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Epigenetic Profiles Distinguish Malignant Pleural Mesothelioma from Lung Adenocarcinoma

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Abstract

Malignant pleural mesothelioma (MPM) is a fatal thoracic malignancy, the epigenetics of which are poorly defined. We performed high-throughput methylation analysis covering 6,157 CpG islands in 20 MPMs and 20 lung adenocarcinomas. Newly identified genes were further analyzed in 50 MPMs and 56 adenocarcinomas via quantitative methylation-specific PCR. Targets of histone H3 lysine 27 trimethylation (H3K27me3) and genetic alterations were also assessed in MPM cells by chromatin immunoprecipitation arrays and comparative genomic hybridization arrays. An average of 387 genes (6.3%) and 544 genes (8.8%) were hypermethylated in MPM and adenocarcinoma, respectively. Hierarchical cluster analysis showed that the two malignancies have characteristic DNA methylation patterns, likely a result of different pathologic processes. In MPM, a separate subset of genes was silenced by H3K27me3 and could be reactivated by treatment with a histone deacetylase inhibitor alone. Integrated analysis of these epigenetic and genetic alterations revealed that only 11% of heterozygously deleted genes were affected by DNA methylation and/or H3K27me3 in MPMs. Among the DNA hypermethylated genes, three (*TMEM30B, KAZALD1*, and *MAPK13*) were specifically methylated only in MPM and could serve as potential diagnostic markers. Interestingly, a subset of MPM cases (4 cases, 20%) had very low levels of DNA methylation and substantially longer survival, suggesting that the epigenetic alterations are one mechanism affecting progression of this disease. Our findings show a characteristic epigenetic profile of MPM and uncover multiple distinct epigenetic abnormalities that lead to the silencing of tumor suppressor genes in MPM and could serve as diagnostic or prognostic targets. [Cancer Res 2009;69(23):9073–82]

Introduction

Malignant pleural mesothelioma (MPM) is an aggressive tumor that has been associated with asbestos exposure (1). Approximately 10,000 to 15,000 patients worldwide are newly diagnosed with MPM annually, and the number of patients is projected to increase over the next two decades in Asia and the United States (1, 2). Although the inhalation of asbestos is a well-known risk factor, the lack of clinical symptoms in the early stages of MPM as well as of useful diagnostic markers makes early diagnosis virtually impossible. In addition to these difficulties, the relative ineffectiveness of available therapies also contributes to the death of MPM patients shortly after diagnosis (1, 3). Therefore, further molecular analysis of MPM is urgently needed to identify effective markers that could be applied to blood or pleural fluid for an early valid diagnosis.

The central mechanisms underlying MPM formation are still unclear. Several genetic abnormalities seem to be involved in MPM, such as a loss of the *p16* locus or mutations in the *NF2* gene (4–6). However, recent whole-transcriptome sequencing approaches as well as comparative genomic hybridization analyses have revealed relatively few genetic mutations in MPM, about six genes per individual MPM (7, 8). The low frequency of genetic abnormalities raises the question of whether alternative mechanisms might also be contributing to the inactivation of genes, leading to tumor formation.

Dysregulation of epigenetic transcriptional control, particularly aberrant promoter DNA methylation and histone modifications, is a fundamental feature of human malignancies (9). The relationship between promoter DNA hypermethylation and inflammation has been documented in many types of cancers, including MPM (10). It could be that asbestos exposure contributes to MPM formation through this relationship (11–14), because it is known that asbestos induces continuous inflammation instead of directly transforming primary human mesothelial cells in tissue culture (15–17). In addition, recent cumulative studies of aberrant DNA methylation in human cancers showed high rates of aberrant promoter methylation in a subset of cancers, termed the CpG island methylator phenotype, which may also be contributing to MPM formation (18). However, there is currently limited information available regarding the DNA methylation status of MPM.

In addition to DNA methylation, a dysregulation of histone H3 lysine 27 trimethylation (H3K27me3) is known to be involved in several human malignancies (19). Enhancer of zeste 2, a polycomb

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group protein part of polycomb repressor complex 2, has histone methyltransferase activity with substrate specificity for H3K27. Because polycomb group–mediated gene silencing is initiated by the histone deacetylase (HDAC) activity of polycomb repressor complex 2, inhibition of HDAC can efficiently reactivate the H3K27me3 target genes (20, 21). However, this epigenetic event has not been studied in MPM.

To investigate aberrant epigenetic events in MPM, we performed global screening for genes with aberrant DNA hypermethylation using the methylated CpG island amplification microarray (MCAM), which provides reproducible results with a high validation rate and successfully detects genes methylated in normal as well as in cancerous tissues (22, 23). We also conducted combined analysis of MCAM, chromatin immunoprecipitation-microarrays, and array comparative genomic hybridization to show the relationship between these epigenetic and genetic abnormalities in MPMs. Our comprehensive analysis revealed that multiple epigenetic abnormalities play important roles in MPM carcinogenesis and may be valid therapeutic targets.

Materials and Methods

Cell lines. Two MPM cell lines [ACC-MESO-1 (MESO1) and Y-MESO-8A (MESO8)] previously established in our laboratory (24) and one nonmalignant mesothelial cell line (MeT-5A) were used for the study. MeT-5A was purchased from the American Type Culture Collection and cultured according to the instructions (CRL-9444). MESO1 and MESO8 were maintained in RPMI 1640 (Sigma-Aldrich) supplemented with 10% fetal bovine serum (Invitrogen) and antibiotic-antimycotic (Invitrogen) at 37°C in a humidified incubator with 5% CO_2.

Tissue samples. Fifty MPM samples, 56 adenocarcinoma samples, 4 normal mesothelial tissues, and 10 normal lung tissues were obtained from Japanese patients at the Aichi Cancer Center Hospital, Nagoya University Hospital, and the affiliated hospitals. Samples and clinical data were collected after appropriate institutional review board approval was received and written informed consent had been obtained from all patients. We scraped the surface of the resected normal lung from lung cancer cases and obtained normal pleural tissues. Normal lung tissues were obtained from the normal lung of lung cancer cases. Histologic and cytologic examination of both normal mesothelial and lung tissues revealed no remarkable findings as malignant tissues. In these normal tissues, no aberrant methylation was detected in five genes with pyrosequencing analysis (Supplementary Table S1).

DNA preparation. Genomic DNA was extracted using a standard phenol-chloroform method. Fully methylated DNA was prepared by treating genomic DNA with *Sss*I methylase (New England Biolabs; ref. 23). Unmethylated DNA was prepared by treating genomic DNA with phi29 DNA polymerase (GenomiPhi DNA Amplification kit; Amersham Biosciences) according to the manufacturer's protocol.

Methylated CpG island amplification-microarray. For MCAM analysis, we analyzed 20 MPMs (average age, 59.1 years; range, 45-78 years) and 20 adenocarcinomas (average age, 62.8 years; range, 44-76 years). A detailed protocol of MCAM has been described previously (22, 23). We used a human custom promoter array (G4497A; Agilent Technologies) containing 15,134 probes corresponding to 6,157 unique genes (23).

Hierarchical clustering analysis. Cluster analysis was done using an agglomerative hierarchical clustering algorithm (23, 25). For specimen clustering, pairwise similarity measures among specimens were calculated using Cluster 3.0 software[13] or Minitab 15 statistical software[14] based on the DNA methylation intensity measurements across all genes.

