Original Article
Genetic and epigenetic methylation defects and implication of the ERMN gene in autism spectrum disorders

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Autism spectrum disorders (ASD) are highly heritable and genetically complex conditions. Although highly penetrant mutations in multiple genes have been identified, they account for the etiology of <1/3 of cases. There is also strong evidence for environmental contribution to ASD, which can be mediated by still poorly explored epigenetic modifications. We searched for methylation changes on blood DNA of 53 male ASD patients and 757 healthy controls using a methylation array (450K Illumina), correlated the variants with transcriptional alterations in blood RNAseq data, and performed a case–control association study of the relevant findings in a larger cohort (394 cases and 500 controls). We found 700 differentially methylated CpGs, most of them hypomethylated in the ASD group (83.9%), with cis-acting expression changes at 7.6% of locations. Relevant findings included: (1) hypomethylation caused by rare genetic variants (meSNVs) at six loci (ERMN, USP24, METTL21C, PDE10A, STX16 and DBT) significantly associated with ASD (q-value < 0.05); and (2) clustered epimutations associated to transcriptional changes in single-ASD patients (n = 4). All meSNVs and clustered epimutations were inherited from unaffected parents. Resequencing of the top candidate genes also revealed a significant load of deleterious mutations affecting ERMN in ASD compared with controls. Our data indicate that inherited methylation alterations detectable in blood DNA, due to either genetic or epigenetic defects, can affect gene expression and contribute to ASD susceptibility most likely in an additive manner, and implicate ERMN as a novel ASD gene.

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Introduction
Autism spectrum disorders (ASD; OMIM 209850) are a group of early-onset neurodevelopmental disorders diagnosed on the basis of two symptom areas: social communication impairments, and restricted repetitive behaviors, interests or activities (DSM-V). The currently estimated prevalence of ASD is 1/42 males and 1/189 females aged 8 years, after a documented prevalence increase during the past two decades.1 There is strong evidence for a genetic etiology of ASD with heritability ranging from 50 to 90%.2,3 However, despite remarkable advances driven by genetics and genomics leading to the identification of single-gene mutations, copy-number changes and double hit models, the etiology of around 70% of ASD cases still remains unknown.4,5 This relatively poor detection rate could be explained in part by the high phenotypic and genetic heterogeneity of ASD with multiple inheritance models, including monogenic, oligogenic and polygenic with gene–environment interactions.6–8 In addition, most genomic studies to date have focused on the analysis of sequence and copy-number changes in the coding part of the genome, therefore, missing putative epimutations and other changes located elsewhere in the genome.

Epigenetics comprises DNA methylation, long non-coding RNA and histone post-translational modifications, which act as regulatory mechanisms of gene expression. Epigenetic aberrations have been associated with a wide range of diseases including ASD.9,10 Several single-gene disorders commonly associated with autism (that is, Fragile-X11 and Rett syndromes12 show multiple epigenetic deregulations, and recurrent genomic alterations in chromosomal regions subjected to imprinting (chr7q, 15q (ref. 13,14)) commonly manifest as ASD. Other epigenetic defects secondary to mutations in genes such as UBE3A15 and OXCTR16 as well as altered CpG methylation in genes such as RORA, BCL1 (ref. 17) and EN-2,18 have also been implicated in autism. Therefore, methylation and imprinting alterations associated or not to genetic anomalies, may be responsible for additional cases of ASD. Although epigenetics is still a poorly explored field in ASD, the current genome-wide technologies permit to assess DNA methylation in the available tissues. To date, several small-size case–control studies have addressed methylation abnormalities in ASD searching for differences in twin pairs discordant for the disease on cell line or blood DNA,17,19 investigating DNA from different brain regions,20,21 or looking for effects of advanced maternal age on buccal epithelium as a surrogate of ectodermal cells.22 Methylation analyses of promoter regions of genes in blood DNA failed to detect relevant changes in an initial study (analyzing 1505 regions in 70 patients),23 while reporting
hypermethylation at ENO2 in 14.5% ASD cases (analyzing 16,000 regions in 131 patients).24

In this study we aimed to identify methylation aberrations in blood DNA of a cohort of ASD patients in a search for testable epigenetic biomarkers contributing to ASD etiology. Functional consequences were analyzed by RNAseq of blood RNA, integrating the analysis of epigenetic variants and their transcriptional consequences. Finally, we performed a case–control study of the resulting rare variants using an independent and larger ASD sample in order to increase the power and significance of the associations, as well as a screening for mutations affecting the coding sequence in the previously identified genes.

