Prevalence of Germline BAP1, CDKN2A, and CDK4 Mutations in an Australian Population-Based Sample of Cutaneous Melanoma Cases

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Mutations in Cyclin-Dependent Kinase Inhibitor 2A (CDKN2A) and Cyclin-Dependent Kinase 4 (CDK4) contribute to susceptibility in approximately 40% of high-density cutaneous melanoma (CMM) families and about 2% of unselected CMM cases. BRCA-1 associated protein-1 (BAP1) has been more recently shown to predispose to CMM and uveal melanoma (UMM) in some families; however, its contribution to CMM development in the general population is unreported. We sought to determine the contribution of these genes to CMM susceptibility in a population-based sample of cases from Australia. We genotyped 1,109 probands from Queensland families and found that approximately 1.31% harbored mutations in CDKN2A, including some with novel missense mutations (p.R22W, p.G35R and p.I49F). BAP1 missense variants occurred in 0.63% of cases but no CDK4 variants were observed in the sample. This is the first estimate of the contribution of BAP1 and CDK4 to a population-based sample of CMM and supports the previously reported estimate of CDKN2A germline mutation prevalence.

Keywords: BAP1, CDK4, CDKN2A, cutaneous melanoma, germline mutation

Many environmental and genetic factors play a part in melanomagenesis. While exposure to ultraviolet radiation plays a significant role in melanoma development, an underlying genetic predisposition also contributes to an individual’s risk. Studies have shown that ~10% of cutaneous malignant melanoma (CMM) cases occur in people that have a family history of melanoma (Gruis et al., 1995; Hussussian et al., 1994; MacGeoch et al., 1994; Soufir et al., 1998; Walker et al., 1995; Zuo et al., 1996). Known high-risk genes account for susceptibility in a proportion of these families. The major CMM predisposition locus CDKN2A encodes two tumor suppressors, p16INK4A and p14ARF, that inhibit progression of cancer cells by inducing senescence or apoptosis, respectively (de Snoo & Hayward, 2005; Palmieri et al., 2009). CDKN2A is thus involved in two of the most important tumor suppressor pathways, the p53 and the retinoblastoma (RB) pathways.

The largest study of germline mutations in CDKN2A in families to date was conducted by the International Melanoma Genetics Consortium (GenoMEL), in which 466 families from North America, Europe, Asia, and Australia were genotyped for mutations in CDKN2A and CDK4 (Goldstein et al., 2006). They found 41% of high-density families (defined by case-load depending on the region of origin) carried germline mutations in either p16 (38%), p14 (1.5%) or CDK4 (1%). Overall, 57 unique mutations in p16 were attributed to increased CMM risk. In contrast, only two variants in CDK4 have been attributed to CMM risk; p.R24C and p.R24H (Sofir et al., 1998; Zuo et al., 1996). A study into the prevalence of CDKN2A and CDK4 mutations in CMM cases from a Greek hospital-based sample found that 5% of cases (16 of 320) harbored a mutation in one of these genes (Nikolaou et al., 2011). But, to date, there are only two published studies determining the prevalence of high-risk predisposition loci in population-based samples of CMM cases. The Genes Environment and Melanoma (GEM) study genotyped probands from nine different geographical regions in the USA, Canada, Italy, and Australia...
(Begg et al., 2005). They discovered 65 CDKN2A mutation carriers in a sample of 3,550 affected individuals, equating to a population frequency of ~2%. A second study looked at the contribution of CDKN2A to melanoma in a population-based sample of cases \(N = 482\) from Queensland (Aitken et al., 1999), from which it was estimated that CDKN2A mutations occur in 0.2% of population-based Queensland CMM cases (Aitken et al., 1999).

**BAP1** is a tumor suppressor gene located on chromosome 3 that has also been associated with predisposition to CMM. In a seminal study, somatic BAP1 mutations were first observed in a panel of sporadic UMM cases; notably, a single UMM case also carried a germline BAP1 mutation (Harbour et al., 2010). Since then, BAP1 has been linked to predisposition of a spectrum of cancer types extending beyond UMM to include CMM, mesothelioma, renal cell carcinoma, basal cell carcinoma, as well as a distinct type of benign melanocytic tumor (Abdel-Rahman et al., 2011; Aoude et al., 2013; Carbone et al., 2012; Cheung et al., 2013; de la Fouchardiere et al., 2014; Harbour et al., 2010; Hoiom et al., 2013; Njauw et al., 2012; Popova et al., 2013; Testa et al., 2011; Wad et al., 2014; Wiesner et al., 2011). Population-based and clinic-based prevalence studies show that BAP1 germline mutations contribute to only a small proportion of UMM cases overall (3–4%; Aoude et al., 2013; Njauw et al., 2012) but the contribution of such mutations to a population-based sample of CMM cases has not been reported.