Methylation analysis. We performed bisulfite treatment as described previously (26, 27). The DNA methylation levels were measured using Pyrosequencing technology. For each assay, the setup included both positive controls (samples after *Sss*I treatment) and negative controls (samples after whole-genome amplification using GenomiPhi V2), with mixing experiments to rule out bias, and repeat experiments to assess reproducibility (28). Conventional methylation-specific PCR (MSP) was also carried out for the *transmembrane protein 30B* (*TMEM30B*), *Kazal-type serine protease inhibitor domain 1* (*KAZALD1*), and *mitogen-activated protein kinase 13* (*MAPK13*) genes. PCR products were visualized on 6% polyacrylamide or 3% agarose gels stained with ethidium bromide. MSP products were subsequently confirmed by bisulfite sequencing analysis. Quantitative MSP was also carried out using SYBR Green (Applied Biosystems). In addition to primers designed specifically for the gene of interest, an internal reference primer set designed for *LINE1*, which can amplify *LINE1* loci irrespective of DNA methylation status, was included in the analysis to normalize for input DNA. The percentage methylated reference is calculated by dividing the GENE:LINE1 ratio of the sample by the GENE:LINE1 ratio of the *Sss*I-treated methylated DNA and multiplying by 100 (29). To determine the cutoff value for the classification of methylated and unmethylated loci, we compared the percentage methylated reference and the methylation level from pyrosequencing analysis in each gene. The best discrimination cutoff values were 7% for *TMEM30B*, 5% for *KAZALD1*, and 5% for *MAPK13*. Primer sequences and PCR conditions are shown in Supplementary Table S2. All of the primers were designed to examine the methylation status of CpGs within 0.5 kb of the transcription start site.

Trichostatin A and 5-aza-2′-deoxycytidine treatment of cells. Cells were treated with 5-aza-2′-deoxycytidine (5Aza-dC; Sigma-Aldrich) or trichostatin A (MP Biomedicals) as described previously (23).

Chromatin immunoprecipitation-microarrays. Chromatin immunoprecipitation was done based on the previously published methods (21, 30). Trimethylated H3K27-specific samples and the input samples were labeled with Cy5 and Cy3, respectively. Labeled chromatin immunoprecipitation products were hybridized to CpG microarray using the same protocol as MCAM. A Cy5/Cy3 signal in excess of 1.5 was considered as an enrichment of H3K27me3 (Supplementary Table S3).

Quantitative reverse transcription-PCR analyses. Total RNA was isolated using Trizol (Invitrogen). RNA (2 μg) was reverse transcribed with MPMLV (Promega). TaqMan quantitative reverse transcription-PCRs and SYBR Green quantitative reverse transcription-PCRs were carried out in triplicate for the target genes (Applied Biosystems). Primer sequences are shown in Supplementary Table S2.

Statistical analysis. Associations between methylation status and clinicopathologic variables were analyzed by the Mann-Whitney *U* test, Fisher's exact test, Kruskal-Wallis test, or a linear regression model. The Kaplan-Meier method was used to estimate overall survival. The Cox proportional hazards models were used for estimation of hazard ratio. All reported *P* values were two-sided, with $P < 0.05$ considered statistically significant. Calculations were carried out with either StatView software version 5.0 (Abacus Concepts) or Stata version 8 (StataCorp).

Results

DNA methylation profiling by MCAM analysis in MPM and adenocarcinoma. To compare the global DNA methylation profiles of MPM and adenocarcinoma, we analyzed 20 samples of each using MCAM. Technical replications of MCAM were done for six cases of MPM and highly reproducible methylation profiles were obtained among the replicates ($R^2 = 0.93$; Supplementary Fig. S1). A Cy5/Cy3 signal in excess of 2.0 in MCAM was considered methylation-positive in a previous study (23). In the present study, 18 randomly selected genes were subsequently assessed by pyrosequencing analysis in MPM and adenocarcinoma samples. A methylation level >15% was considered methylation-positive (23). A high concordance was observed between the methylation status by

[13] http://rana.lbl.gov/EisenSoftware.htm
[14] http://www.minitab.com

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MCAM and pyrosequencing analyses (specificity, 90%; sensitivity, 82%; Supplementary Table S4) as was also shown in previous studies (22, 23). We will hereafter consider a signal ratio >2.0 in MCAM as methylation-positive.

In the cohybridization of MCA products from normal mesothelium DNA and normal lung tissue DNA, a high concordance in the methylation status was observed (R^2 = 0.87; Fig. 1*A*), suggesting that tissue-specific methylation is rare in these two tissues.

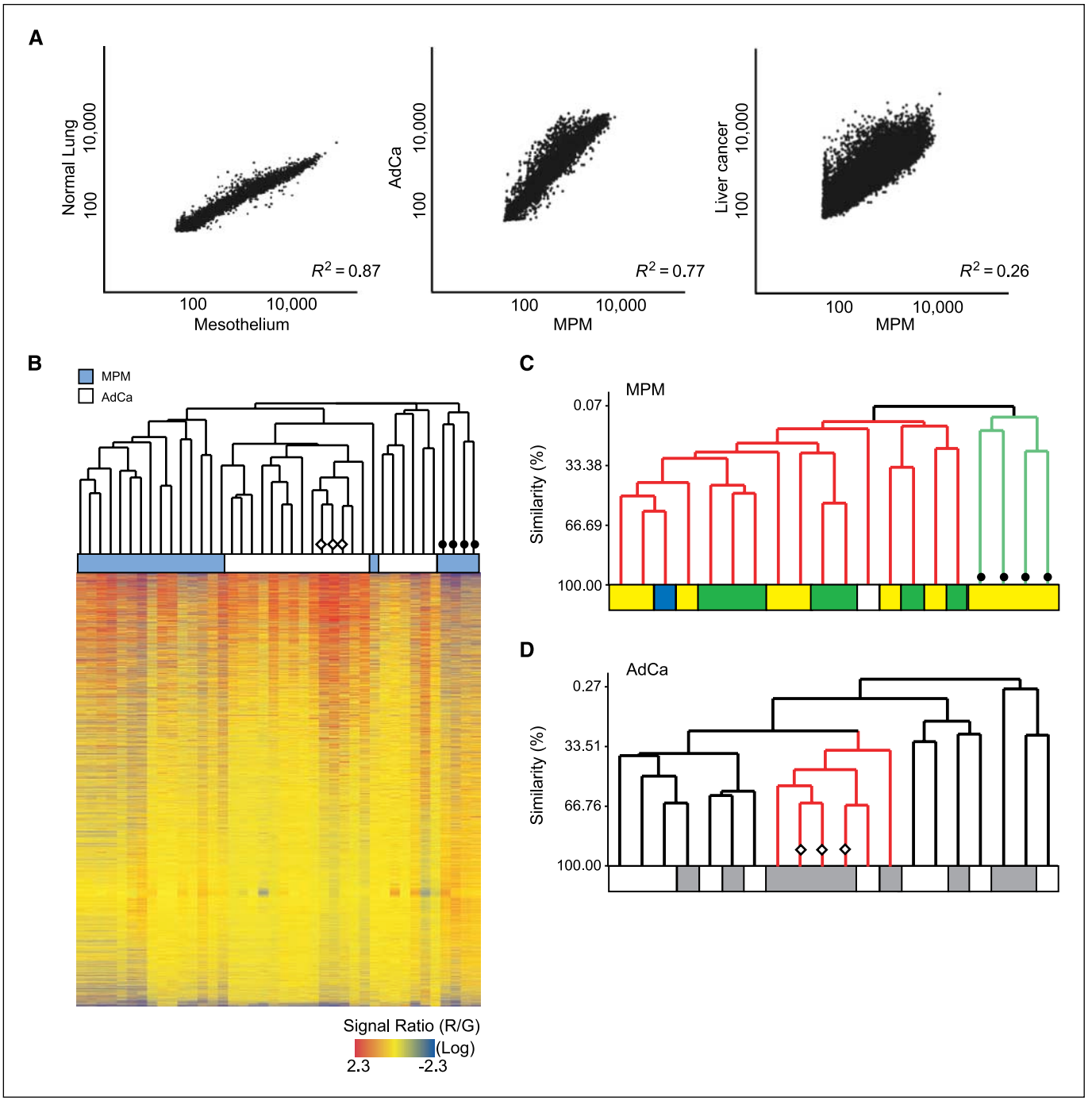

Figure 1. DNA methylation profiling by MCAM analysis. *A,* scatter plot analysis of signal intensity (log scale) between normal mesothelium (mixture of two cases) and normal lung tissue (mixture of four cases; *left*), MPM and adenocarcinoma (*AdCa*; both a mixture of four cases in both tumors; *middle*), and MPM and liver cancer (both a mixture of four cases in both tumors, *right*). The coefficient of determination (R^2) in the linear regression model is indicated in each analysis. *B,* dendrogram and heat-map overview of hierarchical cluster analysis of DNA methylation data from 40 samples (*blue boxes,* MPM; *white boxes,* adenocarcinoma) using all 6,157 genes (*Y axis*). Color corresponds to methylation level as indicated in the $\log_2$-transformed scale bar below the matrix. *Red* and *blue,* high and low levels, respectively; *black circle,* <300 genes methylated in these MPMs; *open diamond,* >950 genes methylated in these adenocarcinomas. *C,* defining subclasses in MPMs using hierarchical clustering. All 6,157 genes were used for the analysis of 20 MPMs. *Y axis,* similarity. Color boxes indicate histologic subtype of MPM. *Yellow, green, blue,* and *white boxes,* epithelial, biphasic, sarcomatoid, and variants, respectively; *black circle,* same MPMs as in *B. D,* subclasses in adenocarcinomas using hierarchical clustering. *Y axis,* similarity. *Gray* and *white boxes,* smokers and nonsmokers, respectively; *open diamond,* same adenocarcinomas as in *B.*

