Homozygous Deletion of CDKN2A and Codeletion of the Methylthioadenosine Phosphorylase Gene in the Majority of Pleural Mesotheliomas

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ABSTRACT

Purpose: Homozygous deletions at chromosome region 9p21 targeting the CDKN2A gene have been reported as a common cytogenetic abnormality in mesothelioma. MTAP, a gene ~100-kb telomeric to CDKN2A, encodes methylthioadenosine phosphorylase, an enzyme essential in the salvage of cellular adenine and methionine, and its codeletion with CDKN2A has been reported in other tumors. The aim of this study was to define the prevalence of homozygous deletion of CDKN2A alone or in combination with MTAP in a large series of pleural mesothelioma.

Experimental Design: We used a fluorescent in situ hybridization assay for CDKN2A and MTAP on interphase nuclei in imprints of frozen tissue from 95 cases of pleural mesothelioma. Histologically, the cases were classified as epithelial (71), biphasic (19) and sarcomatous (5). In each experiment, a 9p21 locus specific probe and a chromosome 9 centromeric probe were used and fluorescent in situ hybridization signals for both probes were simultaneously recorded in at least 100 nuclei. Cases were considered homozygously deleted if both 9p21 signals were lost in at least 20% of nuclei.

Results: Overall, 70 cases (74%) had homozygous deletion of CDKN2A. MTAP was codeleted in 64 of these cases (91%). No case with MTAP deletion without CDKN2A deletion was identified. Homozygous loss of CDKN2A was seen in 49 of 71 epithelial (70%), 16 of 19 biphasic (89%), and 5 of 5 sarcomatous (100%) mesotheliomas.

Conclusions: Homozygous deletion of CDKN2A is seen in the majority of pleural mesotheliomas, and MTAP is codeleted in most of these cases. Previous cell line studies have shown that loss of MTAP renders cells dependent on de novo synthesis of purine derivatives. Thus, the particularly high prevalence of MTAP codeletion in mesothelioma makes it an ideal candidate for trials of targeted therapy using inhibitors of de novo AMP synthesis (e.g., l-alanosine).

INTRODUCTION

Malignant mesothelioma is an aggressive neoplasm of the serosal membranes of the body cavities. The majority of cases occur in patients exposed to asbestos. The diagnosis is often difficult because in most cases mesothelioma has an insidious onset, and the patients present with nonspecific symptoms. Recent advances in multimodality management have resulted in moderately improved survival but mainly for patients with stage I disease (1–3).

The molecular pathogenesis of malignant mesothelioma appears to involve a still poorly understood combination of exposure to environmental (asbestos) and infectious (SV40) agents and somatic genetic alterations (most commonly in CDKN2A and NF1), as recently reviewed elsewhere (4). Cytogenetic and molecular studies have identified several frequent genetic alterations in mesothelioma (5, 6), of which one of the most common is homozygous deletion of the 9p21 locus within a cluster of genes that includes CDKN2B, CDKN2A, and MTAP. CDKN2B and CDKN2A encode cell cycle regulatory proteins, whereas MTAP encodes methylthioadenosine phosphorylase, an enzyme essential in the salvage pathway of AMP synthesis and in methionine synthesis. Results from several groups suggest that the prevalence of CDKN2A deletion in malignant mesothelioma is up to 72% among primary tumors and may be even higher in mesothelioma cell lines (7–9). In addition, as in other cancer types, studies of mesothelioma have described CDKN2A promoter methylation as an alternative mechanism of CDKN2A inactivation in some nondeleted cases (10).

CDKN2A encodes two important cell cycle regulatory proteins, the p16 protein (11) and, in an alternative reading frame, the p14ARF protein (12). P16, a cyclin-dependent kinase inhibitor, acts through CDK4/CDK6 and blocks the phosphorylation of the RB protein, and p14ARF binds MDM2, thus preventing the latter from binding p53 and targeting it for degradation (reviewed in Ref. 13).

MTAP converts methylthioadenosine, a product of polynucleotide synthetase, to adenine and methylthioribose-1-phosphate. The former is used for AMP and the latter for methionine synthesis (Fig. 1). Thus, tumor cells that lack MTAP are completely dependent on de novo synthesis of purine derivatives for the generation of AMP and, therefore, are potentially sensitive to inhibitors of the de novo purine synthesis pathway (e.g., l-alanosine).

On the basis of studies of several tumor types, it appears that the 9p21 deletions targeting CDKN2A are usually large and often also include CDKN2B and MTAP (14–16). However, there have been no systematic studies of the frequency of
codeletion of CDKN2A and MTAP in malignant mesotheliomas. To address this issue, we have used FISH\(^3\) with probes corresponding to CDKN2A or MTAP to determine the frequency of CDKN2A-MTAP codeletion in 95 cases of primary pleural malignant mesothelioma. Our results confirm the high prevalence of CDKN2A deletion in mesotheliomas and suggest that this tumor may be an especially attractive candidate for MTAP-directed therapy.

