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Genome-Wide Profiling of Methylation Identifies Novel Targets with Aberrant Hyper-methylation and Reduced Expression in Low-Risk Myelodysplastic Syndromes

Epigenetic Regulation in Low-Risk Myelodysplastic Syndromes

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Abstract

Gene expression profiling signatures may be used to classify the subtypes of MDS patients. However, there are few reports on the global methylation status in MDS. The integration of genome-wide epigenetic regulatory marks with gene expression levels would provide additional information regarding the biological differences between MDS and healthy controls. Gene expression and methylation status were measured using high-density microarrays. A total of 552 differentially methylated CpG loci were identified as being present in low-risk MDS; hyper-methylated genes were more frequent than hypo-methylated genes. In addition, mRNA expression profiling identified 1005 genes that significantly differed between low-risk MDS and the control group. Integrative analysis of the epigenetic and expression profiles revealed that 66.7% of the hyper-methylated genes were under-expressed in low-risk MDS cases. Gene network analysis revealed molecular mechanisms associated with the low-risk MDS group, including altered apoptosis pathways. The two key apoptotic genes BCL2 and ETS1 were identified as silenced genes. In addition, the immune response and miRNA biogenesis were affected by the hyper-methylation and under-expression of IL27RA and DICER1. Our integrative analysis revealed that aberrant epigenetic regulation is a hallmark of low-risk MDS patients and could play a central role in these diseases.

Keywords: gene expression profile, methylation, low-risk MDS, apoptosis, BCL2, ETS1 transcription factor targets.
Introduction

Myelodysplastic syndromes (MDS) are a heterogeneous group of clonal myeloid stem cell disorders affecting mainly elderly patients. MDS are characterized by cytopenia of the peripheral blood (PB), hypercellularity of the bone marrow (BM) and morphological alterations in one or more hematopoietic cell lineages (1). According to the WHO classification, MDS can be classified as low- or high-risk depending on the percentage of blast cells in the BM (2). In most cases, the presence of cytogenetic aberrations, such as alterations on chromosomes 5, 7, and 8, are the hallmark of MDS, but other abnormalities in signal transduction, transcription activity, cell-cycle control, mitochondrial DNA, angiogenesis and epigenetic changes have also been associated with MDS (3).

DNA methylation is an epigenetic process that involves the addition of a methyl group \((CH_3)\) to the 5-position carbon of the cytosine pyrimidine ring in a CpG dinucleotide. This process is carried out in an orchestrated reaction that includes DNA methyltransferases, methyl-binding domain proteins, and histone deacetylases (4). DNA cytosine methylation is the best characterized epigenetic event leading to the stabilization of the genome, the remodeling of the chromatin and the regulation of gene transcription (5;6). In addition, not only the presence of epigenetic marks but also their location and density play a crucial role in regulating these processes (7;8). A close correlation between DNA hyper-methylation and transcriptional silencing has been established in many systems (9).

Epigenetic alterations are now accepted as having a role in carcinogenesis. DNA hyper-methylation in cancer is associated with the silencing of tumor-suppressor genes, whereas hypo-methylation has been described as playing a causal role in progressive tumor formation and in promoting chromosomal instability (5;7;9-11).
Tumor suppressors are not the only genes affected by aberrant methylation; abnormally methylated genes with other functions are also subject to silencing in human cancer, including those involved in DNA repair, apoptosis, angiogenesis, cell cycle regulation and cell-to-cell interaction (12). Hence, epigenetic modifications in promoter and/or regulatory regions that lead to transcriptional silencing of genes and development of cancer are important events requiring to be studied in any oncopathological state and they are attractive therapeutic targets.

Gene expression profiling studies have been performed in MDS with the aim of identifying genes and biological pathways of relevance in these diseases (13;14). These studies have identified gene expression signatures distinguishing specific subgroups of MDS and have helped improve our understanding of the biology of these diseases (15). However, the molecular pathogenesis of MDS is still not fully understood. Moreover, only part of the cellular information is present at the mRNA level, and transcriptional activity is dependent on many factors, including epigenetic modifications. Nevertheless, the methylation patterns of genes have not been as well explored in low-risk MDS as in other hematopoietic malignancies, and most epigenetic studies have focused on the analysis of a few tumor suppressor genes (16).

The underlying mechanisms of altered DNA methylation in low-risk MDS and the target genes affected by methylation remain unknown. To gain insight into the knowledge of the molecular mechanisms present in low-risk MDS, an integrative study of methylation and gene expression profiles was carried out. In this report, we identify genes with reduced levels of expression in response to increased methylation levels in nearby CpG islands. Overall, we highlight candidate DNA methylation changes associated with MDS that may warrant further investigation as potential clinical targets.
**Materials and Methods**

**Samples collection and cell separation**

A total of 83 low-risk MDS patients and 36 age-matched controls without haematological malignancies were included in the study (Supplementary Table 1). MDS were classified according to the World Health Organization (WHO) criteria (2). Mononuclear cells were isolated from BM samples of low-risk MDS patients and controls by density gradient (Ficoll). A cohort of 18 patients with low-risk MDS and seven controls were included in a simultaneous integrative study of methylation and expression, while the whole series was used as a control group of expression data. The study was approved by the Local Ethical Committees and written informed consent was obtained from each patient.

