Two Distinct Gene Expression Signatures in Pediatric Acute Lymphoblastic Leukemia with MLL Rearrangements

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ABSTRACT

Acute lymphoblastic leukemia (ALL) with 11q23 translocations is usually associated with MLL gene rearrangement, but little is known about its leukemogenesis. We analyzed the gene expression profiles of pediatric ALL samples according to their translocations. Using oligonucleotide microarray analysis, we identified distinct expression profiles for 23 ALL samples with 11q23 translocations, including t(4;11) (n = 15), t(11;19) (n = 6), and t(5;11) (n = 2), compared with 9 ALL samples with other translocations, including t(12;21) (n = 6) and t(11;19) (n = 3). Gene expression scores of FLT3, MEIS1, and CD44 for samples with MLL rearrangements were particularly high compared with those for other ALL samples. Statistical analysis of the gene expression profiles for the 21 ALL samples with MLL rearrangements at diagnosis revealed two subgroups that exclusively correlated with prognosis but not with any other clinico-pathological factor. The transcription factors CBFB and CD7 were highly expressed in the poor and good prognosis subgroups, respectively. In addition, their downstream target genes were differentially expressed. These findings provide new insights into the biological mechanisms of leukemogenesis and prognosis for pediatric ALL with MLL rearrangements.

INTRODUCTION

The prognosis of children with ALL has improved remarkably over the last 2 decades (1–3). This success has been achieved by using risk-directed therapy, which was developed after the realization that pediatric ALL is a heterogeneous disease (4). However, 20–25% of ALL patients still experience a relapse. Attempts to classify pediatric ALL into therapeutically relevant risk categories have relied mainly on clinical parameters, including age and WBC count at diagnosis, as well as increasing our understanding of leukemogenesis. The MLL gene (also known as ALL-1 or HRX), located at 11q23, encodes a protein of 3969 amino acids containing zinc fingers and AT-hook motifs and has homology with Drosophila trithorax protein (5). The MLL gene fuses with >30 genes on various partner chromosomes (10–12) and is highly conserved across species. Through its regulation of the HOX genes, MLL is essential for normal mammalian development and hematopoiesis. Although the function of the various MLL fusion genes and proteins is poorly understood, it appears that their fusion proteins disrupt the ability of wild-type MLL to regulate HOX gene expression, leading to leukemogenesis (13).

Recently, a genomic approach to cancer classification, including leukemia classification (14–17), based on gene expression monitoring using DNA microarrays, has been reported, with a distinct gene expression in pediatric T-ALL shown to be associated with a poor prognosis (17). MLL-RE-ALL has been reported to have characteristic, distinct gene expression profiles that are consistent with an early hematopoietic progenitor cell expressing selected multilineage markers and individual HOX genes. Clustering algorithms reveal that, based on their gene expression patterns, acute leukemia with MLL rearrangements can be clearly separated from conventional ALL and AML (18), suggesting that they constitute a distinct disease. Among MLL-RE-ALLs, infant patients have a poor prognosis. However, children >1 years old have a relatively good prognosis (4). We used an oligonucleotide microarray to analyze the expression of >12,600 genes in leukemic cells from 31 pediatric ALL patients, comprising 3 groups, with differential prognoses, irrespective of their translocation partner chromosomes.

MATERIALS AND METHODS

Leukemia Samples. Leukemia cells from the bone marrow or peripheral blood of ALL patients were obtained with informed consent at diagnosis or relapse. In each case, the percentage of blasts was >90%. CD19 was expressed in all samples, but CD2, CD5, and CD7 were not expressed in any samples. We analyzed 32 ALL samples with chromosomal translocations, comprising 3 groups with t(1;19), 6 with t(12;21), and 23 with MLL rearrangements, including 15 t(4;11), 6 with t(11;19), and 2 with t(5;11). Samples were obtained from one patient with t(4;11) and only at relapse from one MLL-RE-ALL sample. Therefore, the remaining 21 samples were obtained only at diagnosis. All of the translocations were subjected to karyotype analysis, fluorescence in situ hybridization, and/or Southern blot analyses, and MLL partner genes were confirmed by RT-PCR as described elsewhere (11, 19–21). The t(1;19), t(12;21), t(4;11), and t(11;19) samples were found...
to have E2A-PBX1 (22), TEL-AMLI, MLL-AF4 (19), MLL-ENL (19), and MLL-AF5q31 (11) fusion genes, respectively. Infant MLL-Re-ALL patients were mainly treated according to the MLL-96 protocol (23).

