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Linköping University Post Print

N.B.: When citing this work, cite the original article.

Original Publication:
http://dx.doi.org/10.3988/jcn.2014.10.2.108
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http://synapse.koreamed.org/
Postprint available at: Linköping University Electronic Press
http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-106282
Idiopathic Small Fiber Neuropathy: Phenotype, Etiologies, and the Search for Fabry Disease

Kristin Samuelsson, Konstantinos Kostulas, Magnus Vrethem, Arndt Rolfs, Rayomand Press

Background and Purpose The etiology of small fiber neuropathy (SFN) often remains unclear. Since SFN may be the only symptom of late-onset Fabry disease, it may be underdiagnosed in patients with idiopathic polyneuropathy. We aimed to uncover the etiological causes of seemingly idiopathic SFN by applying a focused investigatory procedure, to describe the clinical phenotype of true idiopathic SFN, and to elucidate the possible prevalence of late-onset Fabry disease in these patients.

Methods Forty-seven adults younger than 60 years with seemingly idiopathic pure or predominantly small fiber sensory neuropathy underwent a standardized focused etiological and clinical investigation. The patients deemed to have true idiopathic SFN underwent genetic analysis of the alpha-galactosidase A gene (GLA) that encodes the enzyme alpha-galactosidase A (Fabry disease).

Results The following etiologies were identified in 12 patients: impaired glucose tolerance (58.3%), diabetes mellitus (16.6%), alcohol abuse (8.3%), mitochondrial disease (8.3%), and hereditary neuropathy (8.3%). Genetic alterations of unknown clinical significance in GLA were detected in 6 of the 29 patients with true idiopathic SFN, but this rate did not differ significantly from that in healthy controls (n=203). None of the patients with genetic alterations in GLA had significant biochemical abnormalities simultaneously in blood, urine, and skin tissue.

Conclusions A focused investigation may aid in uncovering further etiological factors in patients with seemingly idiopathic SFN, such as impaired glucose tolerance. However, idiopathic SFN in young to middle-aged Swedish patients does not seem to be due to late-onset Fabry disease.

Key Words etiology, Fabry disease, idiopathic, impaired glucose tolerance, small fiber neuropathy.
Despite knowledge of these factors, the reported etiology of SFN has remained unclear in 23–93% of investigated patients. The clinical features and the spectrum of different types of secondary SFN due to the above-mentioned etiologies have been described previously. However, there have been few reports of the clinical phenotype of idiopathic SFN.

Diagnosing SFN is difficult since the small caliber nerve fibers cannot be investigated with routine electrophysiological tests. The main methods currently used for assessing SFN are quantitative sensory testing (QST), which measures the detection thresholds for warm and cold sensations, skin biopsy for quantifying the intraepidermal nerve fiber density, and the quantitative sudomotor axon reflex test, which evaluates the postganglionic sympathetic sudomotor function.

Fabry disease is an X-linked lysosomal storage disorder due to a partial or complete deficiency of the enzyme α-galactosidase A (α-GAL), resulting in accumulation of glycosphingolipids in different organs. Symptoms from the peripheral nervous system (PNS) involvement are common. More than 500 mutations are described in the alpha-galactosidase A gene (GLA) that encodes the enzyme α-GAL. It is known that heterozygous women have disease manifestations, with many of them being severely affected. There is also a milder variant of Fabry disease, where the onset of symptoms occurs later in life. The initial symptoms of late-onset Fabry disease are usually cardiomyopathy, renal disease, or neurological diseases such as stroke or neuropathy.

SFN is the main manifestation of Fabry disease in the PNS, though large fiber axonal sensorimotor polyneuropathy may also occur. Fabry disease is suspected to be underdiagnosed in the general population and possibly also in patients with polyneuropathy of unknown cause. Very few studies have examined the possible association between late-onset Fabry disease and isolated SFN. In a recent study examining a small cohort with patients with idiopathic SFN, Tanislav et al. detected one patient with Fabry disease and four patients with a complex intronic haplotype in GLA and pathological biomarkers. Since the disease is treatable with enzyme replacement therapy, early diagnosis is of great importance.