**DNA and RNA isolation**

Genomic DNA from subject samples was isolated using a DNeasy blood and tissue kit, following the manufacturer’s protocol. DNA was eluted in AE buffer (Qiagen, Hilden, Germany). Total RNA from cells was extracted by homogenization in TRIZOL (Invitrogen, Carlsbad, CA, USA), following the manufacturer’s protocol, then treated with RQ1 RNAse-Free DNase (Promega, Madison, USA) to eliminate genomic DNA contamination, and finally purified with RNeasy Minikit (Qiagen). The quantity and quality of the RNA were determined with an Agilent 2100 Bioanalyzer (Santa Clara, CA, USA).

**Methylation CpG island amplification and microarray studies (MCAM)**

Methylated CpG Island Amplification and Microarray (MCAM) is a two-color array technique that quantifies methylation by hybridizing equimolar amounts of subject versus control DNA to an array (17). The University Health Network human 12K CpG...
microarray (UHN, Toronto, Canada) contains 12,192 CpG island clones. Each clone
can be annotated with up to three gene symbols, depending on whether the CpG site
lies upstream, downstream or within the gene. The methylation assay was done largely
as described previously (17), but with the following modifications: DNA was purified
after double digestion, methylated CpG amplification (MCA) reaction and labeling were
done using the QIAquick PCR purification kit (Qiagen) without any indicator in the
buffer PB. RMCA primers (Eurogentec, Southampton, UK) were used at ligation and
MCA reaction stages. The MCA reaction was performed using 5 U HotStarTaq+
(Qiagen) and samples were aliquoted without primers before being heated to 82 °C.
The primers were held at 95 °C for 1 min before adding 4 μL to each tube. Cycling
conditions were: 95 °C for 10 min before 30 cycles of 95 °C for 1 min, 65 °C for 90 s,
72 °C for 2 min, and finally 72 °C for 10 min, and before holding at 4 °C. Samples were
hybridized to UHN HCGI12K CpG microarrays. After hybridization, microarrays were
washed as follows: 3 × 15 min at 55 °C with wash 1 in a rotating oven, then on a
gyrating platform 2 × 3 min at room temperature (R.T.) 1x SSC, 2 × 3 min at R.T. Wash
2: 2 × 3 min at R.T. 0.1 × SSC, 2 × 3 min at R.T. Millipore H₂O. Finally, slides were
rinsed with H₂O and centrifuged for 7 min at 370 g to dry. They were scanned with an
Axon GenePix 4400A scanner (MDS Analytical Technologies, Molecular Devices,
Sunnyvale, CA, USA) using Genepix Pro 7 software (MDS Analytical Technologies).

Bioinformatic analysis
The output GPR files from Gene Pix Pro 7.15 were imported into the R/Bioconductor
Marray program and quality control diagnostic plots were generated and assessed.
Poor-quality arrays were removed from the analysis and repeated. The log ratio of
median red (Cy5-labeled subject sample) to median green (Cy3-labeled universal
control) processed (dye-normalized) signal intensities were computed using the LIMMA
R/Bioconductor program. Probes that had been flagged by Gene Pix Pro 7.15 as bad,
absent or not found were removed. A genomic smoothing step was then performed in which a weighted average across 1000 bp was calculated for each CpG clone. In order to determine the degree of enrichment, the Partek Genomics Suite ANOVA tool was used and the n-fold change using the geometric mean (for log-transformed data). Probesets that differed significantly (p < 0.10) between the low-risk MDS and control groups were selected for further analysis.

**Gene expression microarray studies**

Gene expression profiling (GEP) studies were done as part of the Microarray Innovations in LEukemia (MILE) study (18). GeneChips Human Genome U133 Plus 2.0 arrays (Affymetrix, High Wycombe, UK) are gene expression arrays containing 54,613 oligonucleotide probesets that map onto 18,950 human gene loci, following gene-based remapping of the probes (19). Labeling and hybridization were performed according to protocols from Affymetrix. Briefly, 100 ng of total RNA was amplified and labeled using the GeneChip two-cycle cDNA synthesis kit and GeneChip IVT labeling kit (Affymetrix Inc.) and then hybridized to the Human Genome U133 Plus 2.0 microarray, after quality checking on GeneChips Test3 Arrays. Washing and scanning were done using Fluidics Station 400 and GeneChip Scanner (Affymetrix Inc.). In addition, the Human Exon 1.0 ST microarrays (Affymetrix) were used in the study.

**Bioinformatic analysis**

The Robust Microarray Analysis (RMA) algorithm was applied to the raw data from the expression arrays to carry out background correction, intra- and inter-normalization, and to calculate the expression signal (20). The Significant Analysis of Microarrays (SAM) algorithm was used to identify genes with statistically significant changes in expression between different classes (21). For this differential expression analysis, samples were permuted over 100 cycles using the two-class (unpaired) and multiclass
response format, considering variances not to be equal for the genes. Significant genes were selected on the basis of the false discovery rate (FDR), which was used to correct the p-values, assuming an FDR threshold of <0.15, which allowed better overlap with the data from the methylation study. To select each gene, the p-values of the statistical tests were transformed to q-values using the FDR threshold indicated. All the calculations described here were done using R and Bioconductor.