The primary aim of this study was to more fully quantify the contribution of constitutional CDKN2A and CDK4 mutations in an Australian population-based sample of CMM cases. A secondary aim was to determine the prevalence of germline BAP1 mutations in this sample.

**Materials and Methods**

**Ethics**

Written consent was obtained for each participant in this study. Ethics approval was obtained from the QIMR Berghofer Human Research Ethics Committee (HREC).

**Study Cohort**

Samples were ascertained as part of the Q-MEGA project, a population-based study from Queensland investigating the associations between genes and environment in CMM development (Baxter et al., 2008). Q-MEGA is made up of four distinct CMM case sample collections: childhood, adolescent, men over 50 years, and the Queensland Familial Melanoma Project (QFMP; Aitken et al., 1996). Individuals who presented with histologically confirmed CMM and were reported to the Queensland Cancer Registry between the years 1982 and 1990 were approached to participate in the QFMP study \(N = 12,006\). This accounted for approximately 95% of CMM cases diagnosed in Queensland over this period (Aitken et al., 1996). Cases were asked to fill out a questionnaire pertaining to family history, pigmentation, freckling, mole count, and likelihood of sunburn. In the instance where an individual had a family history of melanoma, the first degree relatives and affected cases were also ascertained. A follow-up study in 2002–2005 collected updated data and additional blood samples. A total of 1,897 individual families were sampled and stratified into three categories according to a standardized family risk index, previously described (Aitken et al., 1994). Generally, although there were a few exceptions, individuals with no family history of CMM were categorized as low-risk \(N = 1,392\), two-case families were categorized as intermediate-risk \(N = 414\) and families with three or more cases were categorized as high-risk \(N = 91\). Additionally, twins with CMM collected in Queensland and New South Wales were included (Shekar et al., 2009). For the current study a random selection of 1,109 cases from across the 2,599 probands in Q-MEGA was used (Table 1). Selection was based on the order in which DNA samples were replated into 384 well plates.

**Sample Preparation**

Blood samples were obtained from 2,599 probands (Table 1) ascertained through the Q-MEGA studies (Baxter et al., 2008). Genomic DNA was extracted using a standard salting out method (Miller et al., 1988).

**Targeted Sequencing of CDKN2A and BAP1 using the Ion Torrent PGM**

Melanoma cases were assessed for variants in BAP1 and CDKN2A in a targeted sequencing approach. Using Ion AmpliSeq library kits (Life Technologies, CA, USA), 10 ng
of genomic DNA from each proband were amplified using custom-designed primer pools. The panel was designed to generate coverage of 40X across all regions with amplicon lengths of 150 bp to 250 bp. BAP1 and CDKN2A had coverage of 96% and 97%, respectively. Ion Xpress barcode adapters 1–64 were used to pool samples. Unamplified libraries were purified using Agencourt Ampure XP reagent (Beckman Coulter, CA, USA) in order to eliminate fragments < 100 bp and increase the proportion of on-target reads. Libraries were equalized to ~100 pM using Ion Library Equalizer kits then combined into a single sample. A portion of the library (4 µL) was then diluted in 21 µL nuclease-free water to create a working stock. Using OT2 200 Kits (Life Technologies, CA, USA), clonal amplification and template enrichment of the Ion Sphere particles was performed. The template quality was assessed using a Qubit 2.0 (Life Technologies, CA, USA). Finally, Ion 318v2 chips were run on a Personal Genome Machine (Life Technologies, CA, USA) with 500 run flows per chip.

Overall, 1,109 samples had mean sequence coverage of 30X and therefore the sequencing of these samples was considered to be of sufficient depth to give accurate reads. Sequence data were analyzed using Torrent Suite software (Life Technologies, CA, USA). In order to minimize the false positive rates, filtering criteria were applied to the output. First, variants were required to have minimum of four reads for the reference and four reads for the alternative alleles. The variant allele also had to comprise at least 20% of the total read count. Quality score had to be > 40. Synonymous variants were excluded. Variants occurring commonly in the NHLBI Exome Sequencing Project (ESP6500; minor allele frequency (MAF) > 0.01) were also excluded as they are unlikely to be high-risk predisposition variants, but rather, common population polymorphisms. This sculpted the final list of variants, which were verified using Sanger sequencing. As a previous study has reported the CDKN2A mutations in the QFMP high-risk cohort (Aitken et al., 1999), the results of which have been replicated here. Variants occurring commonly in the overall prevalence statistics. Of the variants seen here, three are novel and have not been previously reported to the Leiden Open Variation Database (p.R22W, p.G35R, and p.A121T). All occur at evolutionarily conserved amino acids (Figure 1), and although none of these variants have been reported as somatic mutations in CMM, they are unlikely to be high-risk predisposition variants, but rather, common population polymorphisms. This sculpted the final list of variants, which were verified using Sanger sequencing. As a previous study has reported the CDKN2A mutations in the QFMP high-risk cohort (Aitken et al., 1999), the results of which have been replicated here. Variants occurring commonly in the overall prevalence statistics. Sanger sequencing was used to validate the CDKN2A and BAP1 variants identified through targeted sequencing. See Supplementary Table S1 for the list of primers used. Supplementary material is available on the Cambridge Journals Online website.