This study had three aims. First, we aimed to describe the clinical phenotype of SFN in patients where previous investigation at primary- or secondary-care centers had not revealed an etiology, hence leading to the diagnosis of idiopathic SFN. Second, we intended to show the spectrum of etiological factors that could be identified in this group of seemingly idiopathic SFN, if a standardized focused investigation procedure was applied. Finally, we chose to focus on one of the many uncommon causes of neuropathy, namely Fabry disease. Late-onset Fabry disease, which is known to be associated with isolated neuropathy, is suspected to be underdiagnosed. We therefore investigated whether Fabry disease could be a cause of idiopathic SFN with or without large fiber involvement in young to middle-aged patients.

**Methods**

**Patients**

Patients younger than 60 years with idiopathic SFN with or without large fiber sensorimotor axonal polyneuropathy were recruited from the Departments of Neurology and Neurophysiology at Karolinska University Hospital in Stockholm, the University Hospital in Linköping, and through collaboration with private-practice neurology and neurophysiology departments in Stockholm between September 2007 and October 2009. In addition, the diagnosis register from February 2002 to April 2009 at the Department of Neurophysiology at Karolinska University Hospital was searched for the diagnosis code “small fiber neuropathy”.

Primary care referrals to the department of neurophysiology as well as medical records at the departments of neurology were studied, and patients with a possible etiology identified for SFN were excluded (Fig. 1). The remaining patients with SFN consisted of those where a primary investigation by the family physician or at the department of neurology had not revealed an apparent etiology. These patients were asked to participate in a clinical screening visit at the outpatient clinic in an attempt to reveal any other possible etiology of SFN. All eligible patients were interviewed and underwent a standardized focused investigation (see Methods). After exclusion of other possible etiologies, the patients were invited to participate in the genetic part of the study examining for Fabry disease (Fig. 1). Written informed consent was obtained from all patients prior to participation. The study was approved by the local ethical committee at Karolinska Institutet, Stockholm.

**Controls**

In total, 203 age- and gender-matched healthy anonymous blood donors were used as controls for the genetic analysis, which corresponded to a patient/control ratio of 1:7.

**Methods**

**Diagnostics**

The diagnosis of SFN was based on pathological results of QST using the TSA-II NeuroSensory Analyzer (Medoc Advanced Medical Systems, Durham, NC, USA) to determine detection thresholds for warm and cold sensations, in addition to results of clinical examinations indicating small fiber dysfunction in the extremities. Pathological findings of nerve con-
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DNA analysis

DNA purification was performed in the CSF laboratory of the Department of Neurology, Karolinska University Hospital using a QIAamp DNA Blood Maxi kit (Qiagen, Hilden, Germany). Sequencing analysis of GLA, including the exon-intron boundaries and parts of intron 4, was performed at the Albrecht-Kossel-Institute for Neuroregeneration, Faculty of Medicine, Rostock, Germany. The globotriaosylsphingosine (lyso-Gb₃) level in plasma was detected in all patients according to the method described by Tanislav et al. The following additional biochemical analyses were performed in six patients with genetic alterations in GLA of unknown clinical relevance: the α-GAL activity in blood leukocytes and the globotriaosylceramide (Gb₃) level in blood; and the total Gb₃ and Gb₃-isoform N-tetracosanoyl (Gb₃_24) levels in urine were evaluated using mass spectrometry. A skin biopsy was carried out in the gluteal region to detect possible Gb₃ accumulation. Detection of Gb₃ deposits was performed with immunohistochemistry and electron microscopy. A multiplex ligation-probe assay for the exclusion of large deletions

Fig. 1. Flow chart of excluded and included patients. In total, 213 patients with suspected SFN were identified originally. The numbers of patients excluded and the reasons for exclusion are noted in the figure. Ultimately, 29 patients judged to have an idiopathic SFN were included. The proportion of idiopathic SFN using the basic level of investigation/screening was 25% [33/133 (33=29 included patients + 4 patients who declined participation in the genetic study, and 133=88 in exclusion group A plus 12 in exclusion group B plus 33)]. *Exclusion group A, †Exclusion group B. SFN: small fiber neuropathy.

Standardized focused investigation of possible etiologies of SFN

This work-up consisted of a comprehensive laboratory investigation (Table 1) and a clinical examination. All patients were examined physically by either Dr. K. Samuelsson or Dr. R. Press in the Department of Neurology, Karolinska University Hospital. The examination included determination of family history, medical history, past and present medications, exposure to environmental toxins, and alcohol drinking habits.

To be eligible for inclusion in the part of this study investigating Fabry disease, all possible etiologies of SFN had to be excluded after the above-mentioned standardized focused investigation.
was done in specific cases.