**Real-Time PCR**

To validate the GEP results, the expression levels of four selected genes were analyzed by RT-PCR. First-strand cDNA was generated from 1 µg of total RNA using poly-dT as primers with the M-MLV reverse transcriptase (Promega). Real-time PCR was performed in triplicate. Each 20µl reaction contained 300ng of cDNA, 400 nM of each primer, and 1x iQ SybrGreen Supermix (Bio-Rad, Hercules, CA, USA). Standard curves were run for each transcript to ensure exponential amplification and to rule out non-specific amplification. The expression level of the glyceraldehyde-3-phosphate dehydrogenase (*GAPDH*) gene was used to normalize differences in input cDNA. The reactions were run on an iQ5 Real-Time PCR detection system (Bio-Rad, Hercules, CA, USA). The primers were designed for specific sequences (Supplementary Table 2) and checked with the BLAST algorithm (22). In addition, to measure miRNA-145 and miRNA-196 expression levels, TaqMan qRT-PCR miRNA assay (Applied Biosystem, Carlsbad, California) was performed. The relative expression levels normalized to RNU43 endogenous control was determined using the $2^{-\Delta\Delta Ct}$ method. Each measurement was performed in duplicate.

**Pyrosequencing**

Primers were designed for forward, reverse and sequencing using the PyroMark Assay Design 2.0 program. Primer sequences can be found in Supplementary Table 3.
Bisulfite conversion of DNA was done as described by Frommer et al (23). The hot-start polymerase chain reaction (PCR) was carried out using 2μL (50ng) of bisulfite-treated DNA. PCR was performed following the manufacturer’s instructions. Pyrosequencing was carried out using the Q24 System (Qiagen), also in accordance with the manufacturer's protocols.

**Integrative functional analysis of methylation and expression data**

To analyze the functional enrichment of the selected gene lists we used the DAVID bioinformatic resource (http://david.abcc.ncifcrf.gov/) (24) and the web-delivered bioinformatics tool set IPA (Ingenuity Pathway Analysis 9.0; http://www.ingenuity.com). These tools allow the identification of functional modules and the most relevant biological processes present in the gene lists performing statistical enrichment analysis based on contingency tests. The Metacore Analytical Suite (Genego Inc., St. Joseph, MI, USA) was also used for the network analysis of some of the initial data from differentially methylated/expressed genes. Metacore’s shortest path algorithm was applied to derive a network for the selected genes. Biological processes enriched in differentially methylated/expressed gene lists were identified and p-values determined using Metacore’s enrichment analysis workflow.

The common transcription factor binding sites (TFBSs) were analyzed using search tools that allowed the sequences upstream of the genes of a given query list to be explored, for the purpose of finding significant candidate promoter regions. These tools search for sequence profiles similar to the TFBS defined in JASPAR (http://jaspar.cgb.ki.se/). The bioinformatic tools used were: oPOSSUM (http://www.cisreg.ca/cgi-bin/oPOSSUM/opossum) (25); TransFind (http://transfind.sys-bio.net/index.php/home.html) (26); Pscan (http://159.149.109.9/pscan/) (27); and TFM-Explorer (http://bioinfo.lifl.fr/cgi-bin/TFME/tfme.py) (28).
Results

Low-risk MDS and normal BM have distinct DNA methylation profiles

The methylation profiles of low-risk MDS patients were compared with those of controls using the 12K CpG array. Statistically significant changes in the level of CpG island methylation were identified. A total of 552 CpG loci were sufficiently differentially methylated between the two groups to give a value of $p < 0.10$. These loci were associated with 817 annotated gene symbols: 457 genes were hyper-methylated in low-risk MDS, and 360 genes were hypo-methylated. The median fold changes were 1.85 (7.82 to 1.09) and -1.65 (-4.73 to -1.11), respectively (Supplementary Table 4). The three most representative cellular functions for genes commonly altered by methylation were GM-CSF signaling (e.g., LYN, GNB2L1 and ZNF225), apoptosis-HTR1A signaling (e.g., BCL2 and MAP2K1) and TGF-beta-dependent induction of EMT via SMADs (e.g., SMAD2, HN1 and CDH2). In addition, four of the top ten cellular functions deregulated by methylation were related to the immune response (Table 1). Amongst the genes involved in this response, IL27RA and CD28 were hyper-methylated whilst IL6 and CD96 were hypo-methylated in MDS patients.

Gene expression profiling distinguishes low-risk MDS from normal BM

The GEP from the BM of low-risk MDS patients was compared with that from the BM of healthy individuals. 1975 genes showed significant differences (FDR cut-off < 0.15) in mRNA expression levels between the two groups: 764 were over-expressed whilst 1211 genes were under-expressed in low-risk MDS (Supplementary Table 5). This number was reduced to 1005 genes when an FDR cut-off of < 0.10 (444 up-regulated and 561 down-regulated genes) was applied. These genes were selected for further investigation. Hierarchical clustering, selecting for differentially expressed genes, resulted in a good separation of the two groups analyzed, except in three patients (Figure 1). These samples had a less differential profile although they were distinct.
from the controls. Interestingly, two of them displayed chromosomal alterations that were not present in any other patients: a loss on 5q and a monosomy 7. The most over-expressed gene in low-risk MDS (R.fold=8.08) was GDF15, which has a role in regulating inflammatory and apoptotic pathways during disease processes. By contrast, cellular development, post-translational modification and the cell-mediated immune response were the most frequently deregulated molecular and cellular functions (Supplementary Figure 1). In addition, cellular growth and proliferation was the function involving the largest group of genes: 121 molecules, of which BCL2, ETS1 and FLT3 were highlighted as down-regulated genes in MDS patients (Supplementary Table 5). It should be noted that nucleosome assembly, chromatin organization and DNA packaging were also significant functions that were altered in low-risk MDS. In this respect, a total of 33 up-regulated histone genes involved in these three functions were observed in low-risk MDS (Supplementary Table 5).