**MATERIALS AND METHODS**

We studied 96 frozen tissue specimens from 95 patients (17 females, mean age: 55.8 years, range: 30–76 years; 78 males, mean age: 63.2, range: 32–77 years) collected between 1992 and 2000. Samples were procured at MSKCC under an approved Institutional Review Board protocol. The diagnosis in each case was confirmed by histological examination and electron microscopy or immunohistochemistry if necessary. Histologically, the cases included 71 epithelioid, 19 biphasic, and 5 sarcomatoid subtypes. We also studied three mesothelioma cell lines (JMN, NCI-H2052, NCI-H28; gifts of Frank Sirotnak, MSKCC) and used an Ewing’s sarcoma cell line (A673; American Type Culture Collection, Manassas, VA) with known homozygous 9p21 deletion (17) and normal peripheral blood lymphocytes as controls.

**Slide Preparation.** Tissue imprints of the frozen tissue were air dried followed by fixation in modified Carnoy’s fixative (methanol:glacial acetic acid = 3:1) for 30 min and then by air drying. The slides were stored on −20°C until hybridization. The first and last imprints were stained with Diff Quik to evaluate the presence of tumor cells. Pretreatment with collagenase H and postfixation with formalin were performed as described previously (18).

**Probe Preparation.** Plasmid DNA from clones P1-1063 and P1-1069 (Ref. 11; gift of Alex Kamb, Myriad Genetics, Salt Lake City, UT) containing a fragment of human genomic DNA ∼100 kb from the CDKN2A and MTAP regions, respectively (Fig. 1), was isolated from large scale bacterial cultures using standard methods (Qiagen plasmid maxi kit; Qiagen, Inc., Valencia, CA). Labeled probe was prepared by nick translation (Nick translation kit; Vysis, Inc., Downers Grove, IL) using spectrum green- or spectrum aqua-labeled dUTP (Vysis, Inc.), following the manufacturer’s instructions. The chromosome 9 centromere probe used for two- or three-color FISH, labeled with spectrum green or spectrum aqua, respectively, was CEP-9 (Vysis, Inc.). Probes were stored at −20°C.

**FISH.** In each experiment, dual color FISH was performed using a spectrum green-labeled CEP9 probe and a spectrum orange-labeled CDKN2A (P1-1063) or MTAP (P1-1069) probe and Ewing’s sarcoma cell line A673 (with known homozygous deletion of CDKN2A; Ref. 17) and normal peripheral blood lymphocytes served as positive and negative controls, respectively. The slides and probe DNA was denatured separately in 70% formamide/2× SSC (pH 7.4, 73–75°C, 5 min). After denaturation, the slides were dehydrated in an ice-cold graded ethanol series, and the probe mix was applied. Slides were coverslipped, sealed with rubber cement, and overnight hybridization was performed in a humid chamber at 37°C. Posthybridization wash was performed in 1× SSC/0.3% NP40 (72–73°C, 2 min). The air-dried slides were then stained with 4’,6-diamidino-2-phenyldinol-II (Vysis, Inc.).

**Scoring.** Slides were examined and images were obtained using an epifluorescent microscope (Olympus BX40; Olympus, Melville, NY) equipped with appropriate filters and

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\(^3\) The abbreviations used are: FISH, fluorescent in situ hybridization; MSKCC, Memorial Sloan-Kettering Cancer Center.

\(^4\) Internet address: http://www.emsembl.org.
Signal number for both probes was recorded simultaneously in at least 100 nuclei. Cases with >20% of nuclei lacking both signals for the locus-specific probe (CDKN2A or MTAP) and showing at least one signal for the CEP-9 probe were considered homozygously deleted.

**PCR.** To confirm the identity of the P1 clones P1-1063 and P1-1069, used as FISH probes, we verified by PCR that they contained CDKN2A and MTAP, respectively. For CDKN2A, we used primers for exon-1\(\beta\) (5′-GAAAGAAGGAGG-GGCTG-3′ and 5′-GCGCTACCTGATTCCAATTC-3′) and exon-1\(\beta\) (5′-CCCAGTCTGCAGTTAATTC-3′ and 5′-GTCTAAGTCGTTGTAACCG-3′; gift of Paola Capodieci, MSKCC), in separate reactions. The annealing temperature for CDKN2A exon-1\(\beta\) primers was 55°C and for CDKN2A exon-1\(\beta\) primers was 55°C (35 cycles) using an iCycler (Bio-Rad, Hercules, CA). For MTAP, we used primers for exons 2–7 (gift of Richard Gorlick, MSKCC), as described elsewhere (19).