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Although ~70% of hypermethylated genes in MPMs were also found to be methylated in adenocarcinoma, a subset of loci were differently methylated in each tumor (R^2 = 0.77; Fig. 1*A*; Supplementary Fig. S2*A*). Interestingly, a larger number of loci were differently methylated in MPM and liver cancer (ref. 23; R^2 = 0.26), suggesting that the methylation profiles of MPM and adenocarcinoma have more in common (Fig. 1*A*).

Unsupervised hierarchical clustering analysis using the methylation status of 6,157 genes showed that adenocarcinomas seemed to be more frequently methylated than MPMs and that a subset of adenocarcinomas was extensively methylated (Fig. 1*B*). The majority of the MPM and adenocarcinoma samples could be classified into distinct subgroups according to DNA methylation status.

DNA methylation status affects clinicopathologic features of MPM and adenocarcinoma. Unsupervised hierarchical clustering analysis of MPMs using the 6,157-gene methylation status indicated two major subgroups, one of which had only the epithelial type of MPMs with less methylation (<300 genes; 4 cases; Fig. 1*C*). This subgroup tended to have longer survival rates than the other (19.5 ± 13.7 versus 14.5 ± 3.3 months; hazard ratio, 0.48; 95% confidence interval, 0.10-2.21; P = 0.3; Supplementary Fig. S3*A*). Interestingly, when we selected 445 genes that are commonly methylated in more than one-third of MPM cases, MPMs could be divided into two groups using this set of genes: high methylation group (n = 8) and low methylation group (n = 10; Supplementary Fig. S3*B*; Supplementary Table S5). Patients with low methylation lived significantly longer (21.6 ± 13.3 months) than those with high methylation (6.8 ± 4.1 months; hazard ratio, 0.16; 95% confidence interval, 0.04-0.63; P < 0.01; Supplementary Fig. S3*C*).

Adenocarcinomas were divided into four subgroups (Fig. 1*D*). One subgroup consisted of six adenocarcinoma samples that had more methylated genes than the other samples (911 ± 220 versus 387 ± 231 genes; P < 0.01) and came mostly from smokers (5 of 6 cases; mean pack-years smoked, 68.6 ± 22.9 years). Smokers had significantly more methylated genes than nonsmokers in adenocarcinoma (728 ± 338 versus 360 ± 206 genes; P = 0.02; Table 1). The majority of methylated genes (82%) in nonsmokers were also methylated in smokers (Supplementary Fig. S2*B*). In contrast, there were numbers of specifically methylated genes in smokers, suggesting that smoking affects DNA methylation in a set of genes.

Asbestos exposure appeared to have little effect on methylation status in MPM (exposure 386 ± 203 genes versus nonexposure 320 ± 118 genes; P = 0.4; Table 1). In addition, >60% of methylated genes in asbestos exposure cases were also methylated in asbestos nonexposure cases and vice versa (Supplementary Fig. S2*C*).

The numbers of methylated genes in stages I and II were significantly fewer than those in stages III and IV in both MPM and adenocarcinoma (P < 0.05), suggesting that DNA methylation increases in frequency as the diseases progress.

Distinct DNA methylation patterns between MPM and adenocarcinoma. Less than 700 genes were methylated in most of the MPMs, with the average being 387 genes (range, 120-755 genes; Fig. 2*A*) compared with 544 genes (range, 133-1,212 genes) in adenocarcinomas. In addition, genes commonly hypermethylated

Table 1. Incidence of hypermethylated genes and clinicopathologic parameters

	MPM		Adenocarcinoma	
	n (%)	No. methylated genes	*n* (%)	No. methylated genes
Age (y)*				
<65	14 (75)	388 ± 193	10 (50)	546 ± 404
≥65	5 (25)	430 ± 212	10 (50)	542 ± 262
Gender				
Female	2 (10)	261 ± 46	8 (40)	395 ± 218
Male	18 (90)	401 ± 202	12 (60)	643 ± 364
Asbestos exposure*				
Exposed	14 (78)	386 ± 203		
Not exposed	4 (22)	320 ± 118		
Histology				
Epithelial	11 (55)	356 ± 208		
Biphasic	7 (35)	403 ± 172		
Sarcomatoid	1 (5)	700		
Variants	1 (5)	297		
Stage*†				
I	1 (6)	211	12 (60)	427 ± 269
II	4 (25)	174 ± 76	4 (20)	748 ± 473
III	6 (38)	394 ± 179	4 (20)	691 ± 259
IV	5 (31)	308 ± 162	0 (0)	
Smoking status*				
Smoker	14 (88)	367 ± 204	10 (50)	728 ± 338‡
Nonsmoker	2 (12)	261	10 (50)	360 ± 206

*Clinical data of some patients were unavailable.
†Number of methylated genes in I and II is significantly smaller than in III and IV in MPMs and adenocarcinomas (P < 0.05).
‡Number of methylated genes in this group is significantly higher (P < 0.05) than in the other group.

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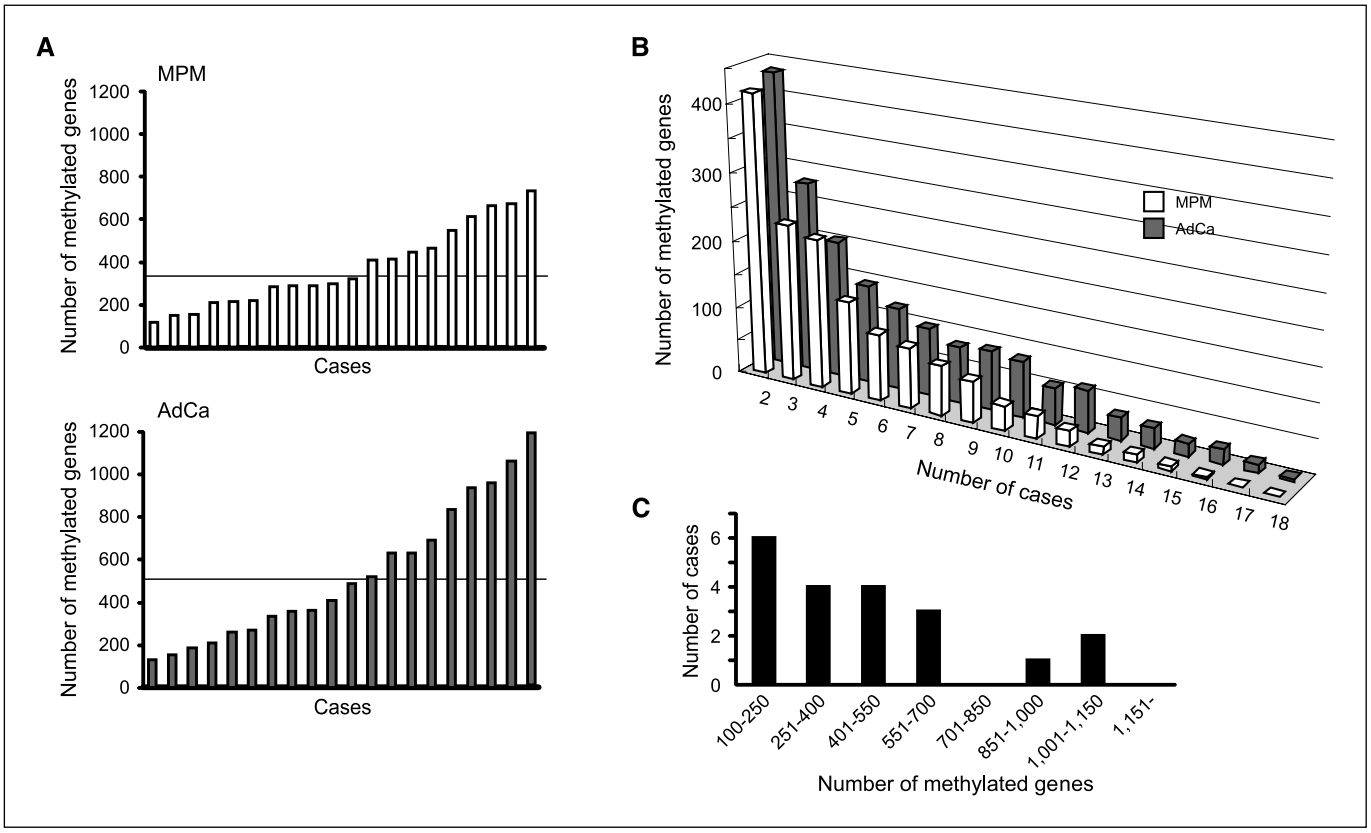