**Hyper-methylation correlates with decreased gene expression in low-risk MDS**

An integrative approach involving methylation and expression profiling was used to characterize genomic changes between low-risk MDS patients and healthy controls. Comparison of the 817 putative target genes of differential methylation and the 1975 genes of differential expression allowed the detection of gene loci that experienced both concurrent changes in low-risk MDS patients. In total, 91 genes were both differentially methylated and differentially expressed (Figure 2A): 37 of these (41%) were hypo-methylated, and 54 (59%) were hyper-methylated (Figure 2B). Thirteen of the genes that were hypo-methylated in low-risk MDS also featured up-regulated gene expression (35%), all with a value of p < 0.10 in both the methylation and expression analyses. UBE2D3, ING1 and RRAS2 were highlighted in this group of genes (Table 2).
Interestingly, a high proportion (66.7%) of hyper-methylated genes was also downregulated (all with a value of p < 0.10 in the methylation and expression analyses). This combination represented the highest association between methylation and expression with respect to the other possible combinations and was consistent with the pattern expected for silenced genes. For this reason, this group of 36 genes was examined further (Figure 2B; Table 3). Using functional enrichment, we observed that the most well represented categories in this gene set were regulation of gene expression, RNA process, immune response, regulation of cell differentiation, and cell adhesion and apoptosis (Figure 3). Finally, we externally validated the most significant genes for the top altered functions: regulation of gene expression (ETS1), RNA process (DICER1), the immune response (IL27RA) and apoptosis (BCL2). The under-expression of these genes was confirmed in the larger cohort of 83 MDS patients by expression arrays (Supplementary Figure 2). In addition, the differential methylation and expression of all four genes from the integrative group was confirmed by pyrosequencing and Q-PCR, respectively, and there was a 100% correlation between these techniques and the previous results.

Hyper-methylation of the ETS1 transcription factor is linked to gene down-regulation in low-risk MDS

As ETS1 is a transcription factor, we explored the link between the hyper-methylation of the transcription factor and the down-regulation gene observed in low-risk MDS patients. For this purpose, we analyzed the promoter regions of the 561 genes included in the under-expression signature assigned to low-risk MDS (Table 4). We searched for the TFBSs within this set of 561 genes. The analysis demonstrated that the ETS1 transcription factor, which is hyper-methylated and under-expressed in low-risk MDS, is involved in regulating 83 target genes included in the down-regulation signature of these MDS patients. The most significant functions of these target genes were
delineated and the cell-to-cell signaling and interaction pathway were found to be 
prominently affected. The genes included in this function were FOXP1, ITGAL, ZAP70
and LCK (Table 4). In addition, cell death (apoptosis) was identified as the function with 
greatest number of down-regulated target genes (IL7R, ITGAL, LCK, MAP4K1, PAK2,
PTAFR, TNFSF13, TOPBP1 and TRADD) (Table 4).

DICER1-interacting genes are deregulated in low-risk MDS patients

The identification of DICER1 as a gene that is quite significantly altered by methylation 
and expression in low-risk MDS prompted us to investigate other genes involved in
RNA processing and related to DICER1. ATXN1, NFE2L3 and POP4 proved to have 
direct genetic interactions with DICER1. ATXN1 was under-expressed in low-risk MDS
cases while NFE2L3 and POP4 were hyper-methylated and under-expressed in this 
group of patients (Table 3 and Supplementary Table 5). Moreover, PIWIL4, which was
down-regulated in the low-risk MDS group, was involved in protein-protein interactions
with DICER1. Interestingly, POP4 and PIWIL4 had genetic interactions with the 
RNASE4 gene. This gene was under-expressed in low-risk MDS patients
(Supplementary Table 5). In addition, to analyze the effect of the DICER1 deregulation,
183 miRNAs expression levels were measured. A general down-regulation of miRNAs
was observed in low-risk MDS cases respect to the control group (Wilcoxon p value:
0.039) (Supplementary Figure 3). However, no significant differences in miRNA-145
and miRNA-196 expression between low-risk MDS and controls were observed.

IL27RA and other immune response-related genes are down-regulated in low-risk
MDS patients

An immune response-related analysis was carried out to compare low-risk MDS
patients with the control group. This study showed that three genes involved in the
histocompatibility complex (HLA-DQB1, HLA-DQA1 and HLA-DPB1) were down-
regulated in low-risk MDS. We also found that besides \textit{IL27RA}, which was hyper-methylated and under-expressed in MDS, another nine interleukins and interleukin receptors were under-expressed in the same cohort of patients: \textit{IL16}, \textit{IL32}, \textit{IL1RAP}, \textit{IL2RB}, \textit{IL6R}, \textit{IL7R}, \textit{IL10RA}, \textit{IL10RB} and \textit{IL13RA1} (Supplementary Table 5). Three of them (\textit{IL16}, \textit{IL1RAP} and \textit{IL10RB}) had direct genetic interactions with \textit{IL27RA}.