Results

In total, 213 patients with suspected SFN were identified based on neurophysiological diagnosis codes and collaboration with other neurologists as described above. A review of referral documents and medical records led to the identification of possible etiologies in 88 patients (exclusion group A) (Fig. 1). Forty-seven patients were examined in the outpatient clinic of the Department of Neurology at Karolinska University Hospital by Dr. K. Samuelsson or Dr. R. Press, where they received a standardized focused investigation (Table 1). Eleven other patients were excluded (exclusion group B) (Fig. 1) since several possible disease-associated causes were discovered through the standardized work-up. Twenty-nine patients were finally included in the genetic part of the study (Fig. 1).

Demographics

The mean age of the 29 included patients and their matched controls was 50.2 years [19 women (66%)]. The age did not differ significantly between the included patients with idiopathic SFN and the excluded patients with secondary SFN. There were significantly more women in the inclusion group than in exclusion group A ($p=0.03$). The mean duration of symptoms prior to inclusion was 6.3 years (range 0.5–38 years) (Table 2).

Phenotype description of included patients

Sensory signs and symptoms

Twenty-four of the 29 patients (83%) had a length-dependent distribution of subjective sensory symptoms (Table 3). The remaining five patients (17%) had a non-length-dependent distribution of symptoms that was patchy in the face and trunk in addition to the extremities. Sensory symptoms included numbness, pricking, itching, tingling, coldness, and hyperesthesia. The proportions of patients with reduced pinprick, light-touch, and vibration sensations as well as those with hyperesthesia upon neurological examination are presented in Table 3. The subjective distribution of sensory symptoms usually comprised a larger area than the objective clinical findings [19 of 29 pa-

<table>
<thead>
<tr>
<th>Disease association</th>
<th>Biochemical analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine basal blood samples</td>
<td>Plasma C-reactive protein, sodium, potassium, creatinine, AST, ALT, albumin, and calcium; blood hemoglobin, platelets, leukocytes and sedimentation rate; serum thyroid-stimulating hormone</td>
</tr>
<tr>
<td>Vitamin B12 or folic acid deficiency</td>
<td>Serum cobalamin, blood folate/fasting-serum folate, plasma homocysteine, or serum methylmalonate</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>Glucose level and glycosylated hemoglobin level</td>
</tr>
<tr>
<td>IGT</td>
<td>Oral glucose tolerance test</td>
</tr>
<tr>
<td>Alcohol abuse</td>
<td>Serum percentage of carbohydrate-deficient transferrin, plasma gamma-glutamyltransferase, or blood erythrocyte mean corpuscular volume</td>
</tr>
<tr>
<td>Vasculitis</td>
<td>Rheumatoid factor, antinuclear antibodies, anti-neutrophils, cytoplasmic antibodies, B-cells, complement factors, or hepatitis C</td>
</tr>
<tr>
<td>Monoclonal gammopathies</td>
<td>Serum protein electrophoresis</td>
</tr>
<tr>
<td>Infections</td>
<td>HIV, syphilis</td>
</tr>
<tr>
<td>Celiac disease</td>
<td>Transglutaminase antibodies</td>
</tr>
<tr>
<td>Amyloidosis</td>
<td>Fat biopsy performed in those with a symptom duration of &lt;4 years, or if there were signs of large fiber involvement</td>
</tr>
</tbody>
</table>

ALT: alanine aminotransferase, AST: aspartate aminotransferase, IGT: impaired glucose tolerance, SFN: small fiber neuropathy.

Table 2. Demographics of included patients with idiopathic SFN and those excluded due to identification of one or more etiological causes

<table>
<thead>
<tr>
<th>Demographic variable</th>
<th>Included patients ($n=29$)</th>
<th>Exclusion group A ($n=88$)</th>
<th>Exclusion group B ($n=12$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Median</td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td>Age (years)</td>
<td>50.2</td>
<td>53</td>
<td>25–59</td>
</tr>
<tr>
<td>Symptom duration (years)</td>
<td>6.3</td>
<td>4</td>
<td>0.5–38</td>
</tr>
<tr>
<td>Female, n (%)</td>
<td>19 (66)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Exclusion group A=patients where etiological causes were identified by review of referral documents and medical records. Exclusion group B=patients where etiological causes were identified only after a standardized focused investigation at our tertiary center. $^*$No significant difference between included patients vs. exclusion group A. $^*$Data missing. $^*$Significantly more women in included patients vs. exclusion group A ($p=0.03$). $^*$No significant difference between included patients vs. exclusion group B.