MATERIALS AND METHODS

Study population

We selected 53 unrelated idiopathic ASD male patients, aged from 2 to 14 years (Supplementary Table 1) and referred from several hospitals of the Spanish Health System. All individuals had a diagnosis of ASD based on clinical and psychological evaluations (DSM-IV and ADI-R test). Genetic and biochemical testing for comorbid conditions ( Fragile-X and some metabolic disorders), and molecular karyotyping (aCGH or SNP array) were negative in all cases.

The study was approved by the ethical committee of the collaborating centers involved (CEIC-Parc Salut Mar) and written informed consent was obtained from the parents or legal tutors.

Healthy controls consisted of 10 age-matched Spanish male children analyzed simultaneously. Extraction of DNA and RNA was performed from peripheral blood with the DNA Blood extraction kit (Qiagen, Hilden, Germany), and RNA was isolated from lymphocytes using a ficoll density-gradient (STEMCELL Technologies, Vancouver, BC, Canada), according to the manufacturer’s instructions.

Additional methylation data from 91 controls (males of a wide age range) were obtained from the Center for Research in Environmental Epidemiology (CREAL) and the Bellvitge Institute for Biomedical Research (IDIBELL),25,26 as well as from 656 controls (males and females of European ancestry aged from 19 to 101 years) available through GEO (GSE40279). All 757 control samples were obtained from whole blood, except for 5 from cord blood.

In addition, DNA methylation data (blood, 415 ASD and 405 healthy siblings, males, 6 to 25 years old) obtained with the HumanMethylation27 platform (Illumina, San Diego, CA, USA) were downloaded from dbGAP.

We searched for putative genetic variants in the coding sequence in the previously identified genes. In order to define a putative association of the identified rare variants in ASD patients, we genotyped 32 rare SNVs (Supplementary Table 2) in an additional set of 394 ASD samples (Spanish and ECACC collection) and 500 Spanish controls by Sequenom (San Diego, CA, USA). We used 250 ng of DNA to perform the Sequenom assay, which was conducted at Universitat de València (Valencia, Spain). To compute the statistical association we included all the data (450K, 27k and Sequenom) and compared allelic frequencies. Fisher’s exact test and correction by false discovery rate (FDR) were performed using R (fisher.test function and q-value).35

RNA sequencing

To identify the functional consequences of methylation alterations we performed an RNAseq study in 29 out of the 53 studied samples, from which we obtained good quality RNA from blood (RIN > 7). The RNA library was prepared and sequenced (paired-end 100-bp reads) using illumina HiSeq 2000 (Illumina) and sequence reads aligned (build hg37) using TopHat and Bowtie. Expression was quantified by htseqcount in Conditional Quantiile Normalization counts.36 Data were corrected for batch effect by Combat algorithm (SVA package R).37 We assessed case–control differential expression of the genes flanking 50 kb upstream and downstream the DMCpG, distance used in similar studies.40–42 We selected altered genes by Z-score, selecting Z-scores over 2

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variants calling and Annovar for functional annotation. Rare mutations recommended in expression analysis. 

Galore and mapping was performed using BWA. GATK was used for locating in the DMRs. DMCpGs, as well as for the subset of genes with significant association and genetic alterations (meSNVs) and 5 to epigenetic modifications in selected genes. To determine the number of deleterious mutations in selected genes. To determine whether the burden of deleterious mutations is higher in ASD, we use exome data from controls in the EXAC database, and compared the mutational load in cases and controls (Fisher’s test FDR corrected).

Gene ontology analysis

We searched for enriched pathways in DAVIDGo database, and for over-represented functions using CPDB for all the genes associated to the DMCpGs, as well as for the subset of genes with significant association and located in the DMRs.

RESULTS

Methylation alterations in blood DNA of ASD

Clustering and principal component analyses showed a random distribution of the methylation data from patients and controls with no common patterns or systemic differences between groups independently of the normalization method applied (Supplementary Figures 1 and 2). A similar result was obtained in the differential methylation analysis comparing cases with controls as groups, with no significant differentially methylated CpG (DM CpGs) identified (q-value < 0.01).