Figure 2. Comparison of distinct DNA methylation patterns between MPM and adenocarcinoma. *A,* number of methylated genes in each case. *Line,* average numbers of methylated genes (387 and 544 genes in MPM and adenocarcinoma, respectively). *B,* number of genes (*Y axis*) that were commonly methylated in *x* number of cases, where *x* is the axis in MPM (*white*) or adenocarcinoma (*gray*). *C,* bimodal distribution of methylated genes out of 1,457 loci in adenocarcinoma. The number of methylated genes (*X axis*) is plotted against the number of cases (*Y axis*).

in >10 MPMs were quite rare (<40 genes), whereas >80 genes were commonly hypermethylated in 10 adenocarcinomas, suggesting that hypermethylated genes vary more in each MPM case ($P < 0.01$; Fig. 2*B*). Notably, analysis of 1,457 genes that were methylated in >2 adenocarcinoma cases showed the bimodal distribution of methylation pattern as shown previously in CpG island methylator phenotype–positive tumor (ref. 31; Fig. 2*C*).

Two epigenetic mechanisms regulating gene expression in MPM cell lines. We next examined the changes in expression of genes identified by MCAM analysis before and after epigenetic treatments (Fig. 3*A*). These genes were methylated to some extent and were silenced in both MPM cell lines, MESO1 and MESO8, in contrast to their high expression levels in normal mesothelial tissue. Each gene in the different cell lines responded differently to the epigenetic treatments. *Ankyrin 1* (*ANK1*) was reactivated by the DNA methyltransferase inhibitor, 5Aza-dC, in a dose-dependent manner but was not reactivated by a HDAC inhibitor trichostatin A alone, which is the typical response to epigenetic treatment in DNA methylation target genes (32). *Progesterone receptor* (*PGR*) was reactivated by both 5Aza-dC and trichostatin A alone regardless of its DNA methylation status. Unexpectedly, the response to trichostatin A treatment in *proenkephalin* (*PENK*) differed between these two cell lines, although the CpG island in both cell lines was densely methylated. These findings, taken together, most likely indicate that another epigenetic mechanism regulates gene expression in MPM cells.

H3K27me3 mediated by polycomb group protein is an alternative silencing mechanism for tumor suppressor genes in human malignancies (19). We examined the H3K27me3 status in the same three genes (Fig. 3*B*). H3K27me3 was enriched in the *PGR* promoter in both cell lines and in the *PENK* promoter in MESO8. No enrichment of H3K27me3 was observed in either the *PENK* promoter in MESO1 or in the *ANK1* promoter in both cell lines that are densely DNA methylated.

Integrated analysis of genetic and epigenetic alterations. To examine H3K27me3 targets and the relation between DNA methylation and H3K27me3 on the CpG promoters in MPM cells, we carried out a chromatin immunoprecipitation-microarray analysis using the same promoter array (Fig. 4*A*). First, we validated the chromatin immunoprecipitation-microarray results by chromatin immunoprecipitation-PCR with randomly selected genes and found good concordance between the two analyses (specificity, 82%; sensitivity, 82%; Supplementary Table S3). We counted the genes that were enriched with H3K27me3 in MESO1 or MESO8 but not enriched in MeT-5A (a nonmalignant mesothelial cell line) and found 113 and 241 target genes in MESO1 and MESO8, respectively (Fig. 4*A*). DNA methylation was more frequently observed than H3K27me3 in the CpG promoters in both cell lines. There was some overlap between DNA-methylated and H3K27me3 target genes; however, the majority of the genes enriched with H3K27me3 revealed no detectable DNA hypermethylation, whereas most genes showing DNA hypermethylation showed no enrichment with H3K27me3. These results suggest that DNA hypermethylation and

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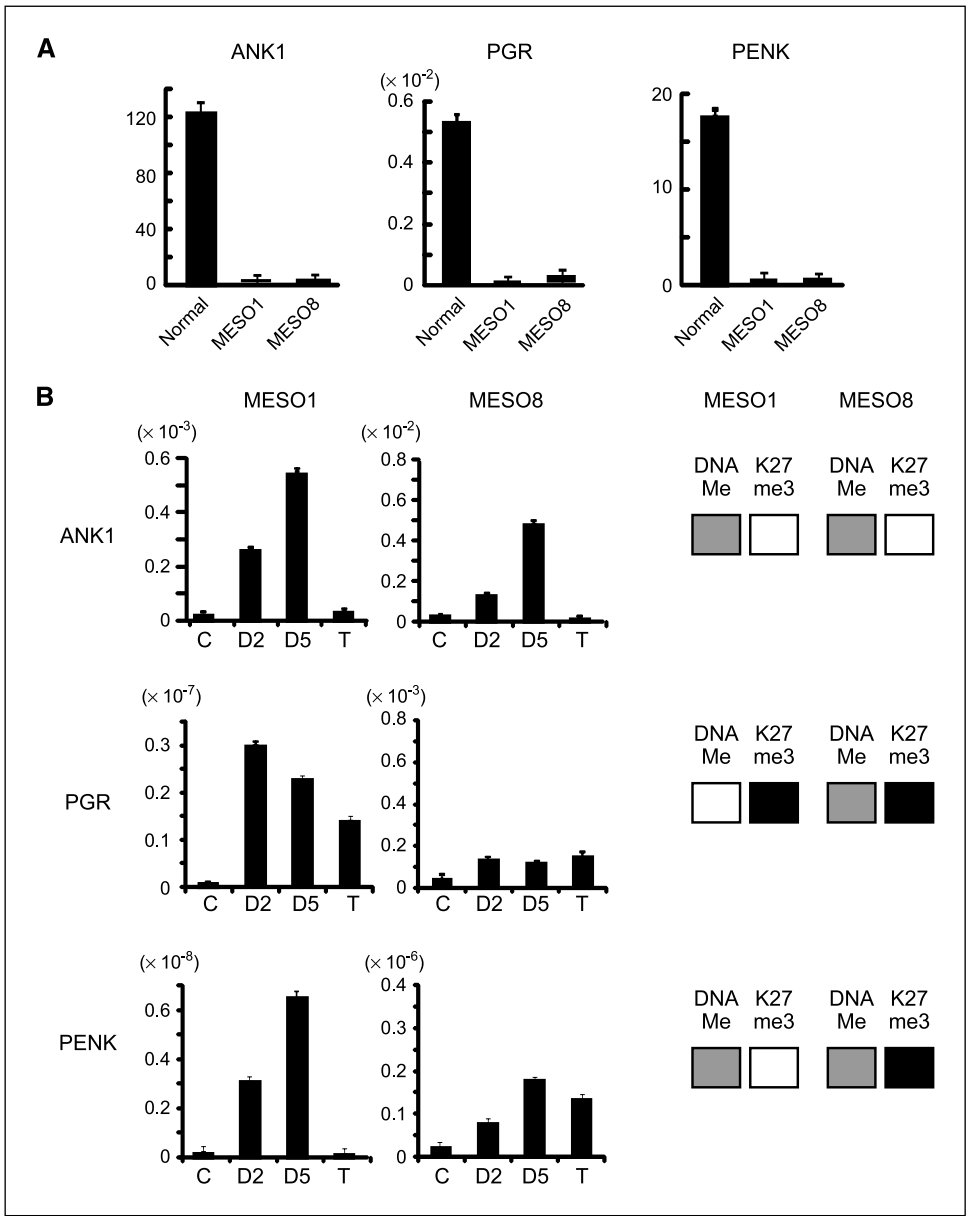