SFN: small fiber neuropathy.
Patients (66%).

**Motor signs and symptoms**

Nine of the 29 patients (31%) reported weakness in the feet, legs, or hands, while two complained of generalized weakness (Table 3). However, only two of the patients with subjective weakness in the extremities had corresponding findings on a physical examination; both of these patients had large fiber involvement.

**Autonomic signs and symptoms**

Autonomic symptoms consisted mainly of orthostatic lightheadedness, hyperhidrosis, erectile dysfunction, and problems related to micturition. Autonomic investigation of heart rate variation was performed in seven of the 29 patients (24%), five of whom also underwent sympathetic skin response testing. The findings of all autonomic tests were normal, regardless of the presence or absence of subjective symptoms.

**Pain and concomitant medication**

Twenty-six of the 29 patients (90%) had neuralgic pain, which appeared only intermittently in two of them. The pain sensation was described as burning, pricking, stabbing, aching, and icy. In addition, 15 of the 29 patients (50%) reported myalgia. Myalgia was distributed most commonly in the neck, shoulder, and back, but in two patients it was more generalized. Fourteen patients (48%) were taking regular pain medication, 10 of whom took drugs specific for neuralgic pain. All other medication used by the patients was also scrutinized in order to identify possible medications known to cause toxic neuropathy. Three patients were being treated with statins, but in neither case was there a temporal association between the initiation of medication and onset of neuropathic symptoms.

**Neurophysiological findings vs. vibration loss**

Nine of the 29 patients (31%) had combined SFN and large fiber axonal neuropathy according to nerve conduction studies. Notably, 41% of the patients with pure SFN had reduced vibration sensation at the ankles.

**Working capacity**

Sixteen of the 29 patients (55%) had reduced working capacity; in nine patients this was directly attributable to SFN.

**Cardiovascular risk factors**

Nine of 28 patients (32%) smoked (data were missing for one patient), and blood lipid data were available for 25 of the 29 patients. Cardiovascular risk factors were defined as follows: 1) pharmaceutical treatment of hypertension or hyperlipidemia, 2) elevated levels of fasting total cholesterol, low-density lipoprotein cholesterol, or triglycerides according to standard laboratory reference values, and 3) early cardiovascular events. Seven of the 25 patients (28%) had cardiovascular risk factors (CV+), while 18 patients did not (CV-). The mean age, gender, smoking, pain, and presence of large fiber involvement did not differ significantly between the CV+ and CV- groups.

**Possible etiologies of SFN among the excluded patients**

Diseases uncovered as a possible cause of SFN after a review of referral documents and medical records (exclusion group A)

Eighty-eight patients were excluded from the total of 213 patients after a review of referral documents and medical records due to identification of neuropathy-associated diseases/conditions (Fig. 1). The associated diseases are listed in Table 4; the most common was diabetes mellitus (37.5%). Sixteen patients had multiple possible etiological factors simultaneously (Table 4).

Diseases uncovered as a possible cause of SFN after a standardized focused investigation (exclusion group B)

A possible etiology was identified in 12 of the 45 patients (27%) who underwent our standardized focused investigation. The most frequent cause identified in these 12 patients was...
Table 4. Exclusion group A. List of diseases identified as the probable etiology by review of referral documents and medical records of 150 patients with SFN

<table>
<thead>
<tr>
<th>Diseases</th>
<th>Number of patients with etiological factor</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diabetes mellitus</td>
<td>39</td>
<td>37.5</td>
</tr>
<tr>
<td>Toxicity caused by drug*</td>
<td>15</td>
<td>14.4</td>
</tr>
<tr>
<td>Connective tissue disease†</td>
<td>10</td>
<td>9.6</td>
</tr>
<tr>
<td>Cobalamin deficiency</td>
<td>7</td>
<td>6.7</td>
</tr>
<tr>
<td>Hepatitis C</td>
<td>6</td>
<td>5.7</td>
</tr>
<tr>
<td>Alcohol abuse</td>
<td>5</td>
<td>4.8</td>
</tr>
<tr>
<td>Hereditary*</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>Renal insufficiency</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>IGT</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>HIV</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>Thyroid disease</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>Celiac disease</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Amyloidosis (FAP)†</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Paraneoplastic†</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Hepatitis B</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Vasculitis</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Mitochondrial disease‡</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Monoclonal gammopathy</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Sarcoidosis**</td>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>Total</td>
<td>104†</td>
<td>100</td>
</tr>
</tbody>
</table>