In order to detect rare methylation defects, we compared each individual ASD patient with the age- and gender-matched control group (n = 10). After assessing differential methylation with the additional control sets with stringent filtering, we identified 700 DMCpGs present in ASD samples (4 to 33 per sample; Figure 1, and Supplementary Table 3). We observed a high concordance between the two normalization methods (93% of the DMCpGs identified). Only 34 additional DMCpGs were found with minfi (Supplementary Table 4). Therefore, the results were not affected by the normalization approaches. To define the consistency of the identified DMCpGs, we performed sequencing validation on the same DNA samples at 98 sites, including 85 isolated CpGs and 13 plausible DMRs. The validation rate, conceived as true genetic or epigenetic variants, was 85% (84/98), 78 sites corresponding to genetic alterations (meSNVs) and 5 to epigenetic modifications in the DMRs.

Most of the 700 DMCpGs (587; 83.9%) in ASD cases showed a relative hypomethylation compared with controls, and mostly changed from a hypermethylated state to an intermediate state (Beta-values from 30 to 60%; Supplementary Figure 3). Regarding genomic location, 544 DMCpGs located within 467 genes and 10 miRNA, whereas 156 DMCpGs were intergenic probes (> 1.5 kb from the gene Transcription Starting Sites; Figure 1). We searched for convergence between the detected genes and core ASD-associated genes compiled in SFARI and AutismKb databases.

Although most DMCpGs were case specific, we found 20 present in two or more ASD patients. Rare SNPs at the CG position (meSNPs) had been described at 9 (45%) of these sites (dbSNP137 and 1000G MAF < 0.005), so we assumed the SNPs were the cause of the DMCpG. Validation and segregation analysis of the remaining DMCpGs (n = 11) revealed that all were also rare single-nucleotide variants (meSNVs) inherited from healthy progenitors (Supplementary Table 5).
Table 1. Summary of the relevant DMCpGs found in this study

