Canavan disease (CD) (OMIM 271900) is an autosomal recessive leukodystrophy characterised by swelling and spongy degeneration of the white matter of the brain. The biochemical marker for the disorder is increased level of N-acetylaspartic acid (NAA) in cerebrospinal fluid and urine owing to aspartoacylase (ASPA) deficiency. 1–3 The disease is caused by mutations in the gene encoding the enzyme aspartoacylase (ASPA, EC 3.5.1.15) at 17p13-ter. 1–4 Clinical features are macrocephaly, head lag, and hypotonia from the age of 3–6 months followed by rapidly progressive severe mental retardation. Life expectancy is usually into the teens and development of optic atrophy is typical. Only symptomatic treatment is possible. The prevalence is highest among Ashkenazi Jews with a carrier frequency of 1 in 38 and two mutations, Y231X and E285A, constitute 98% of the CD alleles in this population. 1–5

Canavan disease is rare in non-Jewish populations and one mutation, A305E (914C→T), is found in about 40% to 60% of the disease alleles reported so far. Mutations are scattered all over the six exons of the aspartoacylase gene. In total, 38 different mutations have been reported of which 35 are listed in The Human Gene Mutation Data Base, Cardiff, UK. 6–14

Prenatal diagnosis by enzyme assay is complicated by technical difficulties. 11–13 Measurement of N-acetylaspartate concentration in amniotic fluid by stable isotope dilution is considered a reliable approach. However, for carrier detection and prenatal diagnosis, mutation detection should be performed. Our aim has been to study the mutational spectrum of the aspartoacylase gene in Norwegian and Swedish patients of non-Jewish origin. This knowledge is essential for patient management and for the design of rational molecular genetic diagnosis.

MATERIALS, METHODS, AND SUBJECTS

Eight Norwegian patients from six families and one Swedish patient (table 1) were identified by clinical characterisation and enzyme investigations. Clinical information was provided by the paediatricians who had followed the patients from the time of diagnosis. All the patients were boys and all parents and sibs were healthy.

The pre- and perinatal periods were unremarkable in all cases except in patient N2 where symptoms started after one week and patient N4 where hypotonia was noted from birth (table 1). Through their mother, patients N2/N3 (family 2) were related to patient N1 (family 1) and through their father they were related to patient N4 (family 3). A fourth family (family 4) could not be linked to the other three families but their ancestors originally came from the same small geographical area.

DNA studies

DNA purification

Genomic DNA was isolated from whole blood by use of an automated DNA extractor (341 Nucleic Acid Purification System DNA extractor, Applied Biosystems), or by salting out methods.

cDNA synthesis

RNA was extracted from cultured skin fibroblast cells by TRI-Reagent reagents according to the manufacturer’s specifications (TIB Molbiol, BRL). Total RNA was reverse transcribed using 100 pmol oligo dT/pg RNA and 200 U Super Script II reverse transcriptase (TIB Molbiol, BRL) at 50°C for 60 minutes.

PCR

Intronic PCR primers flanking each exon were used for PCR amplification and direct sequencing (table 2). All PCR reactions were carried out on a DNA Thermal Cycler/480 (Perkin-Elmer). PCR was performed in a 50 μl volume containing 400 ng genomic DNA, 10 pmol of each primer, 1 mmol/l dNTPs, 10 × Taq polymerase buffer, 25 mmol/l MgCl₂, and 5U Taq polymerase.

DNA sequencing

The PCR products were sequenced with the appropriate primer by the use of PCR product Presequencing Kit (Amersham Life Science) and ABI PRISM BigDye Termination Cycle Sequencing Kit (Perkin-Elmer). The sequences were analysed on an ABI 377 automated sequencer unit.
(Perkin-Elmer) and mutations were detected by manual inspection of the sequence electropherograms.