RNA Extraction and High-Density Oligonucleotide Array Analysis. Total RNA and genomic DNA were isolated from frozen cells using the ISOGEn reagent (Nippon Gene, Tokyo, Japan) according to the manufacturer’s protocol. The quality of total RNA was examined by gel electrophoresis to confirm that the ribosomal 28S and 18S RNA bands were intact. The experimental procedures for GeneChip (Affymetrix, Santa Clara, CA) were performed according to the Affymetrix GeneChip expression analysis technical manual as described previously (24, 25). Briefly, 3–5 µg of total RNA were used to synthesize biotin-labeled cRNA, which was then hybridized to a GeneChip Human U95 V2 oligonucleotide array (Affymetrix). After washing, the arrays were stained with streptavidin-phycoerythrin and analyzed on a Hewlett-Packard Scanner to collect the image data. GeneChip Analysis Suite software 4.0 was used to calculate the AD for each gene probe set on the array, which was shown as an intensity value of the gene expression. The AD values were normalized for each array so that the average of all AD values was 100.

Raw data are available on the Internet.

Statistical Analysis. For each expression data set, where the AD values lay outside the range (10–8000), the value was reset to a minimum of 10 and a maximum of 8000. Subsequently, all values were log transformed for further analysis. Hierarchical clustering analysis was performed using GeneSpring (Silicon Genetics, Inc., Redwood, CA), CLUSTER, and TREEVIEW software (Eisen Lab.; Ref. 26).

Genes that correlated with particular class distinctions were identified as described by Golub et al. (14). We used the signal-to-noise statistic \( (\mu_0 - \mu_1)/\sigma \) (where \( \mu_0 \) and \( \mu_1 \) represent the mean and SD of expression, respectively, for each class). We also carried out 100,000 permutations of the samples by Mantel-Whitney U and Kruskal-Wallis H tests to determine whether the correlations were more significant than would be expected by chance alone. Applying PCA, the coordinates of the first three principal components for each sample were selected. An SVM algorithm (27) was also applied to classify the samples using a modified version of the SVM light.

RT-PCR and Sequence Analysis. cDNA was reverse transcribed from 5 µg of total RNA using a CDNA synthesis kit (Invitrogen, Carlsbad, CA). PCR amplification was performed with the Advantage 2 PCR kit (Clontech, Palo Alto, CA) by incubating at 94°C for 2 min, followed by 35 cycles of 94°C for 30 s and 68°C for 2 min using FLT3-specific primers (F1; 5′-CCCAACTG-CACAGAAAGATCTACAG-3′ and F2; 5′-TACAGGCTTGATTAGGATAG-GTGGAAAGG-3′). The PCR products were purified using a Qiaquick PCR purification kit (Qiagen, Hilden, Germany) and subjected to direct sequencing with primers (5′-CCGCATCGCTGTCAAGAG-3′, 5′-GCCCTGAGA- TTTGATCCGAGTC-3′, 5′-GTGGAGAAAATCTTCTCACTTG3′, 5′-ATCTC-TAGATACCTTCCAAACTC-3′, 5′-AGAGAGGCGACTCATGTACAGAAC-3′, F1 and F2) using DYEnamic ET Terminator Kits (Amersham Biosciences, Piscataway, NJ) on an Applied Biosystems DNA sequencer. Internal tandem duplications of the FLT3 gene were investigated by RT-PCR using the primers (5′-TGGTGCGAGTACTCTAAAACA-3′ and 5′-ATCTCTAGTACCTTTCCCAAAC-3′) and electrophoresis as described previously (20).

Genomic PCR and Restriction Fragment-length Polymorphism Analysis. We amplified the exon 20 of the FLT3 gene by genomic PCR using the primers (5′-GGTGCACTCATCTAGCTTG3′ and 5′-CCACGTGAGTGCGACTTTACCATG-3′) incubating at 94°C for 2 min, followed by 35 cycles of 94°C for 30 s and 68°C for 30 s. Amplified products were digested with EcoRV and subjected to electrophoresis on an agarose gel (Fig. 4).

