Germline SMARCB1 mutation and somatic NF2 mutations in familial multiple meningiomas

Christiaans, I.; Kenter, S.B.; Brink, H.C.; van Os, T.A.M.; Baas, F.; van den Munckhof, P.; Kidd, A.M.J.; Hulsebos, T.J.M.

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I Christiaans,1 S B Kenter,2 H C Brink,1 T A M van Os,1 F Baas,2 P van den Munckhof,3 A M J Kidd,4 T J M Hulsebos2

ABSTRACT

Background Multiple meningiomas occur in <10% of meningioma patients. Their development may be caused by the presence of a predisposing germline mutation in the neurofibromatosis type 2 (NF2) gene. The predisposing gene in patients with non-NF2 associated multiple meningiomas remains to be identified. Recently, SMARCB1 was reported to be a potential predisposing gene for multiple meningiomas in a family with schwannomatosis and multiple meningiomas. However, involvement of this gene in the development of the meningiomas was not demonstrated.

Results Five affected members of a large family with multiple meningiomas were investigated for the presence of mutations in SMARCB1 and NF2. A missense mutation was identified in exon 2 of SMARCB1 as the causative germline mutation predisposing to multiple meningiomas; furthermore, it was demonstrated that, in accordance with the two-hit hypothesis for tumourigenesis, the mutant allele was retained and the wild-type allele lost in all four investigated meningiomas. In addition, independently somatically acquired NF2 mutations were identified in two meningiomas of one patient with concomitant losses of the wild-type NF2 allele.

Conclusion It is concluded that, analogous to the genetic events in a subset of schwannomatosis associated schwannomas, a four-hit mechanism of tumour suppressor gene inactivation, involving SMARCB1 and NF2, might be operative in familial multiple meningiomas associated meningiomas.

INTRODUCTION

Meningiomas are among the most common intracranial primary tumours (20% of all brain tumours), usually occurring as slowly growing sporadic solitary lesions.1 They also develop in about 50% of patients with neurofibromatosis type 2 (NF2). The hallmark of NF2 is the presence of bilateral vestibular schwannomas. Schwannomas at other locations are found in more than 50% of patients.2–4 NF2 patients carry a heterozygous germline mutation in the NF2 gene and the wild-type copy of this gene is often found to be lost in the NF2 associated tumours.5–7

Multiple meningiomas occur in <10% of patients with meningioma.5 These may be NF2 associated and in those cases develop as the consequence of the presence of a predisposing NF2 germline mutation. Non-NF2 associated multiple meningiomas may occur as sporadic or familial cases. The limited number of meningiomas of familial multiple meningioma patients investigated thus far did not display somatic or constitutional NF2 mutations.9–10 The multiple tumours of sporadic patients were found to carry an identical somatic NF2 mutation, which was not present in their constitutional DNAs.9–10 This might be explained by spread via the cerebrospinal fluid or distant metastasis of a single tumour or as a consequence of mosaicism with undetectable contribution of the NF2 mutation to the constitutional DNA. Alternatively, the non-NF2 sporadic and familial cases suggest that a gene different from NF2 is implicated in the development of non-NF2 associated multiple meningiomas. This contention is supported by an earlier linkage study in a family with meningiomas in which a 15 cM region around and including NF2 was excluded from harbouring the meningioma predisposing gene.11

SMARCB1 is a predisposing gene in schwannomatosis, which is characterised by the presence of multiple schwannomas in the absence of vestibular schwannomas. The gene is involved in about 30–40% of the familial cases, but in no more than 10% of the sporadic cases. In the schwannomas of these patients, the wild-type copy of SMARCB1 is found to be inactivated, usually by deletion. In addition, somatically acquired NF2 mutations have been found in schwannomas of patients with a germline SMARCB1 mutation.12–13