\textit{Hyper-methylation of BCL2 leads to under-expression of the gene and increased apoptosis in low-risk MDS}

The significant alteration of expression and methylation pattern of \textit{BCL2} observed in low-risk MDS patients suggests a deregulation of the control of apoptosis. The genetic and epigenetic signatures of apoptosis-related genes in this group of patients were studied. \textit{BCL2L11} and \textit{MYC} were found to be over-expressed in low-risk MDS patients; in contrast, \textit{BAX} and \textit{CUX1} were under-expressed in this group of patients with respect to the control group. In addition, the \textit{SYK} gene, which was hyper-methylated and under-expressed, was also associated with apoptosis and \textit{BCL2}. In addition, we integrated all these genes in a simple interaction network to reveal the links and associations between them (Figure 4).
Discussion

Aberrant methylation is a potential mechanism for inactivating genes that has been implicated in several hematological malignancies, including MDS (29;30). Nevertheless, until now we have not known whether the low-risk MDS cases have a specific and distinct DNA methylation profile, as has been demonstrated for the gene expression profile (GEP) (15;31). The present study showed that the low-risk MDS patients had a different methylation profile involving 817 genes. Moreover, the GEP study displayed a deregulation of cellular development and post-translational modification genes in low-risk MDS patients. It should be noted that, in addition to these cellular functions, our analysis, performed in mononuclear cells, corroborated the mainly deregulated functions previously described in the GEP analysis of CD34+ cells, such as cellular proliferation (15) and up-regulation of histones involved in nucleosome organization (31). It is of particular note that GDF15, which was previously described as being deregulated in RARS patients (32), was the most over-expressed gene in low-risk MDS patients.

Only a few reports concerning MDS have established a connection between methylation and expression, and most of these epigenetic studies have focused on the analysis of a small number of tumor suppressor genes. For this reason, our study aimed to carry out a combined analysis of the methylation and the GEPs in low-risk MDS patients. To our knowledge, this is the first time the same cohort of patients has been used to analyze both profiles in MDS. The integrative study identified DNA methylation markers that could lead to the down-regulation of some genes involved in important cellular functions in low-risk MDS: \textit{BCL2}, \textit{ETS1}, \textit{IL27RA} and \textit{DICER1}.

MDS are characterized by ineffective hematopoiesis that results in peripheral blood cytopenias, despite the hypercellular dysplasia in bone marrow. Previous studies
suggested that the increased apoptosis of the bone marrow myeloid precursors is an important factor in the ineffective hematopoiesis of MDS patients. These studies also showed that the increased programmed cell death probably represents a pathophysiological mechanism rather than a compensatory process to counteract increased cell growth (31;33;34). Members of the BCL2 family are major regulators of these apoptotic pathways. The present study shows that BCL2 expression was significantly weaker in mononuclear low-risk MDS cells than in normal individuals. These results are in accordance with previous studies that showed reduced BCL2 expression in CD34+ cells of patients with early MDS subtypes (35). Furthermore, our study showed that BCL2 had significantly higher methylation levels in low-risk MDS samples. Consistent with the increasing evidence for a fundamental role of epigenetic silencing of apoptotic pathways in cancer (36-38), the hyper-methylation and the inverse correlation of mRNA expression of BCL2 would be expected to promote apoptosis in MDS patients. The under-expression of BCL2 in low-risk MDS due to aberrant methylation deserves further investigation as a low-risk MDS biomarker and supports a role for apoptosis-targeted therapy in these patients in the future.

Our study found hyper-methylation and under-expression of the ETS1 gene in the same group of low-risk MDS patients compared with the control group. Several studies have indicated that the level of ETS expression is reduced during tumorigenesis. These analyses show that ETS1 suppresses tumorigenicity and the cases with a high level of ETS1 expression had better outcomes for disease-free survival than those with a low level (39). These findings suggest that under-expression of ETS1 could have a crucial role in tumor promotion in MDS patients, especially during their early phases. ETS1 is a nuclear phosphoprotein that functions as a transcription factor by binding the target DNA sequences containing a central GGAA/T core motif (ETS-binding site, EBS) (40). The ETS protein influences the expression of genes that are involved in various...
biological processes, including hematopoiesis, cellular proliferation, differentiation, development, transformation and apoptosis (41). Over 400 ETS1 target genes have been defined to date, based upon the presence of functional EBS in their regulatory regions (41). To investigate whether a decrease in ETS1 expression in low-risk MDS patients had a functional effect, the expression levels of ETS1 target genes were examined and a significant difference in the level of expression of 83 target genes in the patient group relative to control group was observed. Likewise, several other studies have demonstrated co-expression of ETS factors and presumptive ETS target genes in solid tumors (42-44).