| REF_ID | Position (hg19) | Gene | No. of cases | Variant type and segregation (case1/case2 and so on) | Meth. avg. ASD/CNT | RNAseq expression | Association study | Reported in ASD |
|--------|----------------|------|--------------|---------------------------------------------------|-------------------|------------------|-------------------|-----------------|
| **ASD-CNT** | **No. of ASD-CNT** | **MAF ASD-CNT** | **P-value (OR (CI))** |
| **DMCs with statistically significant association** |
| cg059640000 | chr:1:5564130 | USP24 | 2 | meSNP MAF < 0.002, n.a. | 0.597/0.891 | Normal levels | 447–1,349 | 0.0067–0.0019 | 0.033; 3.64 (0.92–15.11) | C |
| cg17937591 | chr:1:10062053 | DBT | 1 | meSNP MAF < 0.005; M | 0.521/0.891 | ASD; 23; (OE) | 446–1,349 | 0.0045–0.0007 | 0.037; 6.07 (0.87–67.28) | C, R |
| cg05777410 | chr:2:58162587 | GALNTS-ERMN | 2 | meSNV; M/M | 0.462/0.911 | ASD; 5; ERMN (OE) | 445–1,348 | 0.0056–0.0004 | 0.0045; 15.21 (1.7–717.62) | C, R |
| cg19001113 | chr:6:16607157 | PDE10A | 3 | meSNP; P/M/M | 0.53/0.875 | ASD; 3; 2TX16 | 444–1,349 | 0.0045–0.0007 | 0.0366; 6.11 (0.87–67.74) | C |
| cg05491608 | chr:13:10334696 | METTL12 | 2 | meSNP MAF < 0.001, n.a. | 0.434/0.871 | ASD; 29; MVD | 444–1,348 | 0.0079–0.0022 | 0.023; 3.56 (1.02–12.86) | C |
| cg18904477 | chr:20:57222576 | intergenic | 2 | meSNP MAF < 0.003, n.a. | 0.506/0.887 | ASD; 29; SCARF2 | 444–1,344 | 0.0034–0.0004 | 0.049; 9.13 (0.73–47.87) | C |
| **DMCs without detected controls in the association study** |
| cg03983498 | chr:1:15107291 | ACOT11 | ASD; 4 | meSNV; P inh | 0.502/0.877 | Reduced/OE | 446–1,349 | 0.0011–0 | 0.248; Inf (0.08–Inf) | C |
| cg24131169 | chr:3:31347578 | RXRβ | ASD; 23 | meSNP MAF < 0.001; M | 0.448/0.805 | Reduced/OE | 445–1,349 | 0.0011–0 | 0.248; Inf (0.08–Inf) | C, E |
| cg04552280 | chr:16:12209538 | RPS23P6 | ASD; 3 | meSNP MAF < 0.002; P | 0.53/0.882 | Reduced/OE | 445–1,349 | 0.0011–0 | 0.248; Inf (0.08–Inf) | C, E |
| cg27245147 | chr:16:21687639 | MVD | ASD; 7 | meSNV; P | 0.404/0.829 | Reduced/OE | 318–954 | 0.0016–0 | 0.25; Inf (0.08–Inf) | mDS |
| cg20758953 | chr:22:20762620 | SCARF2 | ASD; 29 | meSNV; not maternal, parental sample n.a. | 0.592/0.990 | Reduced/OE | 446–1,241 | 0.0011–0 | 0.264; Inf (0.07–Inf) | C |
| cg25781162 | chr:24:40065997 | ABCG5 | ASD; 9 | meSNP MAF < 0.004; P | 0.429/0.869 | Reduced | 858–1713 | 0.0023–0 | 0.2529; Inf (0.08–Inf) | C |
| **Region (DMRs) Position (hg19) Patient REF_ID | **Meth. avg. ASD/CNT | **Pyroseq. meth. validation | **RNAseq expression | **Reported in ASD |
| **Validation/ segregation case/parent AVG MAE ASD-CNT** |
| **ASD-SMG7** | chr:1:18343936-18343949 | SMG7 | ASD; 23 | cg27531517, cg15632228 | 0.517/0.057 | Hypermethylation; M inherited | 43.98/45.05 | 0.008; 0 | SMG7 (OE) | C |
| **PIK3CD** | chr:1:9747263-9747772 | PIK3CD | ASD; 25 | cg19309580, cg03653801 | 0.514/0.052 | Hypermethylation; P inherited | 39.18/49.81 | 0.008 | PIK3CD (mild) | R, C |
| **PHACTR1** | chr:13:13274151-13273454 | PHACTR1 | ASD; 25 | cg06873934, cg21538684, cg28027128, cg07912922, cg00460589 | 0.415/0.049 | Hypermethylation; P inherited | 34.36/71.29 | 0.008-0.004 | Not altered | E, C |
| **RNASEURUSD; ZCCHC9** | chr:8:80597143-80597828 | ZCCHC9 | ASD; 13 | cg10569335, cg05602479, cg16993440, cg27010645, cg22211395, cg26543232, cg07673182, cg01306296, cg2439198, cg0149122, cg00407623, cg16288993, cg23462061, cg08813207 | 0.428/0.036 | No sample available | — | — | ZCCHC9 (DR) | C, C |
| **RAB26** | chr:16:2198479-2198777 | RAB26 | ASD; 14 | cg162198479, cg162198777 | 0.36/0.094 | Hypermethylation; M inherited | — | — | RAB26 NE, PKD1 (mild DR) | C, L |

Abbreviations: ASD, autism spectrum disorders; CNV, copy number variant; CI, confidence interval; DMR, differentially methylated regions; DR, downregulated; E, expression; L, linkage analysis; M, maternally inherited; MAF, minor allele frequency; mDS, micro deletion syndromes; Meth. avg. ASD/CNT, methylation average ratio of all CpGs in the region between the ASD case and the controls; n.a., not available; OE, overexpressed; OR, odds ratio; P, paternally inherited; Pyroseq.meth, Pyrosequencing method; R, related diseases; SNV, single-nucleotide variant. *Statistically significant q-value (FDR correction). **Statistically significant nominal P-value. ***Closest transcription starting site gene name.
We also found five DMRs in four different patients (one patient had two DMRs). Methylation levels were validated, and we discarded underlying genetic changes by dosage analysis with MLPA probes in the region and by sequencing of the flanking intervals. These clustered epimutations were inherited in three cases, two from the father and one from the mother, with identical degree and extension in the parental samples (Table 1 and Supplementary Figures 4–7). A search for DMRs with less-stringent methylation differences using the COMB-P algorithm revealed six additional regions, but they were also found altered in several controls and then not considered as ASD specific.