RESULTS

Gene Expression Profiling Can Identify the Translocation Type in ALL Samples. We analyzed 32 pro-B or early pre-B ALL samples, including those with MLL rearrangements (n = 23), TEL-AMLI (n = 6), and E2A-PBX1 (n = 3), with Affymetrix oligonucleotide microarrays containing 12,600 probe sets. All samples showed high CD19 expression signals. Relatively higher expression of CD44 and lower of CD10 (MME), CD22, CD24, and CD79B were found in patients with MLL rearrangements rather than in those with TEL-AMLI and E2A-PBX1 (supplementary information is available on the Internet).

The results of the PCA were plotted with three-dimensional scaling to determine whether we could identify the ALL translocation types from their gene expression profiles. Samples carrying MLL rearrangements, those with TEL-AMLI and E2A-PBX1, were resolved with this method. In contrast, no distinct subgroups were observed for defined MLL rearrangements, such as MLL-ENL, MLL-AF4, or MLL-AF5q31 fusion genes (Fig. 1A). To classify the samples according to the similarity of their gene expression patterns and classify the genes according to the expression similarities over the samples, we applied a two-dimensional hierarchical clustering algorithm. In this analysis, samples with TEL-AMLI and E2A-PBX1 fusion were also subclassified into their respective clusters (Fig. 1B).

We next selected a list of genes whose expression patterns were
correlated with particular translocations (MLL rearrangements, E2A-PBX1 and TEL-AML1) using signal-to-noise analysis (supplementary Fig. 7; Ref. 14). Among 50 genes that were uniquely expressed in a subset of MLL rearrangements, 13 genes were also found in 50 unique genes for MLL-Re-ALL in a previous report (18). These included LGALS1, CD44, CD45, and PMX1. Furthermore, we found that FLT3 and MEIS1 were expressed highly, and CD10 (MME) was less expressed in the samples with MLL rearrangements.

Two Distinct Patterns of Gene Expression among MLL-Re-ALL Samples. Gene expression patterns for leukemias with MLL rearrangements have been reported to be unique compared with those in other ALL without MLL rearrangements or AML (18). To investigate the variations in gene expression patterns among MLL-Re-ALL samples, we used a two-dimensional hierarchical clustering analysis on gene expression profiles for our 23 MLL-Re-ALL samples. This analysis produced two major sample clusters (Fig. 2). Two expression profiles generated from samples at onset and relapse from the same patient were classified in the same cluster. Excluding the two relapse samples, a random permutation test showed that the expression profiles of these two groups were statistically different (P < 0.01 by Mann-Whitney U test, see supplementary Fig. 9). Fourteen hundred of the 4200 genes expressed in this analysis showed distinct (P < 0.05) expression patterns between the two major clusters of MLL-Re-ALL samples. These probabilities were more significant than those between the two groups based on translocations (6 MLL-ENL samples versus 13 MLL-AF4 samples). In fact, samples No. 20 and No. 21 carrying different MLL-partner genes had a correlation value of 0.49, which was much higher than the value of 0.07 found between samples No. 1 and No. 20 that have the same MLL partner gene. The two groups of patients were not significant in age or WBC counts at diagnosis (by Mann-Whitney U test), gender, or treatment (by χ² test; data not shown).

Gene Expression Signature Has Prognostic Relevance for MLL. To elucidate the possible clinical significance associated with the two main expression profile groups, Kaplan-Meier analysis was performed for relapse and survival (Fig. 3). Excluding the two samples obtained at relapse, Kaplan-Meier analysis showed that Cluster B in Fig. 2 was associated with a distinctly favorable prognosis. As shown in Fig. 3B, the overall probability of survival at 3 years was 92 ± 8% SE for Cluster B and 0% for Cluster A (P = 0.0005 by Log-rank analysis). The probability of event-free survival at 3 years was 73 ± 14% for Cluster B and 0% for Cluster A (P = 0.01). MLL-Re-ALL patients <1 year old are reportedly associated with a poor prognosis, whereas those with t(4;11) and >1 year old have relatively good prognosis (2, 4, 6). In our study, only 1 patient (No. 22 on Fig. 2) was older than 1 year and subclassified in the favorable cluster B.