### Mutation detection by PCR and restriction enzyme analyses

In order to facilitate detection of mutations D114Y (340G→T) and D249V (746A→T), assays were developed based on PCR on genomic DNA followed by restriction enzyme digestion and agarose gel electrophoresis. PCR components were as described above. A DNA fragment encompassing D114Y (340G→T) was amplified with primers pCANmF and pCANmR (table 2) at the following cycling conditions: denaturation at 95°C for five minutes followed by 36 cycles with denaturation at 94°C for 30 seconds and annealing/extension at 64°C for 30 seconds. A DNA fragment containing mutation 746A→T (D249V) was amplified with primers Caex6F and CAR3 (table 1) under the following conditions: denaturation at 95°C for five minutes followed by 30 cycles with denaturation at 94°C for one minute, annealing at 55°C for 30 seconds, and extension at 72°C for one minute. The use of restriction enzyme SnaBI allowed us to discriminate between the D114 and 114Y alleles, whereas the use of MboI allowed discrimination between the D249 and 249V alleles. Restriction enzyme digestion was performed according to the manufacturer’s specifications.

### Results

#### Case reports

The clinical findings were very similar for all the nine cases and typical for CD: hypotonia developing into spastic tetraplegia, macrocephaly, mental retardation, head lag, and visual impairment. As indicated in table 1, brain biopsy or raised urinary concentrations of NAA led to the diagnosis of Canavan disease. Notably, three of the patients are still alive at the ages of 25, 21, and 15 (N1, N7, and S9, respectively).

Patient N1 showed delayed development at 3 months. Later, he also developed epilepsy, asthma, and diabetes mellitus.

Patient N2 showed failure to thrive, irritability, and spasticity at the age of 1 week. The diagnosis was not established at the time of death, at the age of 7 months. His younger brother, born 6 years later (patient N3), died at the age of 8 months, severely mentally retarded, blind, and spastic. A brain biopsy showed spongy degeneration and Canavan disease was diagnosed and deduced also for his brother (N2).

Patient N4 showed hypotonia, failure to thrive, and irritability immediately after birth. At three months, he had hyperreflexia, spastic lower legs, and made no visual contact. Urinary NAA levels were markedly raised.

The parents of patients N5 and N6 (brothers) originate from the same small geographical area as the three previously mentioned Norwegian families (N1-N4). Cerebral CT scan

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Clinical summary and mutations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family</td>
<td>Patient</td>
</tr>
<tr>
<td>1</td>
<td>N1</td>
</tr>
<tr>
<td>2</td>
<td>N2*</td>
</tr>
<tr>
<td>3</td>
<td>N3</td>
</tr>
<tr>
<td>4</td>
<td>N4</td>
</tr>
<tr>
<td>5</td>
<td>N5*</td>
</tr>
<tr>
<td>6</td>
<td>N6*</td>
</tr>
<tr>
<td>7</td>
<td>N7</td>
</tr>
<tr>
<td>8</td>
<td>N8</td>
</tr>
<tr>
<td>9</td>
<td>N9</td>
</tr>
</tbody>
</table>

N1: previously reported by Kvittingen et al. S9: previously reported by Hagenfeldt et al. UNAA: urine N-acetylaspartic acid.

*Identification of the mutations was based on the genotypes of their parents (N5 and N6) or affected brother (N2).