Figure 3. Relationship between gene expression and epigenetic alterations in MPM cell lines. *A,* gene expression was measured by quantitative PCR in normal mesothelial tissue, MESO1, and MESO8. *Y axis,* relative values of mRNA expression for each gene to glyceraldehyde-3-phosphate dehydrogenase. *Bars,* SD from experiments in triplicate. *B,* reactivation of silenced genes by DNA methyltransferase inhibitor (5Aza-dC) or HDAC inhibitor (trichostatin A) in three representative genes. After treatment with either PBS (control; *C*), 2 μmol/L (*D2*) or 5 μmol/L (*D5*) 5Aza-dC, or trichostatin A (*T*), each silenced gene was reactivated. *Y axis,* relative values of mRNA expression for each gene to glyceraldehyde-3-phosphate dehydrogenase. *Right columns,* status of DNA methylation (*DNA Me*) and H3K27me3 (*K27me3*). Regarding levels of DNA methylation in these genes, each gene shows high (*gray*; DNA methylation level >60%) or low (*white*; DNA methylation level <10%) methylation. For H3K27me3, each gene shows enrichment (*black*) or nonenrichment (*white*) of H3K27me3. DNA methylation levels were assayed by pyrosequencing and H3K27me3 status was assayed by chromatin immunoprecipitation-microarray and chromatin immunoprecipitation-PCR.

H3K27me3 may contribute to cancer development through the silencing of specific target genes in MPM cells (Fig. 4*A* and *B*).

We next carried out an integrated genetic and epigenetic analysis using array comparative genomic hybridization data that we have reported previously in the same cell lines (33). A total of 5,746 genes covered by both MCAM and comparative genomic hybridization arrays were analyzed. Genomic deletions were detected in 190 and 565 genes in MESO1 and MESO8, respectively. The majority of those genes showed heterozygous deletions, whereas only 8 and 3 genes showed homozygous deletions in MESO1 and MESO8, respectively (Fig. 4*B*). Twenty-one of 190 (11%, MESO1) and 63 of 565 (11%, MESO8) deleted genes were also affected by DNA methylation or H3K27me3, most of which were affected by heterozygous deletions and DNA methylation. Interestingly, all these three events were observed in one gene in MESO8, *A-kinase anchor protein 12* (*AKAP12*), which has been reported as a tumor suppressor gene and a target of DNA methylation in childhood myeloid malignancies (34). Representative analyses of chromosomes 9 and 10 where two important tumor suppressor genes, *CDKN2A* and *PTEN*, were homozygously deleted, showed that genetic deletion is rare. It was also found that genetic deletion, DNA methylation, and H3K27me3 do not frequently overlap on the same loci in these chromosomes (Fig. 4*C*).

Identification of MPM-specific methylation markers. DNA methylation has been proposed as a powerful potential marker for cancer diagnosis (35). To identify specific methylation markers for MPM, we first selected 8 genes from the MCAM analysis, which were methylation-positive (Cy5/Cy3 > 2.0) in at least four MPMs and methylation-negative in all of the adenocarcinomas (Fig. 5*A*). We validated the genes by MSP and found that three of them, *TMEM30B, KAZALD1*, and *MAPK13*, were the best specific methylation markers for MPM (Fig. 5*B* and *C*). In the same set of MPMs analyzed by MCAM, DNA methylation was detected by MSP analysis in 11 (58%), 8 (42%), and 2 (11%) cases of 19 in the *TMEM30B, KAZALD1*, and *MAPK13* genes, respectively.

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To confirm whether these methylation markers might prove valid in another group of MPM patients, we obtained an additional 31 MPM samples from a different institution. Altogether, the methylation status of these three genes was analyzed in 50 MPMs by quantitative MSP (Fig. 5*D*). DNA methylation occurred in 19 cases (38%) in *TMEM30B*, 24 (48%) in *KAZALD1*, and 19 (38%) in *MAPK13*. In contrast, no substantial DNA methylation was detected in those three genes in 56 adenocarcinomas (Fig. 5*C* and *D*). The sensitivity and specificity of hypermethylation in at least one of the above three genes for a differential diagnosis of MPM from adenocarcinoma were found to be 72% and 100%, respectively. Kaplan-Meier survival analysis on methylation status of these three MPM-specific methylation genes revealed that MPM patients with no methylation tended to have prolonged survival (n = 11; 17.0 ± 13.9 months) compared with those with at least one gene methylated (n = 34; 12.1 ± 7.8 months; hazard ratio, 0.58; 95% confidence interval = 0.26-1.28; P = 0.17; Supplementary Fig. S3*D*).

Discussion

In this study, we analyzed and compared the DNA methylation status of MPM and adenocarcinoma to highlight the methylation profile of MPM. Although normal mesothelium and lung tissue develop from different germ layers (mesoderm and endoderm, respectively), their hypermethylation profiles are very similar (R^2 = 0.87), indicating that tissue-specific methylation differences in these two normal tissues are infrequent. Previous genome-wide methylation analyses of a variety of normal tissues have consistently shown that tissue-specific methylation is quite rare, thus validating our findings (22, 36, 37). By contrast, the differences in hypermethylated genes between MPM and adenocarcinoma were more numerous than in normal tissues, which might be a result of different pathologic processes in the two malignancies.

A previous study of the methylation status of seven loci showed that methylation is less prevalent in MPM than in adenocarcinoma (11). Our own global DNA methylation analysis revealed that hypermethylated genes are less frequent and more varied overall in MPM than in adenocarcinoma. Fewer than 700 genes were methylated in most of the MPMs (average hypermethylated genes, 387 ± 196 genes). This contrasted with a subset of adenocarcinoma samples, all of them from smokers (mean pack-years smoked, 67.3 ± 14.2 years) that were extensively methylated (>950 genes). In adenocarcinoma, smoking seems to be a mechanism driving tumors into distinct epigenetic subclasses. It has been suggested that certain adenocarcinomas can be predisposed to hypermethylation and a phenotype known as CpG island methylator phenotype