*The drugs responsible were chemotherapeutic drugs, including bortezomib, cisplatin, and thalidomide in 10 of the 15 patients; metronidazole in two of the 15 patients; adalimumab, interferon alfa, and phenytoin in individual patients; Systemic lupus erythematosus (n=2), psoriatic arthritis (n=2), rheumatoid arthritis (n=2), Churg-Strauss syndrome (n=1), Sjögren syndrome (n=1), unspecified connective tissue disorder (n=1), and Behçet disease (n=1). †Genetically verified Hereditary Sensory Neuropathy II (n=1), clinically suspected Hereditary Sensory Autonomic Neuropathy (n=1), genetically verified Spinocerebellar Ataxia 3 (n=1), and clinically suspected axonal Charcot-Marie-Tooth variant (n=1). ‡Genetic amyloid polyneuropathy, Rectal cancer, §Suspected based on clinical and electrophysiological data, **Suspected based on clinical data. ††Sixteen of 88 patients had multiple possible disease-associated causes simultaneously.

IGT (58.3%). Interestingly, the glycosylated hemoglobin levels did not differ between the subgroups with and without IGT (data not shown). Other identified causes are listed in Table 5. Two patients were excluded for other reasons (Fig. 1). The proportion of patients with idiopathic SFN who underwent our standardized focused investigation was 73% (Fig. 1).

Genetic investigation of Fabry disease among the patients with idiopathic SFN

Genetic results

Six of the 29 patients had genetic alterations in GLA of unknown clinical relevance (Table 6). Two patients had the complex intrinsic haplotype IVS0-10C>T [rs2071225], IVS4-16A>G [rs2071397], IVS6-22C>T [rs2071228]. One patient had an exon mutation, c.937G>T [D313Y], which is the so-called pseudodeficiency allele. Twenty-nine of the 203 controls had genetic alterations in GLA of unknown clinical relevance. One control, a 58-year-old man, had an exon mutation: c.352C>T [R118C]. In all, 21% of the patients and 15% of the controls had genetic alterations of unknown clinical relevance in GLA. This difference was not significant statistically.

Biochemical analysis

All patients had normal levels of lyso-Gb, in blood. Additional analyses were performed for the six patients with alterations in GLA. All Gb, levels in blood were normal, and all skin biopsies were negative. Urine Gb, was elevated in two patients; one had the following intronic changes: IVS4-854--853delAG, c.352C>T [R118C], c.937G>T [D313Y]. The urine Gb, levels in these two patients (reference value <35 ng/mg creatinine). The results of a multiplex ligation-probe assay were normal in both patients. Additional clinical evaluations (electrocardiography, transthoracic echocardiography, ophthalmologic investigation, and urine protein levels) were also normal in these two patients, indicating the absence of clinical signs of Fabry disease.

Clinical features

Pain and fiber size (pure small fiber or mixed small and large fiber) involvement did not differ significantly between the six patients with genetic alterations in GLA of unknown clinical relevance and the remaining 23 included patients.

Discussion

Previous studies have found the percentage of SFN patients with unknown or idiopathic etiology to vary between 23% and 93%. The proportion of idiopathic SFN among all patients with SFN depends on the quality of the evaluation for the etiology at the primary, secondary, and tertiary levels. A review of referral documents and medical records in the present study led to various conditions being identified as a possible cause of SFN in 88 of 133 screened patients (66%), with diabetes mellitus being the most common identifiable cause (37.5%). When the remainder of the patients with seemingly idiopathic SFN underwent a standardized focused investigation at our neuromuscular tertiary center, a possible etiology was uncovered in an additional 12 of 45 investigated patients.
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Table 5. Exclusion group B. List of diseases identified as an etiology by the standardized focused investigation of 45 patients with seemingly idiopathic SFN

<table>
<thead>
<tr>
<th>Diseases</th>
<th>Number</th>
<th>Percentage with an identifiable cause (n=12)</th>
<th>Percentage of total investigated patients (n=45)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGT</td>
<td>7</td>
<td>58.3</td>
<td>15.6</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>2</td>
<td>16.6</td>
<td>4.4</td>
</tr>
<tr>
<td>Alcohol abuse</td>
<td>1</td>
<td>8.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Mitochondrial disease*</td>
<td>1</td>
<td>8.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Hereditary neuropathy*</td>
<td>1</td>
<td>8.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>100</td>
<td>26.7</td>
</tr>
</tbody>
</table>

*Genetically verified novel mtDNA mutation, † Clinically suspected HSAN.