#### Table 2  | List of primers |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primer name</td>
<td>Sequence Derived from GenBank accession number</td>
</tr>
<tr>
<td>cDNA primers</td>
<td></td>
</tr>
<tr>
<td>CAF1</td>
<td>5’CTGTACCTTGGCCTTTTGTTGA 567156.1</td>
</tr>
<tr>
<td>CAF3</td>
<td>5’CTGATTGGCAGACTTCCCTTCTCT 567156.1</td>
</tr>
<tr>
<td>CAR3</td>
<td>5’ACACCGTGTAAAGATGAAGCT 567156.1</td>
</tr>
<tr>
<td>Genomic DNA primers</td>
<td></td>
</tr>
<tr>
<td>Cax1F</td>
<td>5’CTCCGTATCGCAGAAAATCAAGA 170466</td>
</tr>
<tr>
<td>Cax1R</td>
<td>5’CACACCTACCATTTACAGCAAA</td>
</tr>
<tr>
<td>Cax2F</td>
<td>5’TCTGACAGGAGATTGTGTCTCA 170467</td>
</tr>
<tr>
<td>Cax2R</td>
<td>5’CAAGTCTTTTCTGCTATATAA</td>
</tr>
<tr>
<td>Cax3F</td>
<td>5’GGGTITTTATTCCAAGAAGACGT 170468</td>
</tr>
<tr>
<td>Cax3R</td>
<td>5’CTTCTGAGTTTCTAGCTAAGACAT</td>
</tr>
<tr>
<td>Cax4F</td>
<td>5’AGTGACTATCTTCCTCTCTCTT 170469</td>
</tr>
<tr>
<td>Cax4R</td>
<td>5’CTGTACCCAGGTCCTAATTGTA</td>
</tr>
<tr>
<td>Cax5F</td>
<td>5’CCAGAGATGTTTGAATTGCCA 170470</td>
</tr>
<tr>
<td>Cax5R</td>
<td>5’TGCTCTTATGAGCTTAAACTCTCT</td>
</tr>
<tr>
<td>pCANmF</td>
<td>5’TATATACACAGGCAGAAAAATGTCATCGTAGTTGCCTACTGAGT 170471</td>
</tr>
<tr>
<td>pCANmR</td>
<td>5’CCATGTTGGAAGGGGTTGCTGTTACCTG</td>
</tr>
</tbody>
</table>

To allow the discrimination between alleles D114 and 114Y (340G→T) the primers pCANmF and pCANmR were modified in the following way. For pCANmF the nine nucleotides at the 5′ end are derived from the 3′ splice acceptor of intron 1.2 In order to create an internal SnaBI control restriction site nucleotides C21, A22, and A24 (in bold, numbered from the 5′ end) were replaced with A, C, and T (underlined), respectively. For pCANmR, nucleotides A25 and G27 were replaced with T and C (underlined), respectively. These replacements allowed SnaBI digestion of the mutant 114Y allele while leaving the D114 allele resistant.
showed hydrocephalus in both. It was never possible to establish visual contact with patient N5 who showed pronounced head lag at 4.5 months. The steady increase of head circumference in patient N6, from 8-10 weeks, was associated with pronounced irritability and spasticity. Patient N7 showed delayed development from the age of 3 months. The clinical diagnosis was cerebral palsy until Canavan disease was confirmed biochemically at the age of 4.5 years.

The Norwegian patient N8 was diagnosed as having Canavan disease at the age of 4.5 months. He had a typical clinical presentation. The clinical findings in the Swedish patient, S9, have been reported previously. He presented delay in mental development and motor milestones from the age of 3 months, a large head circumference, and leucodystrophy on cranial CT scan at the age of 6 months. At the age of 15 years, he presents impaired vision, lack of head control, and severe mental retardation (table 1).

**Mutation analyses**

The study included nine Canavan patients from seven families, of whom three were interrelated. DNA samples from six patients were available for mutation analysis. In three cases, identification of the mutations was based on the genotypes of their parents (N5 and N6) or affected brother (N2). Brief clinical descriptions and genotypes of the Norwegian and Swedish CD patients are listed in table 1.

Two novel missense mutations were identified or deduced in the six probands. In addition, a 1 bp insertion, 245insA, was identified in one patient.