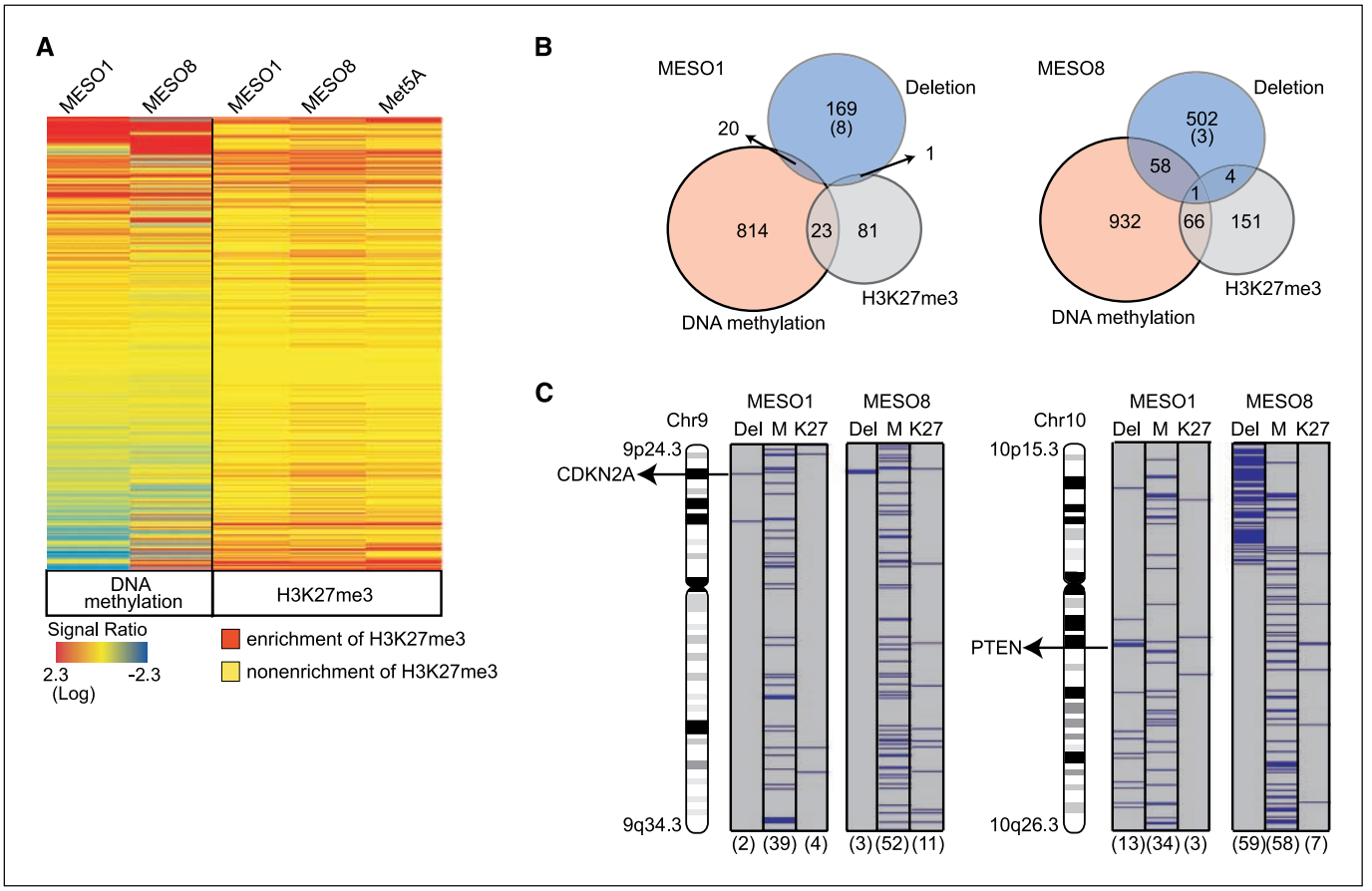

Figure 4. Epigenetic and genetic analysis of MESO1 and MESO8. *A,* unsupervised hierarchical cluster analysis of DNA methylation and H3K27me3 data in two MPM cell lines, MESO1 and MESO8, and a normal mesothelial cell line, MeT-5A, using microarray data of 6,157 genes (*Y axis*). Each cell in the matrix represents the DNA methylation (*red* and *blue,* high and low levels) or H3K27me3 status (*red* and *yellow,* enrichment or nonenrichment of H3K27me3) of each gene in an individual sample. *B,* number of DNA methylation targets, H3K27me3 targets, and deleted genes in MESO1 and MESO8 are shown by Venn diagram. Numbers in parentheses indicate number of homozygously deleted genes. *C,* chromosome view of epigenetic and genetic changes in chromosomes 9 and 10. *Del,* deletion; *M,* DNA methylation; *K27,* H3K27me3. Number of genes involved in each event is shown in parentheses.

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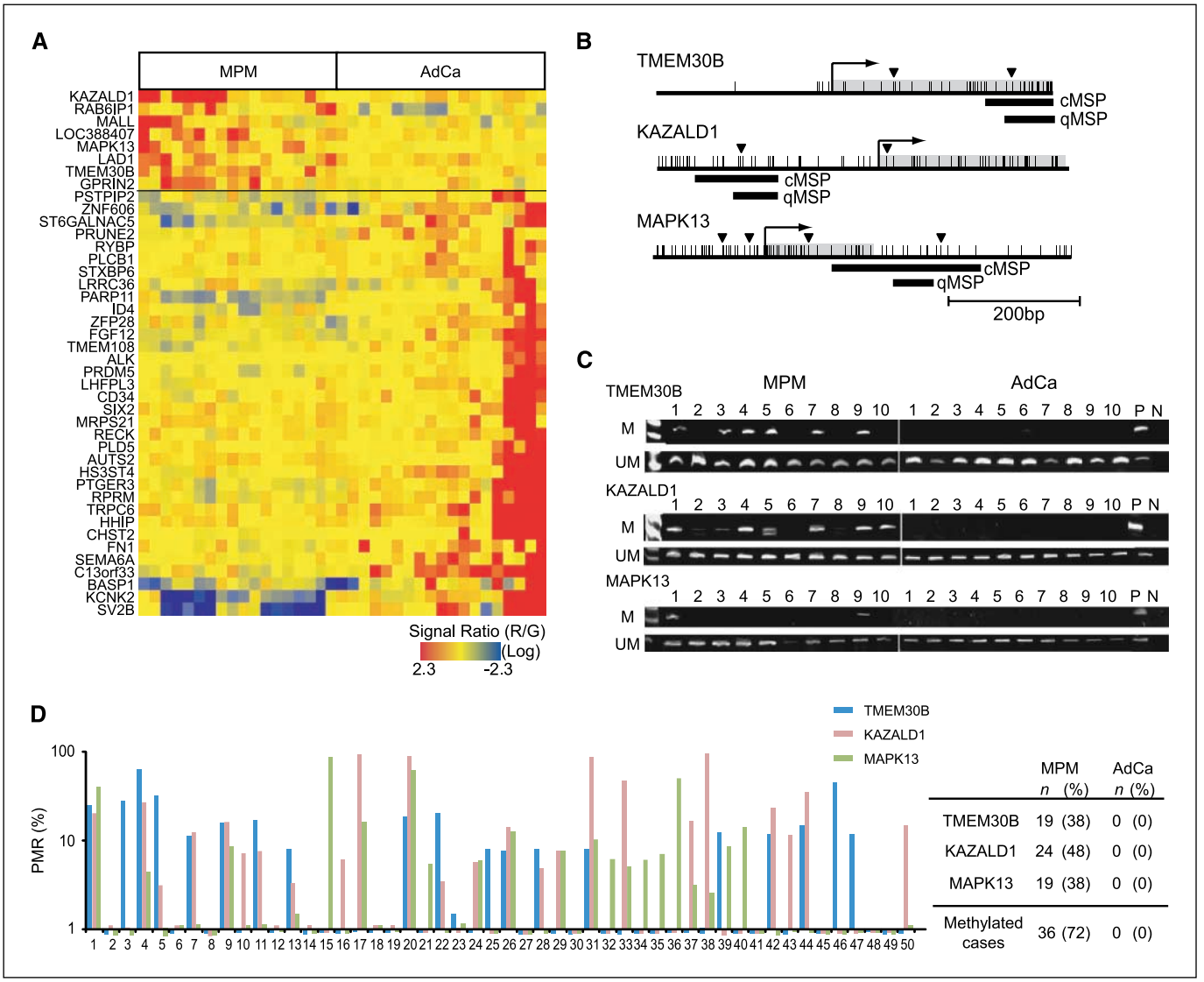

	MPM *n* (%)	AdCa *n* (%)
TMEM30B	19 (38)	0 (0)
KAZALD1	24 (48)	0 (0)
MAPK13	19 (38)	0 (0)
Methylated cases	36 (72)	0 (0)

Figure 5. Identification of specific methylation markers for MPM. *A,* hierarchical clustering using 42 specifically methylated genes in each tumor (8 and 34 genes in MPM and adenocarcinoma, respectively). *B,* diagrams of promoters of three selected genes. Each vertical line represents a single CpG site. The transcription start site (*arrow*), location of exon 1 (*gray box*), *Sma*I/*Xma*I sites (*arrowheads*), and location of MSP assay (*black bar*; *cMSP*, conventional MSP; *qMSP*, quantitative MSP) are indicated. *C,* representative MSP data of *TMEM30B, KAZALD1*, and *MAPK13* in the 10 MPM samples and 10 adenocarcinoma samples used for MCAM analysis. DNA methylation was detected in some MPM samples. *M,* methylated form; *UM,* unmethylated form; *P,* positive control; *N,* no DNA template. Positive controls were *Sss*I-treated DNA for the methylated form and DNA from normal lymphocytes for the unmethylated form. *D,* levels of DNA methylation in *TMEM30B* (*blue columns*), *KAZALD1* (*pink columns*), and *MAPK13* (*green columns*) examined by quantitative MSP. *X axis,* MPM cases. Cases 1 to 10 are the same MPM samples as label in *C*. *Y axis,* percentage methylated reference (%). A summary of the quantitative MSP results is given beside the graph. Methylated cases indicate frequency of hypermethylation in at least one of the three genes.