As reported previously (18), we found that MLL-Re-ALL is characterized by elevated levels of FLT3 expression (shown in supplementary Fig. 8A). The AD values of FLT3 showed no significant difference between the two clusters. Internal tandem duplication of the FLT3 gene has been reported in 20–30% of adult AML (28, 29) and 15% of childhood AML (30). In addition, mutations of the FLT3 gene have been reported in 5% of adult AML (31). We investigated Asp835 mutations of the FLT3 gene by direct sequence and restriction fragment-length polymorphism analysis of genomic PCR products. Three (14%) of 21 MLL-Re-ALL patients, 1 from Cluster A and 2 from Cluster B, were found to have Asp835 mutations (Fig. 4). This was confirmed by sequence analysis of FLT3 cDNA. No other mutations were found in the intracellular region of FLT3 by sequence analysis of
cDNA. RT-PCR analysis failed to reveal internal tandem duplications of the FLT3 in any of the samples (data not shown).

**Biological Aspects between the Two Differential Prognostic Clusters.** To investigate the biological features of the two clusters shown in Fig. 2, signal:noise expression ratios were calculated for the two groups as described previously (14), and the top and bottom 30 ranked genes that differentiated between the two groups were selected (Fig. 5). Transcription factors/coactivators were found among the top 30 discriminating genes for both clusters. In Cluster A (Gene list U), CDPR, TRIP3, CBF2, and in Cluster B (gene list F), CDPR, NCOR1, USF2, ZFP36L2, and SMARCC2 were found among the top discriminating genes. We compared the promoter targets for these transcription factors with the upstream promoter sequences of other genes in our lists. CDP was reported to bind to at least two homeotic CCAAT motifs located upstream of the TATA element and to suppress histone gene expression (32). Four of the genes in gene list U (TRIP3, H2BEFL, C14orf2, and MDH1), with expression suppressed in samples with elevated CDP expression, have two 5'-CCAAT-3' motifs (5'-CCAAT-3'-53-72 bp-5'-CCAAT-3'), located between 500 bp upstream and 100 bp downstream of the transcription start site. This indicates that the expression patterns of these genes may be functionally related.

The precise subclassification of unknown samples into the two clusters by gene expression profiling is especially important in MLL-Re-ALL because there are few conventional methods for predicting the prognosis of those types of ALL. A supervised SVM was used against these higher and lower signal-to-noise genes to classify the samples. The test sample was classified using a leave-one-out model for the remaining 20 samples. Through all 21 cycles, 100% accuracy in predicting prognosis was achieved with between 21 and 1000 genes selected for higher or lower signal-to-noise values (data not shown). This result suggested that the prognosis of MLL-Re-ALL could be predicted reliably by using the expression profiles of selected genes.

**DISCUSSION**

To make an accurate diagnosis of pediatric ALL, many clinical diagnostic examinations are required. It is necessary to consider the interrelationship of various prognostic factors, including chromosomal translocations (1, 2, 4, 12). ALL patients with t (12;21; TEL-AML1) are associated with a good clinical outcome (2, 4), whereas MLL-Re-ALL patients are associated with a poor outcome (1, 2, 4, 10, 12). Our data suggest that MLL-Re-ALL can be diagnosed from gene expression profiles. FLT3, MEIS1, and the 13 genes reported previously (18) were also found in the top 50 genes expressed highly in our MLL-Re-ALL samples. HOX9, a heterodimer partner of MEIS1, was significantly expressed in MLL-Re-ALL samples (P < 0.05 by Mann-Whitney U test).

One of the most interesting findings in this study was the remarkable variance in the gene expression signatures of MLL-Re-ALL. This difference was more significant than that between 13 samples with t (4;11) and 6 with t(11;19). This result strongly suggests that at least two subgroups exist in MLL-Re-ALL independent of the MLL partner genes, with patients in one subgroup (Cluster A) having a remarkably poor prognosis.

It was reported that an internal tandem duplication of FLT3 in AML predicted poor prognosis, and recently, mutations of FLT3 have been reported to be rare in AML (31). Our result showed Asp835 mutations of FLT3 in 3 (14%) of 21 MLL-Re-ALL patients, but we found no tandem duplications of FLT3 similar to our previous report (20). Elevated expression of the FLT3 gene was not associated with either cluster, and Asp835 mutations were not associated with prognosis. Except for SPN, expression of these leukocyte markers, CD10, CD19, CD22, CD24, CD44, CD79B, and TdT, were not significantly correlated with the two clusters (supplementary Fig. 6). It was reported that, with intensive treatment, including hematopoietic stem cell transplantation, 30–40% of MLL-Re-ALL infants remained free of relapse.
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