HSAN: Hereditary Sensory Autonomic Neuropathy, IGT: impaired glucose tolerance, SFN: small fiber neuropathy.

Table 6. Genetic data in controls and patients with idiopathic SFN who have an alteration in GLA, as well as corresponding biochemical results

<table>
<thead>
<tr>
<th>Genetic alteration</th>
<th>Controls, n=203</th>
<th>Patients, n=29</th>
<th>( \alpha )-Gal activity</th>
<th>Blood lyso-Gb3</th>
<th>Blood Gb3</th>
<th>Urine Gb3</th>
<th>Skin Gb3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutation*</td>
<td>1 (0.5)</td>
<td>1 (3.4)</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Elevated</td>
<td>Normal</td>
</tr>
<tr>
<td>Haplotype 1†</td>
<td>22 (10.8)</td>
<td>6 (9.1)††</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Haplotype 2*</td>
<td>4 (2.0)</td>
<td>1 (3.4)</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Haplotype 3‡</td>
<td>1 (0.5)</td>
<td>1 (3.4)</td>
<td>Normal</td>
<td>Normal</td>
<td>Elevated</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Haplotype 4‡</td>
<td>0 (0)</td>
<td>1 (3.4)</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Haplotype 5*</td>
<td>1 (0.5)</td>
<td>0 (0)</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Haplotype 6**</td>
<td>1 (0.5)</td>
<td>0 (0)</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Total</td>
<td>30 (14.7)</td>
<td>6 (20.7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

No significant differences (p <0.05) were evident between the total number of individuals with genetic alterations in GLA, nor for each respective haplotype in patients vs. controls.

*Patient c.937G>T [D313Y], control c.352C>T [R118C]. The considered pathological or unclear results of single nucleotide polymorphism combinations in the haplotypes are in italics. † Haplotype 1=IVS0-10C>T [rs2071225], IVS2-81--77delICAGCC, IVS4-16A>G [rs2071397], IVS6-22C>T [rs2071228], ‡ Haplotype 2=IVS4-854--853delAG, IVS0-12A>G [rs3027585], IVS4+68A>G [rs3027589], IVS6-22C>T [rs2071228], †† Haplotype 3=IVS4-854--853delAG, IVS0-12A>G [rs3027585], IVS2-81--77delICAGCC, IVS4+68A>G [rs3027589], IVS6-16A>G [rs2071397], IVS6-22C>T [rs2071228], ¶ Haplotype 4=IVS4+18 G>A, IVS4+771C>T [rs5991933], IVS6-22C>T [rs2071228], ** Haplotype 5=IVS3-72--68delAAATAA, \( \alpha \)-Gal activity Normal Normal Normal Normal Normal Normal Normal Normal

(27%), with IGT being the most common associated condition (58.3% of the 12 patients).

The proportion of idiopathic SFN diagnoses based on the initial basic level of investigation was 25% (33 of 133 patients) (Fig. 1, Table 4), probably corresponding to the result of etiological investigations at the primary/secondary care centers. The proportion of patients with idiopathic SFN among the group that had undergone the standardized focused investigation was larger; that is, 73% (33 of 45 patients). This could represent the proportion of patients with idiopathic SFN in the total population of patients with SFN investigated at a tertiary center.

To our knowledge this is the first controlled study investigating if Fabry disease can be a cause of idiopathic polyneuropathy. We found genetic alterations in GLA of unknown clinical relevance in both the patients and controls, with the frequency of the genetic variants not differing significantly between these two groups.

Phenotypic description of patients with no identifiable etiology of SFN despite a standardized focused investigation

Twenty of the included patients had pure SFN and nine patients had additional axonal large fiber involvement based on the results of nerve conduction studies. The occurrence of large fiber involvement was permitted in this study since this can be present in patients with Fabry disease, especially late in the course of the disease.32,44 Also with regards to large fiber involvement, patients with idiopathic polyneuropathy are much more likely to be present in the subgroup with axonal rather than demyelinating sensorimotor neuropathy, since the latter subtype of neuropathy is more commonly due to inflammatory or hereditary causes. Length-dependent SFN (LD-SFN) is more common than non-length-dependent SFN (NLD-SFN).10