(18, 38). Our results revealed that simultaneous accumulation of DNA methylation was found in adenocarcinoma, which revealed that a subset of adenocarcinoma exhibited CpG island methylator phenotype, whereas MPM rarely did so. Continuous inflammation from asbestos seems to be a driving force in inducing hypermethylation in MPM, and an association between asbestos burden and the methylation profile has been indicated (13, 14). Smoking may act as a stronger epimutagene (39) than asbestos as we have shown here. Nevertheless, these observations might also indicate a distinct mechanism for the acquisition of aberrant DNA methylation during the formation of MPM and adenocarcinoma.

DNA methylation of several genes seems to affect the clinicopathologic phenotype of MPM (40). In this study, we classified MPMs into two groups by methylation profile of a certain gene set; MPMs with low frequency of DNA methylation showed a significantly longer survival rate. These data indicate that accumulation of DNA methylation in multiple loci is one mechanism affecting the progression of this disease.

In the MPM cell lines, we found different responses to epigenetic treatment in silenced genes. A typical DNA methylation target gene, *ANK1*, was reactivated by DNA methyltransferase inhibitor 5Aza-dC but not by HDAC inhibitor trichostatin A alone as reported previously (32). However, two genes, *PENK* and *PGR*, were reactivated by both 5Aza-dC and trichostatin A. Examination of another epigenetic silencing mechanism, H3K27me3, might explain the intricate situation of gene expression in MPMs. When genes are silenced by DNA methylation alone, 5Aza-dC efficiently reactivates the gene; however, trichostatin A is inert in this situation.

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When genes are silenced by H3K27me3, both trichostatin A and 5Aza-dC affect gene activity regardless of DNA methylation status. This is consistent with the recent genome-wide analyses of polycomb group–mediated H3K27me3 silencing machinery in prostate cancers showing that a particular set of genes is dominantly silenced by H3K27me3 independent of DNA methylation and can be reactivated by a HDAC inhibitor (21, 41). The reason why silenced *PGR* without DNA methylation was reactivated by 5Aza-dC is not clear (MESO1 in Fig. 3*B*). This might be explained by the several studies suggesting that 5Aza-dC can act independently of its ability to inhibit DNA methylation, inducing the activation of unmethylated genes (42–44).

Integrated analysis of DNA methylation, H3K27me3, and array comparative genomic hybridization data in 5,746 genes in MPM cell lines has revealed that DNA methylation is a major silencing mechanism in CpG promoters and that H3K27me3 regulates a subset of genes, whereas deletions of loci are less frequent. By virtue of this combined analysis, we discovered that, on CpG promoter regions, ~11% of genes were affected by both genetic and epigenetic alterations in MPM, which generally results in their being silenced. These data indicate that multiple epigenetic abnormalities may work in harmony with genetic defects to inactivate a tumor suppressor gene through Knudson's two-hits model, in which a mutation or heterozygous deletion combines with DNA methylation and/or H3K27me3 to inactivate two alleles. Clinical trials using a different HDAC inhibitor, suberoylanilide hydroxamic acid, have been conducted in recurrent MPMs, but that drug is ineffective for the treatment of this disease (45). This might be partially explained by evidence showing that the HDAC inhibitor could not reactivate the genes silenced by DNA methylation. Taken together, our data suggest that the targeting DNA methylation in addition to H3K27me3 might be of great benefit and could improve the treatment of MPM.

DNA methylation has been proposed as a powerful marker for MPM diagnosis (11, 12). However, a previous examination of the methylation status of both MPM and adenocarcinoma showed that hypermethylation of the candidate markers was detected in both MPMs and adenocarcinomas to some extent, although at different frequencies. In addition, methylation markers specific for MPM have not been reported previously. Our analysis showed that hypermethylation of certain loci was frequently detected in MPM and that three genes in particular, *TMEM30B* (46), *KAZALD1* (47), and *MAPK13* (48), were specifically methylated in MPM. Their aberrant methylation could serve as informative markers to distinguish MPMs from adenocarcinomas and could be applicable for the samples obtained from less invasive procedures, such as serum and pleural effusion. A larger study is needed to validate these three genes as useful diagnostic markers for MPM.

In summary, a global methylation analysis comparing MPM and adenocarcinoma can decipher characteristic DNA methylation patterns in MPM. Because multiple epigenetic abnormalities might contribute to tumorigenesis through the silencing of particular cancer-related genes, targeting these epigenetic mechanisms could potentially be effective treatments for clinical use in MPM. Finally, here we propose potential markers that could be of diagnostic value for use in MPMs.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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MIAME accession numbers: Array Express: E-TABM-813 (MCAM data of 20 MPMs and 20 adenocarcinomas), E-TABM-781 (chromatin immunoprecipitation-microarray in MPM cells), and E-TABM-808 (MCAM data in MPM cells).