We wondered whether SMARCB1 might be a predisposing gene in multiple meningiomas as well. Support for this candidacy is given by the location of SMARCB1, which is proximal to marker D22S1, that is outside the region excluded by linkage analysis.14 Furthermore, somatic SMARCB1 mutations have been shown to occur in sporadic meningiomas, albeit at low frequency, that is <5% of tumours.19–21 Evidence for the involvement of SMARCB1 in multiple meningiomas was recently reported by Bacci et al.22 who showed the inheritance of a germline SMARCB1 mutation in a family with schwannomatosis and multiple meningiomas. However, the mutational status of SMARCB1 (and of NF2) in the meningiomas of the patients was not clarified. In another recent study, no germline SMARCB1 mutation could be detected in 47 patients with multiple meningiomas, including eight familial cases.23

In this study, we investigated a large family with three members affected by multiple meningiomas and two with a single meningioma. We identified the causative germline SMARCB1 mutation segregating with (multiple) meningiomas in this family and demonstrated inactivation by deletion of the wild-type copy of SMARCB1 and additional bi-allelic
and independent inactivation of \(NF2\) in meningiomas of the patients.

**PATIENTS AND METHODS**

**Patients**

Informed consent was obtained from all family members for using their body materials. The proband (III-6 in figure 1) was referred to our outpatient clinic with a suspected diagnosis of \(NF2\) because of multiple meningiomas. At the age of 54 years she presented with epilepsy. CT of the brain showed three extra-axial lesions along the falx cerebri, which were suspected of being meningiomas. Two lesions were resected and pathological examination confirmed the diagnosis of meningioma. At the age of 51 years, our proband developed sensory problems and paraplegia of the legs. MRI of the brain and spinal cord showed an intradural extramedullary lesion at thoracic level (T) 7, suspected of being a meningioma. The lesion was removed and turned out to be a psammomatous meningioma, WHO grade I. An uncle of our proband (II-6 in figure 1) underwent surgery on a spinal psammomatous meningioma at T10 at age 53. A fibrous meningioma at T6 was removed from the spinal cord of her daughter (III-1 in figure 1) at the age of 40 years.

None of the affected family members had neurofibromas, café-au-lait spots or freckling. Their clinical characteristics are summarised in table 1.

**DNA and RNA samples**

A frozen tissue sample of a brain meningioma M1 of patient III-6 and formalin fixed, paraffin embedded (FFPE) tissue samples of one meningioma each of patients II-6, II-9, and III-1, and the brain and spinal cord meningiomas (M1, M2) of patient III-6, were available for molecular analysis. DNA was extracted and purified from blood samples and the tumour tissue samples according to standard methods. DNA extracted from the meningioma of patient II-9 was too heavily degraded for reliable molecular analyses.

Total RNA was extracted and purified from another part of the frozen tissue sample of meningioma M1 of patient III-6 using TRIzol LS Reagent according to the protocol of the manufacturer (Invitrogen, Leek, The Netherlands). One microgram of total RNA was used to synthesise cDNA with random priming according to standard methods.

**Microsatellite analysis**

Genotyping of family members and loss of heterozygosity (LOH) analysis of tumours were performed by using the chromosome 22-specific microsatellite markers of the ABI Prism Linkage Mapping Set version 2.5-HDS and additional marker D22S929. Primer sequences for the latter marker were taken from Legoix et al.24 Data were analysed with Genemapper software version 4.0. (Applied Biosystems, Foster City, California, USA).

**Mutation analysis**

\(SMARCB1\) and \(NF2\) were sequenced by using genomic or cDNA as substrate for amplification by PCR. Primer sequences for mutation analysis of the \(SMARCB1\) and \(NF2\) exons have been published previously.15 For improved performance, some \(SMARCB1\) primers were newly designed (sequences available on request). In degraded DNA extracted from FFPE material, the \(SMARCB1\) exon 2 segment harbouring the missense mutation was sequenced by using forward primer 5'-CCTTTAATAGCCCTTCTGTGCT-3' and reverse primer 5'-TCTTCCACATGGCTAGTCG-3', generating a PCR product of 116 bp.