Patients with LD-SFN typically have leg-onset symmetrical sensory symptoms with a distal-to-proximal gradient, and a delayed spread of symptoms to the upper limbs. On the other
hand, patients with NLD-SFN experience sensory symptoms in a rather patchy asymmetrical distribution in the face, trunk, and upper limbs, in addition to symptoms in the lower limbs. Eighty-three percent of the patients included in this study had LD-SFN. Reports on the gender distribution in SFN have been conflicting, though most studies have found a female predominance.\textsuperscript{1,4,10,13,20-23} We also found a female predominance in patients with SFN: 63% of LD-SFN patients and 80% of NLD-SFN patients were women. The opposite gender distribution of a male predominance has been reported in patients with chronic idiopathic axonal polyneuropathy.\textsuperscript{35-48} The gender difference in neuropathy patients related to the size of affected fibers may indicate gender-related etiological factors and warrants further study.

The morbidity in the group of patients with idiopathic SFN with or without large fiber involvement was high: more than 80% of the 29 patients had continuous neuralgic pain, and (notably) about 50% also reported myalgia. Myalgia is not known to be a coexisting symptom in patients with idiopathic neuropathy. The influence of polyneuropathy on daily activities such as work has been reported previously,\textsuperscript{49,50} but we found reduced work capacity as a direct consequence of idiopathic SFN in 31% of our patients.

**Etiological causes of SFN among the excluded patients**

The second most common etiology identified in exclusion group A was toxic neuropathy, which was mainly caused by chemotherapeutic drugs (14.4%). It is well known that neurotoxic drugs cause SFN,\textsuperscript{2,17,50,51} but the frequency was lower in previous reports\textsuperscript{1,4,10} than in our study. Sarcoïdosis, another described cause of SFN,\textsuperscript{50} was found in one patient in exclusion group A. Serum angiotensin-converting enzyme (S-ACE) was not included in our initial laboratory protocol, so we lacked data regarding S-ACE from five of the 29 patients in the inclusion group. Devigili et al.\textsuperscript{1} reported no cases of sarcoïdosis in their group of 67 SFN patients, though S-ACE was not included in the work-up. On the other hand, Khan and Zhou\textsuperscript{16} tested for S-ACE in their patient group (n=238), and found increased levels suggestive of sarcoïdosis in three patients (1.2%), all of whom had NLD-SFN.

Mitochondrial disease was suspected in two of our patients, but this was verified by DNA analysis in only one of them. That patient was included initially (Fig. 1) and had normal electromyography (EMG) findings prior to inclusion in the study. However, follow-up EMG that was performed due to progressive muscle weakness revealed a myopathic pattern, and a muscle biopsy confirmed myopathy indicative of mitochondrial disease. Biochemical analysis of isolated mitochondria revealed severely reduced complex I activity in the respiratory chain and low adenosine-5’-triphosphate production with all substrates dependent on complex I. Sequencing the mitochondrial DNA obtained from complex I revealed a novel mutation. Polyneuropathies are prevalent in mitochondrial disorders\textsuperscript{1,35} they often present as asymmetric, mostly axonal, sensorimotor multifocal neuropathy,\textsuperscript{83,84} although SFN has been reported as a single manifestation in the PNS in mitochondrial myopathy.\textsuperscript{55}

Impaired glucose tolerance seems to be an underdiagnosed condition in patients with SFN, probably due to primary care physicians or neurologists not performing this test routinely in the work-up of most patients with SFN. Devigili et al.\textsuperscript{1} could identify a possible cause in seven of 28 patients with idiopathic SFN at a 2-year follow-up: two had IGT, four had diabetes mellitus, and one had Sjögren syndrome. We uncovered IGT in 16% of 45 patients with seemingly idiopathic SFN. However, we did not find any correlation between clinical findings in patients with idiopathic SFN and any other cardiovascular risk factors. IGT as an etiology of sensory neuropathy is still debated. However, several studies have indicated that IGT is a strong risk factor for neuropathy,\textsuperscript{44} although Hughes et al. could not confirm that IGT was the etiology for chronic idiopathic axonal polyneuropathy in a controlled study,\textsuperscript{49} and an increased prevalence of large fiber polyneuropathy was not detected among patients with impaired glycemic control.\textsuperscript{36} Hyperlipidemia has been identified as an independent risk factor for polyneuropathy.\textsuperscript{4,45,52} This could not be confirmed in our study, since 72% of our patients lacked risk factors for cardiovascular disease (including hyperlipidemia).