**CDK4 Genotyping using the Sequenom MassArray**

The two known familial melanoma variants in CDK4 (p.R24C and p.R24H) were genotyped in the QFMP probands using a Sequenom iPLEX gold assay (Sequenom Bioscience, CA, USA). The MassArray designer software was used to design the forward, reverse and extension primers for p.R24C (acgtgctgctgtgatcttggctg, acgtgctgctgtgatcttggctg, acgtgctgctgtgatcttggctg, and gacctgctgctgtgatcttggctg) and p.R24H (acgtgctgctgtgatcttggctg, acgtgctgctgtgatcttggctg, acgtgctgctgtgatcttggctg, and tggcacctgtgggatcatc). IPLEX Gold PCR amplification reactions were set up according to standard manufacturer protocols. Cluster plots were analyzed using Typer Analyzer software 4.0.

**Results**

Targeted sequencing of an unselected population of CMM cases from Queensland, Australia revealed 6 of 1,055 cases harbor a missense variant in CDKN2A (Table 2). We report a single incidence of each of the following variants occurring in p16 (NM 000077): p.L16P, p.R22W, p.G35R, and p.I49F. We also report two incidences of p.G101W (rs104894094), a common founder mutation in European melanoma populations (Goldstein et al., 2006). We found a recurrent mutation, p.A121T (rs199888003), in p14 (NM 058195) in two cases. As this residue is not overly conserved in primates (Rhesus, Figure 1), this is likely to be a non-deleterious mutation and is therefore not included in the overall prevalence statistics. Seventy-two cases carried the well-documented CDKN2A a.a148T polymorphism, giving it a MAF of 0.0353. The MAF reported for this variant in the European American cohort (N = 4,300) of the ESP6500 is 0.0225, which correlates well with the occurrence in our sample. CDKN2A a.a148T has also been omitted from the prevalence statistics. Of the variants seen here, three are novel and have not been previously reported to the Leiden Open Variation Database (p.R22W, p.G35R, and p.A121T). All occur at evolutionarily conserved amino acids (Figure 1), and although none of these variants have been reported as somatic mutations in CMM, they are unlikely to be high-risk predisposition variants, but rather, common population polymorphisms. This sculpted the final list of variants, which were verified using Sanger sequencing. As a previous study has reported the CDKN2A mutations in the QFMP high-risk cohort (Aitken et al., 1999), the results of which have been replicated here. Variants occurring commonly in the overall prevalence statistics. Sanger sequencing was used to validate the CDKN2A and BAP1 variants identified through targeted sequencing. See Supplementary Table S1 for the list of primers used. Supplementary material is available on the Cambridge Journals Online website.

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**Results**

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Variants in BAP1 and CDKN2A Identified Through Targeted Sequencing