**RESULTS**

We first confirmed by PCR on DNA from P1 clones 1063 and 1069 that CDKN2A and MTAP were respectively contained within the aliquots used as FISH probes (results not shown). Probe specificity was also verified by triple color FISH (CEP-9 spectrum aqua, P1-1063 spectrum orange, and P1-1069 spectrum green) on metaphase spreads of normal peripheral blood lymphocytes (Fig. 2A). As expected from human genome data and previous publications, P1-1069 is telomeric to P1-1063 on 9p. Thus, CDKN2A and MTAP deletion could be studied separately, using these clones individually.

The FISH results on the mesothelioma frozen tissues are summarized in Table 1. Using probe P1-1063, homozygous deletion was detected in 70 of 95 (74%) cases. By histological subtype, homozygous deletion of CDKN2A was identified in 49 of 71 (69%) cases with epithelioid histology (Fig. 2, B and C), in 16 of 19 (84%) cases with biphasic histology, and in 5 of 5 (100%) cases with sarcomatoid histology. One patient with epithelioid mesothelioma had two specimens from two consecutive surgeries and both had homozygous deletion and were counted as one case.

Using the same scoring criteria, homozygous deletion of MTAP was identified using probe P1-1069 in 64 of 95 cases (67%). No MTAP deletion was seen without CDKN2A deletion. Thus, 64 of 70 (91%) cases with CDKN2A deletion were also codeleted for MTAP.

Chromosome 9 copy number was abnormal in 42 cases (44%), including 28 of 71 (39%) epithelioid, 9 of 19 (47%) biphasic, and 5 of 5 (100%) sarcomatoid cases. Cases with both monosomy and polysomy 9 were identified, however, gains were more common than losses (Fig. 2B).

Homozygous deletion of CDKN2A and MTAP was detected in two of three mesothelioma cell lines (JMN and NCI-H2052), whereas neither gene was deleted in the third cell line (NCI-H28; results not shown).

**Fig. 2**  
A, Three-color FISH of normal peripheral blood lymphocytes with probes for chromosome 9 centromere (Vysis CEP9, spectrum aqua), CDKN2A (P1-1063, spectrum orange) and MTAP (P1-1069, spectrum green). Insets show higher magnification of metaphase and interphase signals. B and C, two-color FISH of frozen mesothelioma tissue imprints showing homozygous deletion of 9p21 genes; B, homozygous deletion of CDKN2A (P1-1063, spectrum orange) with chromosome 9 aneuploidy (Vysis CEP9, spectrum green). The arrow marks a normal nucleus (lymphocyte). C, homozygous deletion of MTAP (P1-1069, spectrum orange) with normal chromosome 9 copy number (Vysis CEP9, spectrum green). No normal nuclei are present in this field.
of pleural mesothelioma demonstrates a prevalence of CDKN2A – 9). The present analysis of 95 cases of malignant mesothelioma (7, 19) is one of the most frequent genetic alterations in CDKN2A. Deletions by FISH has the advantage of being able to identify homozygous deletion of 74%. In the largest previous study of DISCUSSION that included both primary tumor material and corresponding detect homozygous all 21 cell lines but in only 5 of the matching primary tumors (7). In retrospect, some studies that used PCR-based techniques to detect homozygous CDKN2A deletion in primary tumors may have underestimated the proportion of deleted cases because of the contribution of admixed benign cells to the DNA used for PCR assays. Thus, the CDKN2A deletion rate in mesothelioma is among the highest of any studied tumor type. Other tumors with frequent 9p21 deletion include high-grade gliomas (11, 20, 21), acute lymphoblastic leukemia (22, 23), pancreatic adenocarcinomas (24, 25), and bladder carcinomas (14), among others. We also identified 5 cases with hemizygous loss of CDKN2A, of which 4 also showed loss of one copy of MTAP. CDKN2A promoter methylation analysis in these 5 cases showed methylation in one case (P. B. L. M. L., unpublished data).

By histological subtype, we found that homozygous deletion of CDKN2A was somewhat more common in cases with sarcomatous elements (biphasic or pure sarcomatoid) than in cases with epithelioid histology, but this did not achieve statistical significance (88 versus 69%; P = 0.10). However, this trend is of interest because in a smaller series (n = 50), Xiao et al. (8) found a similar difference in the CDKN2A deletion rates in these two histological groups (100 versus 52%; P < 0.001).