Several approaches have been used to demonstrate that ETS and/or the genetic pathways that this gene regulates could be potential targets for therapy. In addition, the methylation and decreased expression of ETS1 has been involved in silencing several genes during cellular senescence (45). Therefore, ETS1 deregulation could be related to cellular senescence. In the same study, the mRNA expression levels of ETS1 in the senescent cells increased significantly with the 5-aza-2'-deoxycytidine treatment. These findings could partially explain the response to 5-aza-2'-deoxycytidine treatment in MDS patients as a result of the possible induction of ETS1.

Apoptosis was the most widely affected function, with nine down-regulated ETS1 targets. The overall apoptosis pathway could be affected in low-risk MDS patients in two ways: (1) methylation and decreased expression of BCL2 with the deregulation of related genes (BCL2L11, MYC, BAX, CUX1 and SYK), and (2) methylation and decreased expression of the ETS1 transcription factor with the deregulation of its apoptosis-related targets. The molecular basis of apoptosis in MDS is largely unknown and comprehensive characterization of epigenetic disruption of apoptosis-related genes in MDS cases is lacking. For this reason, these findings may shed some light on
this matter. In addition, a clearer understanding of the molecular events leading to the deregulation of cell death in MDS should allow us to identify therapeutic targets and diagnostic markers.

IL27RA is a component of the heterodimeric complex receptor IL27R that is involved in immunosuppression by inducing a signal transduction in response to IL27 (46). Our studies identified a marked difference in IL27RA methylation levels between low-risk MDS patients and healthy controls that may be responsible for the under-expression shown by these patients. These results are consistent with recent studies in which IL27RA has been shown to be a promoter of hematopoietic stem cell differentiation, which appears to enhance myelopoiesis in a transgenic mouse system (46). According to this, down-regulation of IL27RA could lead to the ineffective differentiation of hematopoietic progenitors already described in MDS patients by other authors (33). Moreover, animal models with defects in IL27 or its receptor (IL27RA) display enhanced immune responses in a range of infectious and noninfectious situations (47). Therefore, our results are also consistent with these features and with the deregulation of the immune response known in MDS (33). Furthermore, immune response deregulation could be enhanced in low-risk MDS patients due to the genetic interactions between IL27RA and IL16, IL1RAP and IL10RB, and the lower level of expression of histocompatibility complex genes.

DICER1 is an RNase III endonuclease essential for microRNA (miRNA) biogenesis and RNA processing (48). Altered miRNA expression can be expected to occur as a result of variations in pre-miRNA processing by DICER1. Fluctuations in miRNA expression regulate the expression of key tumor suppressor genes and oncogenes (49) and the fate of hematopoietic cells (48). Their global deregulation by the under-expression of DICER1 promotes tumorigenesis. Reduced DICER1 expression has been associated
with multiple solid neoplasias (49). In the current study, we observed that \textit{DICER1} expression levels were widely lower in patients with low-risk MDS. In addition, \textit{DICER1} was hyper-methylated in low-risk MDS, which could be responsible for the \textit{DICER1} under-expression observed in these patients. A deletion in \textit{DICER1} has been recently described in osteoprogenitors that impairs osteoblastic differentiation and the integrity of hematopoiesis and induces bone marrow dysfunction with myelodysplasia (48). These data suggest that the disruption of \textit{DICER1} by methylation or mutation may cause myelodysplasia in mice resembling important features of human MDS. Our findings also showed that \textit{DICER1} had direct genetic interactions with \textit{ATXN1}, \textit{NFE2L3} and \textit{POP4} deregulated genes, which might affect the normal relationship of these genes with \textit{DICER1} and consequently the deregulation of the functions in which they are involved. Furthermore, our data showed an overall slight down-regulation of miRNAs in low-risk MDS (p-value = 0.039) which could be related to the deregulation of \textit{DICER1}. However, no significant differences were found for two miRNAs (miRNA-145 and miRNA-196) that were examined individually.

Recent advances have suggested a potential role for hyper-methylation in cancer because of the transcripational silencing (50). Nevertheless, global DNA hypomethylation in cancer may be as frequent as hyper-methylation (51). Our study showed that \textit{ING1}, \textit{UBE2D3} and \textit{RRAS2} genes were hypo-methylated and over-expressed in low-risk MDS patients. The \textit{ING1} and \textit{UBE2D3} genes are both related to p53. The \textit{ING1} gene encodes a protein that can induce cell growth arrest and apoptosis by cooperating with p53, and \textit{UBE2D3} functions in the ubiquitination of p53. \textit{RRAS2}, previously described as being up-regulated by other authors (33), may play an important role in activating signal transduction pathways that control cell proliferation. Thus, the alteration of these three genes could be implicated in functions previously described as deregulated in MDS (15;33).
In summary, we have generated a DNA methylation profile for low-risk MDS patients that could extend our knowledge of these diseases. RNA expression levels were analyzed and correlated with methylation status, suggesting that DNA hypermethylation events in low-risk MDS are biologically important for gene functions such as gene expression, RNA processes, the immune response and apoptosis. In addition, these epigenetic modifications that lead to transcriptional silencing of genes are attractive therapeutic targets for demethylating agents.
Acknowledgements

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Conflict of interest disclosure: The authors declare no conflict of interest.
Reference List


(44) Span PN, Manders P, Heuvel JJ, Thomas CM, Bosch RR, Beex LV, et al.