<table>
<thead>
<tr>
<th>Sample</th>
<th>Study</th>
<th>Gene</th>
<th>Exon</th>
<th>Position</th>
<th>Reference</th>
<th>NT change</th>
<th>AA change</th>
<th>rsID</th>
<th>ESP6500MAF</th>
<th>European American population</th>
<th>NA</th>
<th>GERP</th>
<th>Estimated constrained elements in the human genome</th>
</tr>
</thead>
<tbody>
<tr>
<td>061090</td>
<td>Intermediate BAP1</td>
<td>13</td>
<td>52437824</td>
<td>NM_004656</td>
<td>c.1337A&gt;T</td>
<td>p.N446I</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td>Tolerated</td>
<td><strong>Damaging</strong></td>
<td><strong>Damaging</strong></td>
</tr>
<tr>
<td>055094</td>
<td>Low BAP1</td>
<td>13</td>
<td>52437234</td>
<td>NM_004656</td>
<td>c.1810G&gt;A</td>
<td>p.V604M</td>
<td>–</td>
<td>-0.000154</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td>Benign</td>
<td>1.49</td>
</tr>
<tr>
<td>006528</td>
<td>Low CDKN2A (p14)</td>
<td>2</td>
<td>21971040</td>
<td>NM_058195</td>
<td>c.361G&gt;A</td>
<td>p.A121T</td>
<td>rs199888003</td>
<td>0.000154</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td>Benign</td>
<td>2.33</td>
</tr>
<tr>
<td>061090</td>
<td>Intermediate BAP1</td>
<td>13</td>
<td>52437824</td>
<td>NM_004656</td>
<td>c.1555C&gt;G</td>
<td>p.P519A</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td>Benign</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>050611</td>
<td>Intermediate CDKN2A (p16)</td>
<td>1</td>
<td>21974762</td>
<td>NM_000077</td>
<td>c.64C&gt;T</td>
<td>p.R22W</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td><strong>Damaging</strong></td>
<td><strong>Damaging</strong></td>
<td>-0.43</td>
</tr>
<tr>
<td>010255</td>
<td>Low CDKN2A (p16)</td>
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<td>21974724</td>
<td>NM_000077</td>
<td>c.103G&gt;A</td>
<td>p.G35R</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td><strong>Probable damaging</strong></td>
<td><strong>Probably damaging</strong></td>
<td>4.84</td>
</tr>
<tr>
<td>051964</td>
<td>Low BAP1</td>
<td>14</td>
<td>52437234</td>
<td>NM_004656</td>
<td>c.1810G&gt;A</td>
<td>p.V604M</td>
<td>–</td>
<td>0.000154</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td>Benign</td>
<td>1.49</td>
</tr>
<tr>
<td>012039</td>
<td>Childhood CDKN2A (p16)</td>
<td>1</td>
<td>21974782</td>
<td>NM_000077</td>
<td>c.145A&gt;T</td>
<td>p.I49F</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td><strong>Damaging</strong></td>
<td><strong>Damaging</strong></td>
<td>4.22</td>
</tr>
<tr>
<td>051362</td>
<td>Intermediate CDKN2A (p16)</td>
<td>1</td>
<td>21974682</td>
<td>NM_000077</td>
<td>c.145A&gt;T</td>
<td>p.I49F</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td><strong>Damaging</strong></td>
<td><strong>Damaging</strong></td>
<td>4.22</td>
</tr>
<tr>
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<td>Low CDKN2A (p16)</td>
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<td>21971057</td>
<td>NM_000077</td>
<td>c.301G&gt;T</td>
<td>p.G101W</td>
<td>rs104894094</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td>Benign</td>
<td>2.33</td>
</tr>
<tr>
<td>061542</td>
<td>Adolescent CDKN2A (p16)</td>
<td>2</td>
<td>21971057</td>
<td>NM_000077</td>
<td>c.301G&gt;T</td>
<td>p.G101W</td>
<td>rs104894094</td>
<td>–</td>
<td>Tolerated</td>
<td>Tolerated</td>
<td>–</td>
<td>Benign</td>
<td>2.33</td>
</tr>
</tbody>
</table>

Note: European American population; NA = not available; GERP = **++** is an estimate of the constrained elements in the human genome.

**Discussion**

We identified CDKN2A missense mutations in 0.57% of melanoma cases in the intermediate, low, twin, childhood, adolescent, and men over 50 cohorts. When this data is combined with that for the QFMP high-risk group published by Aitken et al. (1999), 1.31% of the overall Queensland population-based sample of CMM cases carried a CDKN2A mutation. The estimate for CDKN2A we report here is in keeping with that reported (~2%) in the GEM study (Begg et al., 2005). As might be expected, since CDKN2A mutation has been associated with an increased risk of development of cancer in general (Mukherjee et al., 2012), CDKN2A mutation-positive families in this study are enriched for other cancers (Tables 3 and 4), although absolute numbers are too low to show statistically significant association with any particular cancer type other than melanoma. Furthermore, because the number of mutations we observe is low, there is no statistical difference between the individual Q-MEGA population groups.