We also found that both copies of MTAP were lost in 67% of cases. Because no MTAP deletion was identified without concurrent CDKN2A deletion, this represented a 91% codeletion rate. Two of three mesothelioma cell lines that we studied showed homozygous deletion of both CDKN2A and MTAP, and one cell line showed no loss of either genes. Specific published data on MTAP deletion or codeletion in mesothelioma are limited, but a reexamination of previous studies reveals results consistent with the present data. Olopade et al. (26) found MTAP and CDKN2A codeletion in 5 of 5 mesothelioma cell lines. Prins et al. (9) mapped 9p21 deletions in 12 mesothelioma cell lines. STS marker 1063.7 (known to map between CDKN2A and MTAP) was preserved in 5 cell lines and lost in 7, suggesting that MTAP codeletion may have occurred in the latter 7 cell lines (58%). Because Xiao et al. (8) used a probe mixture of P1-1063 and P1-1069 in their FISH analysis for CDKN2A deletions, their percentage of 72% deleted cases also applies to MTAP. Comparable rates of MTAP deletion or codeletion have only been detected in high-grade gliomas and leukemias (26). Moreover, it is possible that the proportion of mesotheliomas with MTAP inactivation may be even higher than detected in the present series because a minority of cases have been reported to show deletion of only the last four exons of MTAP (27, 28), which may leave enough of the MTAP gene to result in a hybridization signal with the P1-1069 FISH probe. Immunohistochemistry or a combination of microdissection and PCR might help to identify these few additional cases among the 9% of CDKN2A-deleted cases lacking FISH evidence of MTAP codeletion.

Our finding that MTAP was only deleted in the presence of CDKN2A deletion is in agreement with the majority of published studies in other tumor types (14–16, 22, 23, 29). In contrast, some studies have reported a minority of cases with evidence of MTAP deletion without CDKN2A loss among other tumor types (19, 21, 28). The issue remains unresolved because the latter studies have been based on PCR analysis of DNA extracted from tumor tissue and none, to our knowledge, have identified MTAP loss without CDKN2A loss in cell lines or by FISH.

l-Alanosine, the l-isomer of alanosine, is an inhibitor of de novo AMP synthesis that was the subject of a National Cancer Institute-sponsored study between 1978 and 1985 (Refs. 30–32; reviewed in Ref. 33). In Phase I and Phase II studies, ~300 patients (with renal cell carcinoma and malignant melanoma) were treated, but the results were discouraging. However, these tumors were not tested for 9p21 deletions. In addition, subsequent retrospective analysis of the cases failed to identify MTAP deletions in these tumor types (33). Recent in vitro cytotoxicity studies of pediatric T-cell acute lymphoblastic leukemias and adult T-cell leukemia have demonstrated that, as expected, MTAP– leukemia cells are more sensitive to the toxicity of l-alanosine than are MTAP+ leukemic cells (34, 35). Moreover, normal lymphocytes are rescued from l-alanosine toxicity by the MTAP substrate, 5'-deoxyadenosine (34–36). In these independent studies, l-alanosine alone or in combination with a

<table>
<thead>
<tr>
<th>Histological type</th>
<th>Homozygous deletion</th>
<th>MTAP</th>
<th>Chromosome 9 aneuploidy</th>
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<tbody>
<tr>
<td>Epithelioid</td>
<td>49/71</td>
<td>69%</td>
<td>45/71</td>
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<td>Biphasic</td>
<td>16/19</td>
<td>84%</td>
<td>15/19</td>
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<td>Sarcomatoid</td>
<td>5/5</td>
<td>100%</td>
<td>4/5</td>
</tr>
<tr>
<td>Total</td>
<td>70/95</td>
<td>74%</td>
<td>64/95</td>
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Table 1 Summary of FISH data on 95 cases of pleural mesothelioma
salvage agent was shown to be clinically active in tumors with homozygous MTAP deletions. In addition, reintroduction of the MTAP cDNA in CDKN2A/MTAP-pancreatic carcinoma cell lines restored the MTAP-dependent adenine and methionine salvage pathways, decreased the rates of de novo synthesis, and decreased cellular sensitivity to the antipurine-related growth inhibitory actions of methotrexate and azaserine (37).

Malignant mesothelioma is a highly malignant tumor with an aggressive course. Most cases are diagnosed at an advanced stage and have a short survival time (6–10 months), and current chemotherapeutic agents are not effective in the majority of cases. The high deletion rate of the 9p21 locus including the MTAP gene makes mesothelioma a strong candidate for l-alaminosine and other inhibitors of de novo AMP synthesis. The very high prevalence of CDKN2A deletion also makes this tumor an interesting target for gene therapy approaches that restore the function of p16CDKN2A or p14ARF (38, 39) or that target tumor cells with genetic or functional defects in the p53 pathway (40). Finally, the very high prevalence of CDKN2A deletion in mesothelioma can also be used a diagnostic marker in the distinction between reactive and neoplastic mesothelial cells in pleural effusions (41).

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