resource. *Mol Genet Metab* 2014;111:428-38.
11. Rilstone JJ, Alkhatir RA, Minassian BA. Brain dopamine-serotonin vesicular transport disease and its treatment. *N Engl J Med* 2013;368:543-50.
12. Richards S, Aziz N, Bale S, et al. Standards and guidelines for the interpretation of sequence variants: a joint consensus recommendation of the American College of Medical Genetics and Genomics and the Association for Molecular Pathology. *Genet Med* 2015;17:405-24.
13. Pao W, Wang TY, Riely GJ, et al. KRAS mutations and primary resistance of lung adenocarcinomas to gefitinib or erlotinib. *PLoS Med* 2005;2(1):e17.
14. Niemela JE, Lu L, Fleisher TA, et al. Somatic KRAS mutations associated with a human nonmalignant syndrome of autoimmunity and abnormal leukocyte homeostasis. *Blood* 2011;117:2883-6.
15. Zhu X, Petrovski S, Xie P, et al. Whole-exome sequencing in undiagnosed genetic diseases: interpreting 119 trios. *Genet Med* 2015;17:774-81.
16. Pérez B, Mechinaud F, Galambrun C, et al. Germline mutations of the CBL gene define a new genetic syndrome with predisposition to juvenile myelomonocytic leukaemia. *J Med Genet* 2010;47:686-91.
17. van Karnebeek CD, Sly WS, Ross CJ, et al. Mitochondrial carbonic anhydrase VA deficiency resulting from CA5A alterations presents with hyperammonemia in early childhood. *Am J Hum Genet* 2014;94:453-61.
18. McKenna MC, Waagepetersen HS, Schousboe A, Sonnewald U. Neuronal and astrocytic shuttle mechanisms for cytosolic-mitochondrial transfer of reducing equivalents: current evidence and pharmacological tools. *Biochem Pharmacol* 2006;71:399-407.
19. Janer A, van Karnebeek CD, Sasarman F, et al. RMND1 deficiency associated with neonatal lactic acidosis, infantile onset renal failure, deafness, and multiorgan involvement. *Eur J Hum Genet* 2015;23:1301-7.
20. Tarailo-Graovac M, Sinclair G, Stockler-Ipsiroglu S, et al. The genotypic and phenotypic spectrum of PIGA deficiency. *Orphanet J Rare Dis* 2015;10:23.
21. Armstrong L, Biancheri R, Shyr C, et al. AIMP1 deficiency presents as a cortical neurodegenerative disease with infantile onset. *Neurogenetics* 2014;15:157-9.
22. Kevelam SH, Taube JR, van Spaendonk RML, et al. Altered PLP1 splicing causes hypomyelination of early myelinating structures. *Ann Clin Transl Neurol* 2015;2:648-61.
23. Salvarinova R, Ye CX, Rossi A, et al. Expansion of the QARS deficiency phenotype with report of a family with isolated supratentorial brain abnormalities. *Neurogenetics* 2015;16:145-9.
24. Horvath GA, Demos M, Shyr C, et al. Secondary neurotransmitter deficiencies in epilepsy caused by voltage-gated sodium channelopathies: a potential treatment target? *Mol Genet Metab* 2016;117:42-8.
25. Zaharieva IT, Thor MG, Oates EC, et al. Loss-of-function mutations in SCN4A cause severe foetal hypokinesia or "classical" congenital myopathy. *Brain J Neurol* 2015;139:674-91.
26. Nakamura K, Kato M, Osaka H, et al. Clinical spectrum of SCN2A mutations expanding to Ohtahara syndrome. *Neurology* 2013;81:992-8.
27. Yang Y, Muzny DM, Reid JG, et al. Clinical whole-exome sequencing for the diagnosis of mendelian disorders. *N Engl J Med* 2013;369:1502-11.
28. Wright CE, Fitzgerald TW, Jones WD, et al. Genetic diagnosis of developmental disorders in the DDD study: a scalable analysis of genome-wide research data. *Lancet* 2015;385:1305-14.
29. Beaulieu CL, Majewski J, Schwartzentruber J, et al. FORGE Canada Consortium: outcomes of a 2-year national rare-disease gene-discovery project. *Am J Hum Genet* 2014;94:809-17.
30. Hu H, Haas SA, Chelly J, et al. X-exome sequencing of 405 unresolved families identifies seven novel intellectual disability genes. *Mol Psychiatry* 2016;21:133-48.
31. Alazami AM, Patel N, Shamseldin HE, et al. Accelerating novel candidate gene discovery in neurogenetic disorders via whole-exome sequencing of prescreened multiplex consanguineous families. *Cell Rep* 2015;10:148-61.
32. van der Crabben SN, Verhoeven-Duif NM, Brilstra EH, et al. An update on serine deficiency disorders. *J Inher Metab Dis* 2013;36:613-9.
33. Foley KE. Model network: Canadian program aims to generate models for rare disease. *Nat Med* 2015;21:1242-3.
34. Rossi A, Borroni RG, Carrozzo AM, et al. Griscelli syndrome type 2: long-term follow-up after unrelated donor bone marrow transplantation. *Dermatology* 2009;218:376-9.

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