**Genetic alterations in GLA in patients with idiopathic SFN**

A recently published pilot study by Tanislav et al.\textsuperscript{34} found mutations in GLA in 5 of 24 patients (21%) with idiopathic SFN. One patient had a typical mutation for Fabry disease c.424T>C [C142R], and four had a complex intronic haplotype (hereafter referred to as haplotype 1) (Table 6).\textsuperscript{35} These four patients had pathological biomarkers of increased levels of lyso-Gb, and urine Gb, but no clinical manifestations of Fabry disease.\textsuperscript{35} This haplotype has also been reported in a patient with confirmed Fabry disease.\textsuperscript{40} Six of the 29 patients (21%) in the present study showed genetic alterations in GLA of unknown clinical relevance, corroborating the results obtained by Tanislav et al.\textsuperscript{35} Two of these six patients had haplotype 1, but none had altered biomarkers for Fabry disease. However, we found the same results among the controls, since 29 of the 203 controls (14%) had genetic alterations in the GLA gene of unknown clinical relevance. Haplotype 1 was found in 22 of 203 controls (11%). The proportion of individuals with genetic alterations in GLA did not differ significantly between patients and...
controls, which implies that Fabry disease is not a probable underlying cause of isolated SFN in Swedish patients. D313Y was found in one of our patients, who had elevated urine Gb3, but normal lyso-Gb, and no reduction in α-GAL activity. There were no other clinical signs of Fabry disease. Whether or not D313Y is a disease-generating mutation is under debate. The classically affected individuals who have a D313Y alteration also have an additional missense mutation.41,43 Yasuda et al. found the D313Y alteration in 0.45% of subjects in a normal Caucasian population.43 However, D313Y has been found as the single genetic alteration in Fabry disease patients with highly reduced enzymatic activity and end-stage disease,42,43 in those with stroke,44 and in Fabry disease presenting with cardiovascular symptoms.42 We do not have information about any possible associated diseases in our healthy controls. Swedish regulations include Fabry disease as an exclusion criterion for being a blood donor. However, we cannot completely rule out the possibility of undiagnosed symptoms and clinical signs of Fabry disease in the male control with the exon mutation c.352C>T [R118C]. R118C was first identified by Spada et al.44 as a novel missense mutation causing late-onset disease, and was subsequently found in patients who had reduced enzyme activity and symptoms such as renal disease and stroke.42,43

The identification of decreased α-GAL activity or a genetic variation in patients with late-onset Fabry disease is not necessarily related to symptoms such as proteinuria, left ventricular hypertrophy, or pain in the hands or feet.44 Biegstraaten et al.44 propose that SFN should be considered to be due to Fabry disease only in patients with Fabry-specific SFN features; that is, a history of neuropathic pain in the hands and/or feet, with the onset of pain in either childhood or adolescence, or a course that is characterized by ongoing pain with exacerbations that are provoked by fever, exercise, or heat.

Limitations
The relatively small number of patients and the diagnostic limitation of using QST in isolation in this study weaken the conclusions drawn; however, this is the first reported controlled study regarding idiopathic SFN and Fabry disease. We chose to use QST as the main method for diagnosing SFN since its results have been found to be strongly correlated with intraepidermal nerve fiber density in detecting SFN according to the European Federation of Neurological Societies guidelines.38,39 To compensate for the shortcoming of QST sensitivity, we required that all included patients diagnosed with SFN on the basis of pathological QST results also had a clinical evaluation that excluded a CNS disorder as a cause of their sensory symptoms. Another limitation of this study is the heterogeneity of nerve fiber involvement in different patients. We therefore cannot exclude the possibility of alternative results in study groups that include only patients with isolated small fiber involvement. However, no apparent etiological or genetic differences were seen between patients with pure small fiber involvement and those with mixed small and large fiber involvement.

Though the results reported herein are based on a relatively small patient material, they indicate that idiopathic SFN predominantly affects women and is associated with high morbidity due to pain as well as reduced working capacity. A standardized focused investigation is important to uncover the etiology of SFN in patients with seemingly idiopathic neuropathy, and IGT is the most common identifiable cause. Idiopathic SFN in young to middle-aged Swedish patients seems not to be due to late-onset Fabry disease.

Conflicts of Interest
The authors have no financial conflicts of interest.

Acknowledgements
This study was supported by an unrestricted grant from Shire Human Genetic Therapies.

REFERENCES