Transcriptional consequences of DMCpGs

Out of the 476 DMCpGs altered in any of the 29 samples with blood transcriptomic data by RNAseq, we studied expression changes of nearby genes that were expressed in blood (*n* = 630). We observed a strong correlation (Z-score > 2) with expression changes of flanking genes in 7.6% of the loci harboring DMCpGs. Validation and segregation analysis of the 15 DMCpGs outside DMRs revealed that all contained rare inherited meSNVs (Supplementary Table 2, Supplementary Figure 8). Interestingly, a methylation alteration in the promoter of *RNF166* led to a transcriptional alteration of three flanking genes (Figure 2).

Regarding the rare meSNVs present in more than one patient, a significant overexpression of the flanking gene(s) was observed in four cases and a downregulation in one. The meSNV causing hypomethylation within *GALNT5* correlated with overexpression of the nearby *ERMN* gene (Table 1 and Figure 3) in one of the cases (ASD_5). Finally, RNAseq also revealed significant changes of the expression levels of flanking genes in 4/5 of the DMRs (Figure 4).

Rare meSNVs associated to ASD

We first used methylomic (Illumina 27k, Illumina) data from blood DNA of 415 ASD cases and 405 controls as a replication cohort. Only 17 (2.4%) of the 700 DMCpGs were covered by this array. Relative hypomethylation at cg25781162 (*ABCG5*), caused by an inherited meSNP in one of our probands, was also detected in another ASD patient, and absent in controls (Table 1).

To determine whether a selected set of rare meSNVs (found in more than one ASD patient and/or associated with transcriptional effects) were statistically associated to ASD, we genotyped them by Sequenom in an additional 394 ASD and 500 Spanish controls. None of the variants were common in the Spanish control population (MAF < 0.002), discarding population-specific variants. Significant association following multiple testing corrections (q-value < 0.05) was found with five meSNVs (at the loci: *GALNT5-ERMN*, *USP24*, *METTL21C*, *PDE10A* and *DBT*; Table 1). Considering all the data for case–control analyses, six additional meSNVs identified in a single or two ASD patient(s) were absent in all the studied control samples (*n* = 935–1713; Table 1).

We also used pyrosequencing in another cohort of ASD patients (*n* = 75) to check whether three of the clustered DMRs were present in more cases, but all resulted negative. Therefore, most of
these DMRs were patient specific and absent in controls (n = 757), except for one present in 3 of the 757 controls. Taken together, these patient-specific meSNVs and DMRs are still good candidates that cannot be excluded from being associated with ASD risk, although replication in larger data sets would be required.

Deleterious mutations in ERMN associated to ASD
To identify other putative genetic mutations in some genes whose methylation and expression changes showed association with ASD disease, we performed targeted resequencing of the coding regions of 5 selected genes (ERMN, STX16, SMG7-AS1, PIK3CD and ZCCHC9). We completed the screening in additional 279 ASD patients and 105 Spanish controls, used to exclude population-specific variants. No loss-of-function mutations were identified in any of the genes in the ASD cohort, but deleterious missense rare variants were detected. Mutations in ERMN were identified in three unrelated ASD patients, one in two cases (c.830G > A/R277Q) and the second in one case (c.823 T > G/S275A) (Supplementary Table 6). We also reanalyzed 931 exomes of ASD patients (previously reported in O’Roak et al.53 and De Rubeis et al.54) available from dbGAP and the EXAC repository data to define the mutation load. We identified five additional ASD cases harboring the same R277Q mutation and four additional deleterious mutations in ASD patients (Figure 3 and Supplementary Table 6). In the EXAC repository, a total of 327 predicted pathogenic mutations could be found. By comparison, a significant increase in the mutation load of ERMN in ASD with respect to controls was observed (P-value = 0.046), which is much more significant if we exclude three population-specific variants (P-value = 7.97E−05). The finding of a higher mutation burden in ASD patients, along with a positive association with a single meSNV at this locus and the overexpression in carriers of the meSNV, strongly support that ERMN is implicated in ASD. No significant mutation burden was identified in any of the other screened genes in ASD patients.