References

1. Robinson BW, Lake RA. Advances in malignant mesothelioma. N Engl J Med 2005;353:1591–603.
2. Tsiouris A, Walesby RK. Malignant pleural mesothelioma: current concepts in treatment. Nat Clin Pract Oncol 2007;4:344–52.
3. van Meerbeeck JP, Gaafar R, Manegold C, et al. Randomized phase III study of cisplatin with or without raltitrexed in patients with malignant pleural mesothelioma: an intergroup study of the European Organisation for Research and Treatment of Cancer Lung Cancer Group and the National Cancer Institute of Canada. J Clin Oncol 2005;23:6881–9.
4. Cheng JQ, Jhanwar SC, Klein WM, et al. p16 alterations and deletion mapping of 9p21-22 in malignant mesothelioma. Cancer Res 1994;54:5547–51.
5. Sekido Y, Pass HI, Bader S, et al. Neurofibromatosis type 2 (NF2) gene is somatically mutated in mesothelioma but not in lung cancer. Cancer Res 1995;55:1227–31.
6. Bianchi AB, Mitsunaga SI, Cheng JQ, et al. High frequency of inactivating mutations in the neurofibromatosis type 2 gene (NF2) in primary malignant mesotheliomas. Proc Natl Acad Sci U S A 1995;92:10854–8.
7. Sugarbaker DJ, Richards WG, Gordon GJ, et al. Transcriptome sequencing of malignant pleural mesothelioma tumors. Proc Natl Acad Sci U S A 2008;105:3521–6.
8. Krismann M, Muller KM, Jaworska M, Johnen G. Molecular cytogenetic differences between histological subtypes of malignant mesotheliomas: DNA cytometry and comparative genomic hybridization of 90 cases. J Pathol 2002;197:363–71.
9. Jones PA, Baylin SB. The fundamental role of epigenetic events in cancer. Nat Rev Genet 2002;3:415–28.
10. Perwez Hussain S, Harris CC. Inflammation and cancer: an ancient link with novel potentials. Int J Cancer 2007;121:2373–80.
11. Toyooka S, Pass HI, Shivapurkar N, et al. Aberrant methylation and simian virus 40 tag sequences in malignant mesothelioma. Cancer Res 2001;61:5727–30.
12. Tsou JA, Shen LY, Siegmund KD, et al. Distinct DNA methylation profiles in malignant mesothelioma, lung adenocarcinoma, and non-tumor lung. Lung Cancer 2005;47:193–204.
13. Tsou JA, Galler JS, Wali A, et al. DNA methylation profile of 28 potential marker loci in malignant mesothelioma. Lung Cancer 2007;58:220–30.
14. Christensen BC, Houseman EA, Godleski JJ, et al. Epigenetic profiles distinguish pleural mesothelioma from normal pleura and predict lung asbestos burden and clinical outcome. Cancer Res 2009;69:227–34.
15. Xu L, Flynn BJ, Ungar S, et al. Asbestos induction of extended lifespan in normal human mesothelial cells: interindividual susceptibility and SV40 T antigen. Carcinogenesis 1999;20:773–83.
16. Bocchetta M, Di Resta I, Powers A, et al. Human mesothelial cells are unusually susceptible to simian virus 40-mediated transformation and asbestos cocarcinogenicity. Proc Natl Acad Sci U S A 2000;97:10214–9.
17. Yang H, Bocchetta M, Kroczynska B, et al. TNF-α inhibits asbestos-induced cytotoxicity via a NF-κB-dependent pathway, a possible mechanism for asbestos-induced oncogenesis. Proc Natl Acad Sci U S A 2006;103:10397–402.
18. Toyota M, Ahuja N, Ohe-Toyota M, Herman JG, Baylin SB, Issa JP. CpG island methylator phenotype in colorectal cancer. Proc Natl Acad Sci U S A 1999;96:8681–6.
19. Kirmizis A, Bartley SM, Kuzmichev A, et al. Silencing of human polycomb target genes is associated with methylation of histone H3 Lys 27. Genes Dev 2004;18:1592–605.
20. van der Vlag J, Otte AP. Transcriptional repression mediated by the human polycomb-group protein EED involves histone deacetylation. Nat Genet 1999;23:474–8.
21. Kondo Y, Shen L, Cheng AS, et al. Gene silencing in cancer by histone H3 lysine 27 trimethylation independent of promoter DNA methylation. Nat Genet 2008;40:741–50.

Published OnlineFirst November 3, 2009; DOI:10.1158/0008-5472.CAN-09-1595

22. Shen L, Kondo Y, Guo Y, et al. Genome-wide profiling of DNA methylation reveals a class of normally methylated CpG island promoters. PLoS Genet 2007;3:2023–36.
23. Gao W, Kondo Y, Shen L, et al. Variable DNA methylation patterns associated with progression of disease in hepatocellular carcinomas. Carcinogenesis 2008;29:1901–10.
24. Usami N, Fukui T, Kondo M, et al. Establishment and characterization of four malignant pleural mesothelioma cell lines from Japanese patients. Cancer Sci 2006;97:387–94.
25. Eisen MB, Spellman PT, Brown PO, Botstein D. Cluster analysis and display of genome-wide expression patterns. Proc Natl Acad Sci U S A 1998;95:14863–8.
26. Yang AS, Estecio MR, Doshi K, Kondo Y, Tajara EH, Issa JP. A simple method for estimating global DNA methylation using bisulfite PCR of repetitive DNA elements. Nucleic Acids Res 2004;32:e38.
27. Kondo Y, Shen L, Suzuki S, et al. Alterations of DNA methylation and histone modifications contribute to gene silencing in hepatocellular carcinomas. Hepatol Res 2007;37:974–83.
28. Shen L, Guo Y, Chen X, Ahmed S, Issa JP. Optimizing annealing temperature overcomes bias in bisulfite PCR methylation analysis. Biotechniques 2007;42:48, 50, 2 passim.
29. Eads CA, Lord RV, Wickramasinghe K, et al. Epigenetic patterns in the progression of esophageal adenocarcinoma. Cancer Res 2001;61:3410–8.
30. Kondo Y, Shen L, Issa JP. Critical role of histone methylation in tumor suppressor gene silencing in colorectal cancer. Mol Cell Biol 2003;23:206–15.
31. Ogino S, Cantor M, Kawasaki T, et al. CpG island methylator phenotype (CIMP) of colorectal cancer is best characterised by quantitative DNA methylation analysis and prospective cohort studies. Gut 2006;55:1000–6.
32. Cameron EE, Bachman KE, Myohanen S, Herman JG, Baylin SB. Synergy of demethylation and histone deacetylase inhibition in the re-expression of genes silenced in cancer. Nat Genet 1999;21:103–7.
33. Taniguchi T, Karnan S, Fukui T, et al. Genomic profiling of malignant pleural mesothelioma with array-based comparative genomic hybridization shows frequent non-random chromosomal alteration regions including JUN amplification on 1p32. Cancer Sci 2007;98:438–46.
34. Flotho C, Paulun A, Batz C, Niemeyer CM. AKAP12, a gene with tumour suppressor properties, is a target of promoter DNA methylation in childhood myeloid malignancies. Br J Haematol 2007;138:644–50.
35. Belinsky SA. Gene-promoter hypermethylation as a biomarker in lung cancer. Nat Rev Cancer 2004;4:707–17.
36. Estecio MR, Yan PS, Ibrahim AE, et al. High-throughput methylation profiling by MCA coupled to CpG island microarray. Genome Res 2007;17:1529–36.
37. Weber M, Hellmann I, Stadler MB, et al. Distribution, silencing potential and evolutionary impact of promoter DNA methylation in the human genome. Nat Genet 2007;39:457–66.
38. Suzuki M, Shigematsu H, Iizasa T, et al. Exclusive mutation in epidermal growth factor receptor gene, HER-2, and KRAS, synchronous methylation of non-small cell lung cancer. Cancer 2006;106:2200–7.
39. Grady WM. CIMP and colon cancer gets more complicated. Gut 2007;56:1498–500.
40. Fischer JR, Ohnmacht U, Rieger N, et al. Promoter methylation of RASSF1A, RARβ and DAPK predict poor prognosis of patients with malignant mesothelioma. Lung Cancer 2006;54:109–16.
41. Gal-Yam EN, Egger G, Iniguez L, et al. Frequent switching of Polycomb repressive marks and DNA hypermethylation in the PC3 prostate cancer cell line. Proc Natl Acad Sci U S A 2008;105:12979–84.
42. Milutinovic S, Knox JD, Szyf M. DNA methyltransferase inhibition induces the transcription of the tumor suppressor p21(WAF1/CIP1/sdi1). J Biol Chem 2000;275:6353–9.
43. Soengas MS, Capodieci P, Polsky D, et al. Inactivation of the apoptosis effector Apaf-1 in malignant melanoma. Nature 2001;409:207–11.
44. Wozniak RJ, Klimecki WT, Lau SS, Feinstein Y, Futscher BW. 5-Aza-2′-deoxycytidine-mediated reductions in G9A histone methyltransferase and histone H3 K9 di-methylation levels are linked to tumor suppressor gene reactivation. Oncogene 2007;26:77–90.
45. Ramalingam SS, Belani CP, Ruel C, et al. Phase II study of belinostat (PXD101), a histone deacetylase inhibitor, for second line therapy of advanced malignant pleural mesothelioma. J Thorac Oncol 2009;4:97–101.
46. Furuta J, Nobeyama Y, Umebayashi Y, Otsuka F, Kikuchi K, Ushijima T. Silencing of peroxiredoxin 2 and aberrant methylation of 33 CpG islands in putative promoter regions in human malignant melanomas. Cancer Res 2006;66:6080–6.
47. Shibata Y, Tsukazaki T, Hirata K, Xin C, Yamaguchi A. Role of a new member of IGFBP superfamily, IGFBP-rP10, in proliferation and differentiation of osteoblastic cells. Biochem Biophys Res Commun 2004;325:1194–200.
48. Ehrlich M, Sanchez C, Shao C, et al. ICF, an immunodeficiency syndrome: DNA methyltransferase 3B involvement, chromosome anomalies, and gene dysregulation. Autoimmunity 2008;41:253–71.