Figure Legends

Figure 1. GEP of low-risk MDS patients and normal bone marrow samples. The heatmap shows hierarchical clustering of 1005 genes differentially expressed between low-risk MDS and control patients. This gene-set was obtained for an FDR cut-off < 0.10 and included 444 upregulated genes and 561 down-regulated genes. The absolute expression signal obtained for each gene in each sample is represented by a color scale. Green indicates upregulation and red indicates down-regulation, black being the intermediate signal. Each row represents a single gene and each column corresponds to a separate patient sample. The distances in the clustering are based on Pearson correlation coefficients, calculated pair-wise, using the expression signature of each gene in all samples. The unique low-risk MDS cases that displayed chromosomal alterations are showed with a color point: blue for a loss on 5q and orange for a monosomy 7 (GEP: gene expression profile; MDS: myelodysplastic syndrome)

Figure 2. Integrative epi/genomic analysis of low-risk MDS patients compared with controls. A. Total number of differentially expressed and methylated genes in low-risk MDS and healthy controls. 91 differentially methylated genes were also deregulated. B. Quantification of genes identified in a two-way analysis. Bars represent the differentially methylated genes and the two colors within each bar indicate the number of differentially expressed genes. The hyper-methylation and under-expression combination corresponds to the most frequent association between the two analyses with respect to the other possible combinations. (MDS: myelodysplastic syndrome)

Figure 3. Functional analysis of hyper-methylated and under-expressed genes in low-risk MDS patients. Identification of processes significantly enriched in the hyper-
methylation and under-expression profile of low-risk MDS subjects compared with control cases. The functional enrichment of the selected genes was analyzed using DAVID, IPA and Metacore bioinformatics tools. The most representative biological processes with the highest number of genes are included. The best represented category was "Regulation of gene expression", which involves 15 genes. (MDS: myelodysplastic syndrome)

Figure 4. Schematic representation of the deregulated BCL2-related pathway in low-risk MDS patients. Red and green respectively denote gain and loss of expression in the low-risk MDS group relative to control subjects. The yellow genes BCL2 and SYK were hyper-methylated and under-expressed in low-risk MDS, while BCL2L11 and MYC were over-expressed and BAX and CUX1 were under-expressed in the low-risk MDS patients with respect to the control group. An arrow pointing from A to B signifies that A causes B to be activated. Union between molecules shows protein-protein interactions which occur when two or more proteins bind together, often to carry out their biological functions. Many of the most important molecular processes in the cell are carried out by a large number of protein components organized by their protein-protein interactions. Solid and dashed lines respectively indicate direct and indirect interactions between molecules. The gene network was generated with the Ingenuity bioinformatics tool. (MDS: myelodysplastic syndrome)
Table 1. Most representative cellular functions corresponding to the 817 genes deregulated by methylation in low-risk MDS patients.

<table>
<thead>
<tr>
<th>Cellular Function</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development_GM-CSF signaling</td>
<td>5.867E-07</td>
</tr>
<tr>
<td>Apoptosis and survival_HTR1A signaling</td>
<td>0.000007751</td>
</tr>
<tr>
<td>Development_TGF-beta-dependent induction of EMT via SMADs</td>
<td>0.0001066</td>
</tr>
<tr>
<td>Development_VEGF signaling and activation</td>
<td>0.0003635</td>
</tr>
<tr>
<td>Development_Regulation of epithelial-to-mesenchymal transition (EMT)</td>
<td>0.0004061</td>
</tr>
<tr>
<td>Transcription_CREB pathway</td>
<td>0.0004159</td>
</tr>
<tr>
<td>Immune response_CD137 signaling in immune cell</td>
<td>0.0005866</td>
</tr>
<tr>
<td>Immune response_Inflammatory response</td>
<td>0.0006636</td>
</tr>
<tr>
<td>Immune response_Histamine H1 receptor signaling in immune response</td>
<td>0.0006889</td>
</tr>
<tr>
<td>Immune response_Histamine signaling in dendritic cells</td>
<td>0.0008708</td>
</tr>
</tbody>
</table>

Table 2. Integration analysis of hypo-methylated and over-expressed genes in low-risk MDS patients.