General gene ontology analysis
Gene ontology analysis for the total amount of genes (n = 467) revealed six significantly (P-value < 0.05) enriched KEGG pathways (DavidGO; Supplementary Table 7): axon guidance (n = 10 genes), PIP metabolism (n = 5 genes), chemokine signaling (n = 10 genes), focal adhesion (n = 12 genes), adherence (n = 6 genes) and tight junctions (n = 8 genes). Regarding the biological function enrichment annotation chart (CPDB database), we found enrichment in functions such as nervous system development (n = 73 genes), neuron development (n = 30), synaptic transmission (n = 28), cell death (n = 59 genes) and immune response (n = 18 genes). In addition, when analyzing all the significant associated regions and
the DMRs we found only AMPK signaling pathway significantly enriched (CAMKK1 and PIK3CD).

**DISCUSSION**

With the main goal of identifying methylation aberrations as testable epigenetic biomarkers for ASD, we have performed an epigenome-wide association study in blood DNA in a selected cohort of idiopathic ASD patients, and explored the functional consequences on blood transcriptome of a subset. Although ASD is mainly a disorder of neurodevelopment and there are genomic regulatory regions with brain-specific epigenetic states, there is evidence that blood cells can be used as proxies for epigenetic state at the many regions whose epigenetic state is common to multiple tissues.55 We used the 450k methylation array containing selected probes for ~1.7% of the estimated 28 million CpG sites of the human genome. No systemic methylation alterations were identified in this ASD population, as previously shown in other studies of ASD using brain and blood DNA samples.19,56 Despite the small size of our and the previously reported cohorts, the combined data discarded common DMRs in the regions analyzed shared by all ASD patients. In a similar manner to most genetic variants currently associated to ASD, and considering the low-recurrent nature of epigenetic events, low prevalent or individual-specific epimutations would not be detected with this type of group analyses.56 We then searched for individual-specific ASD-related variants using a large number of controls (n = 757), both age matched and adults. We considered that including many controls with a wide age range would provide more power to select ASD-related and significant changes without biased comparisons. Although blood DNA methylation has been shown to vary with aging, the changes are of small magnitude (10% reduction on average) and affecting a small amount of the 450k array probes (2.1–15%).26,57

A total of 700 DMCPGs in 467 genes were detected specifically in the ASD cohort, 13 per patient on average. Interestingly, 83.85% of these DMCPGs showed relative hypomethylation, in agreement with previous reports showing global hypomethylation in blood of ASD patients.58 although all clustered regions showed hypermethylation in ASD cases. The integrative study with blood transcriptome allowed the identification of cis-acting gene expression effects for 7.6% of the DMCPGs, more commonly overexpression associated to hypomethylation. In support of their potential pathogenic implications, 4.5% of the DMCPGs were also found in ASD patients’ brain,21 whereas 6.5% of the genes were ASD-related genes reported by mutation, copy number variant and/or association analyses. Most of the isolated DMCPGs identified were due to meSNVs, and were inherited in all tested cases. The high proportion of meSNVs among DMCPGs was due, at least in part, to the stringent filters applied to focus on the most severe methylation changes (50% or more), expected with mutations at CpG.30 Anyhow, heterozygous SNPs at CpGs are clearly implicated in the allele-specific methylation events, being an important class of cis-regulatory variants connecting genetics to epigenetics.39 The expression changes related to meSNVs can be due to the interference with trans-acting regulatory elements of either the methylation alteration itself, the underlying sequence variant or both factors together.

We identified and validated five DMRs in four ASD patients, with cis-acting expression effects on neighboring genes documented in four regions. Interestingly, all DMRs were inherited events also found in one of the parents. This germline transmission of epimutations could be explained by reprogramming evasion mechanisms50 or by undetected cis-acting genetic or genomic mutations affecting methylation of the region.51 The hypermethylation of the SMG7-antisense and SMG7 promoter region was paradoxically associated with SMG7 overexpression in a single patient (Supplementary Figure 6). SMG7 is involved in nonsense-mediated mRNA decay regulation, a pathway that has also been previously implicated in ASD and related syndromes.62 Other DMRs in single-ASD patients affected the regulation of genes involved in the development and function of the nervous system (PHACTR1,63 PIK3CD64 and PKD165). Methylation deregulation of PIK3CD has been shown in ASD brain,21 and the gene was associated to schizophrenia.56 Similarly, PKD1 expression was found downregulated in ASD67 and also associated to neuropsychiatric diseases, including ASD.58