The CDKN2A p.G35R mutation has been reported to occur somatically in the COSMIC database, but here we report for the first time its occurrence in the germline of an individual presenting with melanoma and colorectal cancer. A study using both functional and computational prediction of p16 mutations has found that the pathogenicity of this mutation is uncertain (Scaini et al., 2014). The p.A148T variant was observed at a frequency of 6.8% in the Queensland melanoma cases. This substitution is generally not thought to be deleterious, but the functional effect of this variant has been debated in the literature (Debniak et al., 2005; Spica et al., 2006). It has been shown to occur more frequently in Celtic populations and therefore its potential association with CMM risk may be due to its prevalence in a more melanoma-prone population (Aitken et al., 1999).
We found that 0.63% of CMM cases harbored germline missense mutations in \textit{BAP1}. This mutation rate is similar to that reported by Njauw et al. (2012) when they screened a hospital-based sample of 193 CMM families for \textit{BAP1} mutation and reported one truncating mutation (0.5%). To date, all disease-associated variants in \textit{BAP1} have been shown to truncate the protein. The variants we report here are all missense mutations that occur at highly conserved residues in mammals (Figure 2). None were predicted to alter splicing; thus, at this stage it is not clear whether they are responsible for melanoma susceptibility in these individuals, or if they represent rare, benign polymorphisms.

We did not observe any mutations in \textit{CDK4}. This result is in keeping with the low frequency of mutations of this
Table 4

Summary of Cancers in Families With Germline BAP1 and CDKN2A Mutations

<table>
<thead>
<tr>
<th>Proband</th>
<th>Gene</th>
<th>AA change</th>
<th>Study</th>
<th>Ages of onset of CMM</th>
<th>Other cancers in proband (age)</th>
<th>Other cancers in family (age)</th>
</tr>
</thead>
<tbody>
<tr>
<td>006090</td>
<td>BAP1</td>
<td>p.G121R</td>
<td>Low</td>
<td>45, 72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>002203</td>
<td>BAP1</td>
<td>p.R150C</td>
<td>Low</td>
<td>32, 57</td>
<td>breast (57)</td>
<td></td>
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<tr>
<td>009341</td>
<td>BAP1</td>
<td>p.P222T</td>
<td>Intermediate</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>011937</td>
<td>BAP1</td>
<td>p.N446I</td>
<td>High</td>
<td>53</td>
<td>lung (65), lung (68)</td>
<td>CMM (37)</td>
</tr>
<tr>
<td>052809</td>
<td>BAP1</td>
<td>p.S519A</td>
<td>Intermediate</td>
<td>41</td>
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<td></td>
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<tr>
<td>050611</td>
<td>BAP1</td>
<td>p.V604M</td>
<td>Intermediate</td>
<td>64</td>
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<td></td>
</tr>
<tr>
<td>051964</td>
<td>BAP1</td>
<td>p.V604M</td>
<td>Low</td>
<td>59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>006528</td>
<td>CDKN2A (p14)</td>
<td>p.A121T</td>
<td>Low</td>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>002507</td>
<td>CDKN2A (p14)</td>
<td>p.A121T</td>
<td>Low</td>
<td>38</td>
<td>lung (65), colorectal (64)</td>
<td></td>
</tr>
<tr>
<td>012039</td>
<td>CDKN2A (p16)</td>
<td>p.L16P</td>
<td>Childhood</td>
<td>12, 18, 22</td>
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<td></td>
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<tr>
<td>050731</td>
<td>CDKN2A (p16)</td>
<td>p.R22W</td>
<td>Intermediate</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>010255</td>
<td>CDKN2A (p16)</td>
<td>p.G35R</td>
<td>Low</td>
<td>78</td>
<td>colorectal (86)</td>
<td></td>
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<tr>
<td>051362</td>
<td>CDKN2A (p16)</td>
<td>p.I49F</td>
<td>Intermediate</td>
<td>26, 26, 27, 29, 45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>008197</td>
<td>CDKN2A (p16)</td>
<td>p.G101W</td>
<td>Low</td>
<td>47, 71</td>
<td></td>
<td></td>
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<tr>
<td>061542</td>
<td>CDKN2A (p16)</td>
<td>p.G101W</td>
<td>Adolescent</td>
<td>18, 30, 30, 35</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: CMM = cutaneous malignant melanoma.

gene reported in the literature. To date, only 17 families worldwide have been documented to carry CDK4 mutations (Puntervoll et al., 2013; Soufir et al., 1998; Zuo et al., 1996). All reported pathogenic mutations in p14 have been splice mutations, whole gene deletions or insertions (Harland et al., 2005; Mistry et al., 2005; Randerson-Moor et al., 2001; Rizos et al., 2001). Currently, no pathogenic missense mutations are known to occur in p14.

In summary, we report three novel variants in CDKN2A and three previously reported mutations, along with seven novel missense variants in BAP1. Germline mutations that we observe for the two genes combined (~2%) thus account for only a small proportion of all CMM cases in this population. This suggests that genes other than the high-penetrance familial melanoma loci are responsible for the bulk of CMM susceptibility in the general population.

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Supplementary Material

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