The cDNA product from meningioma M1 of patient III-6 was sequenced by using forward primer 5'-GACGCCAGGTTC-TACAT-3' in exon 1 and reverse primer 5'-TCTTCCACATGGCTAGTCG-3' at the 3'-end of exon 2, generating a PCR product of 148 bp. All sequence reactions were performed using ABI Big Dye v3.1 chemistry, and the products were sequenced with an ABI 3730 capillary system (Applied Biosystems). Sequences were analysed with CodonCode Aligner (CodonCode Corp, Dedham, Massachusetts, USA).

The HomoloGene program in PubMed was used to perform amino acid sequence alignments (http://www.ncbi.nlm.nih.gov/ pubmed). The PolyPhen and SIFT programs were used to predict the impact of amino acid substitutions on protein function and structure (http://genetics.bwh.harvard.edu/pph and http://sift.jcvi.org, respectively).

**RESULTS**

Sequencing of the nine exons of \(SMARCB1\) in constitutional DNA of proband III-6 revealed a missense mutation in exon 2,
c.143C→T, P48L (figure 2), which also proved to be present in constitutional DNA of the other affected family members (III-7, II-6, II-9, and III-1). The mutation was not found in constitutional DNA of more than 100 control individuals. The proline residue that is replaced by leucine in the resulting SMARCB1 protein is evolutionarily conserved across all species for which sequence information is available (data not shown). In silico analyses with the Polyphen and SIFT programs predicted that the amino acid substitution affects SMARCB1 protein function and is probably damaging.

The four meningiomas that were available for molecular analysis all showed loss of the wild-type C allele, as demonstrated in figure 2 for the brain (M1) and spinal cord (M2) meningioma of the proband (III-6). In accordance with this, genotyping with flanking markers revealed retention of the chromosome 22 segment containing the mutant T-allele in the investigated tumours, as exemplified in figure 2 for marker D22S1174. The data are summarised in figure 1.

To investigate whether the retained SMARCB1 allele was transcribed, we extracted total RNA from frozen tissue of meningioma M1 and reverse transcribed it into cDNA. The cDNA sequence demonstrates that a stable mRNA is transcribed from the retained mutant allele (figure 2).

Schwannomatosis associated schwannomas harbour somatically acquired NF2 mutations. Considering the apparent analogy with schwannomatosis, we wondered whether these mutations might also be present in the meningiomas of the family under study. Although attempts were made to sequence NF2 in all available meningiomas, reliable sequences could only be derived from the frozen tumour M1 and the freshly fixed tumour M2, both of proband III-6. We found a missense mutation in exon 4 of meningioma M1 (c.422T→G, p.L141R) and a nonsense mutation in exon 8 (c.773G→A, p.W258X) of meningioma M2, both being absent in the corresponding constitutional DNA of the patient (figure 3). The leucine residue at position 141 is evolutionarily conserved (data not shown). The Polyphen and SIFT programs predicted that the amino acid substitution caused by the missense mutation affects NF2 protein function and is probably damaging. The sequence recordings indicate loss of the wild-type allele in both tumours. This is substantiated by LOH analysis with the intragenic NF2 marker D22S929, which shows considerable loss of the 132 bp allele in tumour M1 as well as tumour M2 (figure 3). Finally, we sequenced all exons of the NF2 gene in constitutional DNA of the affected family members (III-6, III-7, II-6, II-9, III-1), but did not detect any deviation from the wild-type sequence.