<table>
<thead>
<tr>
<th>Gene Symbol</th>
<th>Expression</th>
<th>Methylation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d-Value</td>
<td>p-Value</td>
</tr>
<tr>
<td>CDH4</td>
<td>4.61</td>
<td>0.000</td>
</tr>
<tr>
<td>RAB8B</td>
<td>4.52</td>
<td>0.000</td>
</tr>
<tr>
<td>UBE2D3</td>
<td>3.4</td>
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<tr>
<td>ING1</td>
<td>3.19</td>
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<tr>
<td>TBPL1</td>
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<tr>
<td>CYB5D1</td>
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<td>0.012</td>
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<td>FADS2</td>
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<td>HCN3</td>
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<td>H2AFJ</td>
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<td>RRAS2</td>
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<td>SYN3</td>
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<td>AAAS</td>
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</tr>
<tr>
<td>FXYD2</td>
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<tr>
<td>Gene Symbol</td>
<td>Expression</td>
<td>Methylation</td>
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<tr>
<td>-------------</td>
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</tr>
<tr>
<td></td>
<td><strong>d-Value</strong></td>
<td><strong>p-Value</strong></td>
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<tr>
<td>PLAGL1</td>
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<tr>
<td>BCL2</td>
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</tr>
<tr>
<td>NELL2</td>
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<td>DICER1</td>
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<tr>
<td>NFE2L3</td>
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<tr>
<td>IL27RA</td>
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<td>ALCAM</td>
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<tr>
<td>OPN3</td>
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<tr>
<td>IER3P1</td>
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<td>BNIP2</td>
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<td>RPS6KA5</td>
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<td>PTPRC</td>
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<td>ZNF37A</td>
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<td>RHOU</td>
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<td>CNOT6L</td>
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<td>RPL36AL</td>
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<td>KLLH8</td>
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<tr>
<td>CENTD1</td>
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<tr>
<td>PH-4</td>
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<td>0.034</td>
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<tr>
<td>FVT1</td>
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<td>0.034</td>
</tr>
<tr>
<td>CD28</td>
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<tr>
<td>CHIT1</td>
<td>-2.24</td>
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<tr>
<td>C10orf11</td>
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</tr>
<tr>
<td>CTSC</td>
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<tr>
<td>RHOQ</td>
<td>-2.18</td>
<td>0.046</td>
</tr>
<tr>
<td>AK2</td>
<td>-2.15</td>
<td>0.049</td>
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</table>
Table 4. ETS1 under-expressed targets involved in deregulated pathways in low-risk MDS patients.

<table>
<thead>
<tr>
<th>Category</th>
<th>p- Value</th>
<th>Number of Genes</th>
<th>Molecules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Death</td>
<td>7.62E-03 - 4.13E-02</td>
<td>9</td>
<td>IL7R, ITGAL, LCK, MAP4K1, PAK2, PTAFR, TNFSF13, TOPBP1, TRADD</td>
</tr>
<tr>
<td>Cellular Function and Maintenance</td>
<td>9.03E-05 - 4.62E-02</td>
<td>6</td>
<td>IL7R, ITGAL, LCK, MAP4K1, ZAP70, FOXP1</td>
</tr>
<tr>
<td>Hematological System Development and Function</td>
<td>1.45E-04 - 4.62E-02</td>
<td>6</td>
<td>IL7R, ITGAL, LCK, MAP4K1, ZAP70, TNFSF13</td>
</tr>
<tr>
<td>Cellular Development</td>
<td>1.47E-03 - 4.62E-02</td>
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</tr>
<tr>
<td>Hematopoiesis</td>
<td>1.47E-03 - 4.62E-02</td>
<td>5</td>
<td>IL7R, ITGAL, LCK, MAP4K1, ZAP70</td>
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<tr>
<td>Cell-To-Cell Signaling and Interaction</td>
<td>9.03E-05 - 3.46E-02</td>
<td>4</td>
<td>FOXP1, ITGAL, ZAP70, LCK</td>
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<tr>
<td>Cell-mediated Immune Response</td>
<td>1.45E-04 - 4.62E-02</td>
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</tr>
<tr>
<td>Genetic Disorder</td>
<td>5.43E-03 - 2.12E-02</td>
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<td>ATXN1, ITGAL, MAP4K1, TRADD</td>
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<td>Molecular Transport</td>
<td>7.01E-03 - 3.65E-02</td>
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<td>LCK, TRAT1, ZAP70, PATAFR</td>
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<tr>
<td>Gene Expression</td>
<td>2.89E-04 - 4.99E-02</td>
<td>3</td>
<td>LCK, ZAP70, LEF1</td>
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<tr>
<td>Cellular Growth and Proliferation</td>
<td>6.63E-03 - 1.49E-02</td>
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<td>IL7R, TNFSF13, ZAP70</td>
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<tr>
<td>Cell Morphology</td>
<td>7.01E-03 - 4.81E-02</td>
<td>3</td>
<td>LCK, LPP, ZAP70</td>
</tr>
<tr>
<td>Cellular Assembly and Organization</td>
<td>7.01E-03 - 4.81E-02</td>
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<td>LCK, PTAFR, ZAP70</td>
</tr>
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<td>Cancer</td>
<td>8.50E-03</td>
<td>2</td>
<td>LCK, ZAP70</td>
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<tr>
<td>Cell Cycle</td>
<td>7.01E-03</td>
<td>1</td>
<td>PTAFR</td>
</tr>
</tbody>
</table>
Figure 1
2A

Total genes differentially methylated: 817

726 genes differentially methylated

91 common genes

1884 genes differentially expressed

Total genes differentially expressed: 1975

2B

Under-expressed genes in low-risk MDS

Over-expressed genes in low-risk MDS

Hypermethylated genes in low-risk MDS

Hypomethylated genes in low-risk MDS

Figure 2

Regulation of Gene Expression: 15

RNA Process: 11

Immune Response: 9

Regulation of Cell Differentiation: 7

Cell Adhesion: 7

Positive Regulation of Apoptosis: 5

Regulation of Cell Cycle: 4

Hemopoiesis: 4

Cell Activation: 4

Cell Morphogenesis: 4

Pathways in Cancer: 4

Regulation of Mononuclear Cell Proliferation: 3

Positive Activation of MAPK Activity: 3

Figure 3
Figure 4