Four probands were homozygous for nucleotide substitution 340G→T in exon 2, resulting in the replacement of Asp with Tyr at amino acid position 114 (D114Y) (results not shown). Homozygosity for nucleotide substitution 746A→T was identified in one Norwegian as well as in the only Swedish patient included in this study (results not shown). This particular point mutation results in the substitution of Asp with Val at amino acid position 249, D249V, of the 313 residue ASPA polypeptide. The nucleotide substitution 746A→T resides in exon 6 in position +2 next to the intron 5/exon 6 border. Thus, the possibility existed that this mutation might cause splicing deficiency. However, RT-PCR combined with cDNA sequencing detected only normal splicing (results not shown). Hence, we conclude that 746A→T causes an amino acid replacement only.

PCR based diagnostic tests were developed for both 340G→T (D114Y) and 746A→T (D249V) (fig 1). Neither D114Y nor D249V were found in a panel of 100 Norwegian control alleles (data not shown).

The Norwegian patient N7 was found to be homozygous for the mutation 245insA. This particular mutation in exon 1 causes a shift in the translational reading frame and, hence, a truncated gene product.

**DISCUSSION**

The majority of non-Jewish Canavan patients investigated originate from southern Europe, United Kingdom, Israel, and Japan. In this work we present brief clinical data and the identification of two novel mutations in Norwegian and Swedish patients with Canavan disease.

The mutation D114Y (340G→T) was found in three related families and in a fourth family originating from the same small geographical region in Norway. It is located in exon 2, resulting in the replacement of the charged, acidic side chain of aspartic acid with the hydrophobic, bulky, aromatic side chain of tyrosine. Hence, the severe consequences of such an alteration can easily be envisaged. Moreover, another amino acid substitution at this particular residue has previously been reported: aspartic acid to glutamic acid (D114E), resulting from 342C→A in a patient of Turkish origin. Such a replacement of Asp with Glu, which conserves the charge and polarity of the side chain but extends the length by only one single methyl group, is apparently sufficient to abolish ASPA activity which was only 0.35% of residual activity. This further shows the importance of residue 114 for the structure/function of the ASPA enzyme.

The mutation D249V (746A→T) was found in one Norwegian and the Swedish patient. The replacement of Asp with Val at amino acid position 249 represents a substitution of a charged, polar side group with an aliphatic, hydrophobic, non-polar side group. The difference in the chemical properties of Asp and Val is consistent with the notion that D249V is abolishing ASPA activity and, hence, is disease causing. Since neither D114Y nor D249V have been reported elsewhere, it is likely that these mutations are specific to Canavan patients from the Scandinavian peninsula.
The mutation, 245insA, a frameshift mutation resulting in a truncated, non-functional gene product, was found in a family from western Norway. This mutation was previously identified in an Italian patient. It is located in a run of seven adenines, a motif previously documented to be prone to misincorporation of an extra base by the DNA polymerase as a result of slipped mispairing at the replication fork.

Both D114 and D249 are conserved in the ASPA genes of cow (93% identity), mouse (86% identity), and, strikingly, also in Cyanobacteria (46% identity). In the ASPA gene of rat (86% identity), however, D249 is conserved whereas D114 is replaced with valine. The D114Y, D249V, and 245insA were the only mutations found in these patients. The fact that they were absent in 100 normal control alleles strongly indicates the pathogenicity of these mutations.

Clinical data showed survival into adulthood in four out of six Norwegian/Swedish patients (table 1). However, since both 114Y/114Y and 249V/249V homozygotes show variable survival time, no genotype-phenotype correlation was evident. Lack of genotype-phenotype correlation has also been previously reported for other CD mutations. It remains to be elucidated how environmental and epigenetic factors may influence the clinical course of Canavan disease. Few data exist concerning residual aspartoacylase activity in CD patients. Such information is crucial to clarify a possible link between genotype, enzyme activity, and clinical phenotype.

Our findings add to the spectrum of mutations in Canavan disease and are essential to the genetic diagnosis and counseling of CD families of Norwegian and Swedish origin. The location and nature of the mutations may contribute to further understanding of the function and structure of the ASPA gene product.

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Swedish patients with Canavan disease missense mutations specific to Norwegian and Swedish patients with Canavan disease

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