Table 1 Clinical characteristics of affected family members

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex (M/F)</th>
<th>Age (years) at diagnosis</th>
<th>Presenting symptom</th>
<th>Meningiomas (n, location)</th>
<th>Schwannomas (n, location)</th>
</tr>
</thead>
<tbody>
<tr>
<td>III-6</td>
<td>F</td>
<td>34</td>
<td>Epilepsy</td>
<td>3 cranial, 1 spinal</td>
<td>—</td>
</tr>
<tr>
<td>III-7</td>
<td>F</td>
<td>37</td>
<td>Chest wall mass</td>
<td>Multiple cranial, 1 spinal</td>
<td>Multiple chest wall, multiple spinal, 1 elbow</td>
</tr>
<tr>
<td>II-6</td>
<td>M</td>
<td>56</td>
<td>Deafness</td>
<td>Multiple spinal</td>
<td>1 vestibular</td>
</tr>
<tr>
<td>II-9</td>
<td>F</td>
<td>53</td>
<td>Paresis legs</td>
<td>1 spinal</td>
<td>—</td>
</tr>
<tr>
<td>III-1</td>
<td>F</td>
<td>40</td>
<td>Sensory problems</td>
<td>1 spinal</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 2 Sequence analysis of part of exon 2 of SMARCB1 and loss of heterozygosity (LOH) analysis with marker D22S1174 in blood and meningioma DNAs of patient III-6. Left: presence of the mutant T allele in constitutional blood (B) DNA and considerable loss of the wild-type C allele in genomic and cDNA of meningioma M1 and in genomic DNA of meningioma M2. Right: Presence of two alleles of marker D22S1174 in blood DNA and considerable loss of the 145 bp allele, marked by arrow, in meningioma M1 and M2 DNA.
Our data, we conclude that, analogous to the genetic events in a subset of schwannomatosis associated schwanomas, as well. However, the vestibular schwannoma was diagnosed at age 56 and such a sporadic unilateral tumour is not uncommon at that age in the general population. Unfortunately, the schwannomas were not available to further investigate the possible involvement of SMARCB1. A schwannoma analysed in the family with schwannomatosis and multiple meningiomas indeed displayed bi-allelic inactivation of SMARCB1. Two other schwannomatosis families, each with one patient developing one or two meningiomas, have been reported. However, the status of SMARCB1 in these tumours was not investigated. Considering the frequent occurrence of meningiomas in the general population, it cannot be excluded that their association with schwannomatosis in the latter families was coincidental. On the other hand, the missense mutation in SMARCB1 in our family, affecting amino acid residue 48, and most probably also in the family presented by Bacci et al., affecting nearby amino acid residue 31, clearly predispose to the development of multiple meningiomas. Therefore, it is possible that the preference for meningioma development is, at least in part, determined by type and location of the SMARCB1 mutation. Alternatively, the co-occurrence of schwannomas and meningiomas in some SMARCB1 families and the sole occurrence of schwanomas in most other SMARCB1 families may point to the existence of modifying genes segregating in these families and affecting the phenotypic expression of the SMARCB1 mutation. Our finding, and that of Bacci et al., that meningiomas are part of the schwannomatosis tumour spectrum may require the diagnostic criteria for this disease be reconsidered. Further investigation of the possible association of type and location of the SMARCB1 mutation and the development of multiple meningiomas and of possible modifying factors will require the identification and clinical evaluation of additional carriers of the mutated gene in our family and in other multiple meningiomas patients and families.

We identified additional independent somatic mutations in the NF2 gene in the brain (M1) and spinal cord (M2) meningiomas of patient III-6 (figure 3). The missense mutation in exon 4 in meningioma M1 caused replacement of the evolutionary conserved leucine residue at position 141 with an amino acid residue 31, cleary predispose to the development of multiple meningiomas. Therefore, it is possible that the preference for meningioma development is, at least in part, determined by type and location of the SMARCB1 mutation. Alternatively, the co-occurrence of schwannomas and meningiomas in some SMARCB1 families and the sole occurrence of schwanomas in most other SMARCB1 families may point to the existence of modifying genes segregating in these families and affecting the phenotypic expression of the SMARCB1 mutation. Our finding, and that of Bacci et al., that meningiomas are part of the schwannomatosis tumour spectrum may require the diagnostic criteria for this disease be reconsidered. Further investigation of the possible association of type and location of the SMARCB1 mutation and the development of multiple meningiomas and of possible modifying factors will require the identification and clinical evaluation of additional carriers of the mutated gene in our family and in other multiple meningiomas patients and families.

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(<10% of cases). It is possible that, as in familial schwannomatosis (30–40% of cases), SMARCB1 involvement is more frequent in familial multiple meningiomas. Alternatively, other genes might be implicated as predisposing genetic factors in both diseases.

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