Through an extended case/control association study, we identified six rare meSNVs significantly associated with ASD. The most significant association was detected with a CpG located
close to an enhancer and DNase hypersensitive site between the GALNT5 and ERMN genes (chr2q24.1). Although GALNT5 is not expressed in blood, ERMN was found overexpressed in one patient presenting the rare meSNV. Moreover, by targeted resequencing, we found that ERMN showed a higher load of rare damaging mutations in ASD patients. ERMN encodes an actin-binding, specific cytoskeletal protein (Ermin) involved in myelination, upregulated during active myelination periods in rat axons. The moesin/actin-binding domain has been shown to be essential for the ability of Ermin to promote arborization and morphological changes in cultured COS-7 cells. Correct myelination is crucial in ASD and mood disorders. Interestingly, ERMN is located within the boundaries of the AUTS5 locus, which has repeatedly shown linkage to autism, language impairment and IQ. Moreover, deletions including ERMN have been reported in patients with developmental delay and impaired communication, and ERMN expression is lower in epileptic patients brains suggesting also a role in the epileptogenic process. In fact, gain of function through overexpression and loss of function through deleterious mutations would suggest delicate gene dosage equilibrium.

The other five rare meSNVs significantly associated are also strong ASD candidates affecting relevant genes. (1) USP24, encodes a deubiquitinating enzyme that has been associated to Parkinson's physiopathology. (2) PDE10A, a paternally imprinted gene highly expressed in specific brain regions, encodes a cyclic nucleotide phosphodiesterase that regulates signal transduction; the gene was found disrupted by a chromosomal translocation in a patient with neurodevelopmental disorder and was proposed as a therapeutic target for cognitive impairment in schizophrenia. (3) METTL21C, encoding a lysine methyltransferase for non-histone proteins, regulates molecular chaperones related to neuroinflammation, such as the Hsp70 found altered in the plasma of some ASD patients. (4) The meSNV on TRM13 associated with overexpression of the nearby DBT, coding for the transacylase E2 subunit of the branched-chain alpha-keto-acid dehydrogenase complex mutated in patients with autosomal recessive urine disease and ASD with epilepsy phenotype. (5) A meSNV showing nominal association was associated with overexpression of SIX16, which is involved in synaptic vesicle transport, a pathway known to be impaired in ASD.

The remaining rare DMCpGs/meSNVs found in single or few ASD patients need additional studies in larger data sets to confirm a potential association with the phenotype. Some of them have been related to ASD by point mutations (C15orf62/DNAJC17 and ADAP1), linkage studies (TLE3), aberrant brain expression (PRCD, LCP1, RXR8 and SETD1A) and copy number variants (n = 11 genes). Other genes were involved in relevant functions as neuron differentiation (SERPINF1, TCP12 and KAL1), neuron signaling (C1QL3) and ubiquitination (DNAJC17 and RAB40B). Pathways enrichment analysis showed significant results in mechanisms previously related to ASD including axonogenesis, cell adhesion, immune chemokine signaling and RIF signaling.

In summary, this epigenome-wide association study integrated with transcriptome in blood samples revealed significant association of ASD with hypomethylation caused by rare meSNVs at several loci, as well as a few clustered epimutations in single-ASD patients. Thus, methylation alterations detectable in blood DNA, due to either genetic or epigenetic defects, can contribute to ASD susceptibility. Given that most probands harbor more than one methylation variant and all of them are inherited from unaffected parents, their contribution to the phenotype is more likely to be additive, in an oligogenic manner. The study also reveals that ERMN is a strong ASD susceptibility gene that can be altered by both rare meSNV and mutations. Additional studies of genome-wide DNA methylation in larger ASD cohorts, integrated with genomic, transcriptomic, proteomic as well as the phenotypic data, are needed to further unravel the complex epipathogeny of this multifactorial disorder.

CONFLICT OF INTEREST
BR-S and LAP-J are currently employee and scientific advisor, respectively, of qGenomics SL. The remaining authors declare no conflict of interest.

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DATA DEPOSITION
The complete methylation data have been deposited in NCBI's Gene Expression Omnibus under accession number GSE83424.

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