Lineage Infidelity of a Human Myelogenous Leukemia Cell Line

By Antonio Palumbo, Jun Minowada, Jan Erikson, Carlo M. Croce, and Giovanni Rovera

We have analyzed the organization and expression of the immunoglobulin heavy and light chain gene in the human myeloblastic leukemic sublines, ML1, ML2, and ML3, and in the human myeloid leukemic cell lines, HL-60, U937, THP1, and K562. ML1, ML2, and ML3 cells, despite a predominant granulocytic phenotype, express a rearrangement of the immunoglobulin heavy chain gene that typically occurs during the early stages of the B cell differentiation pathway. No rearrangement was found in any of the other cell lines tested. These findings strongly support the notion that, at least in some cases, acute myeloid leukemia (AML) cells represent highly atypical cells with profoundly altered gene expression, rather than cells arrested at a well-defined stage of the myeloid lineage.

U937 and THP1, and erythroleukemia K562 cell lines were grown to densities of $5 \times 10^5$ to $1 \times 10^6$ in RPMI medium supplemented with 10% fetal bovine serum.

**DNA Extraction**

Cells ($5 \times 10^6$) were washed twice in 100 mmol/L Tris-HCl, 10 mmol/L EDTA, and resuspended in 2 mL of a solution containing 100 mmol/L EDTA, 10 mg N-lauroyl-sarcosine (Sigma, St Louis, Mo), and 0.5 mg Proteinase K (Boehringer Mannheim, West Germany) and incubated at 50°C for three hours. Suspensions of lysed cells were then extracted three times with saturated phenol and dialyzed extensively in 50 mmol/L Tris-HCl, 10 mmol/L EDTA, and 10 mmol/L NaCl. Samples were incubated with DNAse-free RNAs (100 μg/mL) at 37°C for three hours, extracted twice with a mixture containing 50% (vol/vol) phenol/chloroform, and dialyzed against 1 L of 10 mmol/L Tris-HCl. The extracted DNA was precipitated with ethanol and quantitated by UV spectrophotometry.

**DNA Gel Electrophoresis and Southern Transfer**

Agarose gel (0.8%) electrophoresis was carried out in 40 mmol/L Tris-HCl, 5 mmol/L NaOAc, 2 mmol/L EDTA, pH 8.0. HindIII-digested λ-phage DNA molecular weight markers (Bethesda Research Labs, Md) were included on every gel. Cellular DNA samples were digested with BamHI, EcoRI, or HindIII and subjected to electrophoresis in a horizontal agarose (Bethesda Research Labs) slab gel. Gels were stained for ten minutes with ethidium bromide (1 μg/mL) and photographed under UV light. Transfer of DNA from gels to nitrocellulose sheets (Millipore, Bedford, Mass) was performed essentially as described by Southern.

**Preparation of Labeled Probe DNAs**

The probes for the μ, J, κ, and λ regions used in these studies are schematized in Fig 1. The Jκ probe consisted of a 3.3-kb germline EcoRI–HindIII fragment. The human J region was obtained by subcloning a 3.3-kb fragment of the human genomic DNA clone (H18CP10). This fragment contains 2.2 kb of the human joining (J) region DNA and 1.1 kb of the 3’ end flanking sequences. The Cμ is a 1.2-kb EcoRI fragment subcloned in pBR322, encompassing the...

**Materials and Methods**

**Cells**

Human myeloblastic leukemia ML sublines, ML1, ML2, and ML3, human promyelocytic leukemia HL-60, monocytic leukemia HL-60, U937, THP1, and K562. ML1, ML2, and ML3 cells, despite a predominant granulocytic phenotype, express a rearrangement of the immunoglobulin heavy chain gene that typically occurs during the early stages of the B cell differentiation pathway. No rearrangement was found in any of the other cell lines tested. These findings strongly support the notion that, at least in some cases, acute myeloid leukemia (AML) cells represent highly atypical cells with profoundly altered gene expression, rather than cells arrested at a well-defined stage of the myeloid lineage.
sequences encoding the Cμ, Cα, and Cε components. Cβ is a 500-bp MboI–HindIII fragment subcloned in M13 mp7, equivalent to residues 115 to 415 (T. Rabbitts, MRC Laboratory of Molecular Biology, University Medical School, Cambridge, England; manuscript in preparation). Cα is an 8-kb EcoRI fragment subcloned in pBR322 containing the Ke Oζ Ke Oζ 'genes. 14

The Jα, Cμ, Cε, and Cα probes were labeled with 32P to a specific activity of 0.5 to 2 x 10^6 cpm/μg of DNA before use and hybridized with DNA.

Hybridization

DNA on nitrocellulose filters was hybridized to 32P-labeled probe DNA in a hybridization solution containing 50% (vol/vol) formamide, 0.9 mol/L NaCl, 50 mmol/L HEPES, 5 mmol/L EDTA, 0.2 mg/mL sonicated salmon sperm DNA, 1X Denhardt’s solution at 42°C. After hybridization, the filters were washed, air-dried, and exposed to Kodak XRP-5 film for various periods.

Phenotypic Analysis

Cytochemical stainings (peroxidase and ASI chloroacetate esterase) were performed as described by Kaplow15 and Yam et al.16

Cell surface phenotype was analyzed by indirect immunofluorescence (Ortho Cytofluorograf 50HH, Ortho Instruments, Westwood, Mass) using monoclonal antibody R1B19, which is specific for the granulocytic lineage; monoclonal antibodies LB3.45 and S4.7, specific for cells of the myelomonocytic lineage;17,18 antibody BA, specific for a B cell subset antigen;19 SK37.7, specific for HLA-DR,20 and J5, specific for common acute lymphocytic leukemia antigen (CALLA).20 Membrane IgM, cytoplasmic IgM, and the ability to form rosettes with sheep erythrocytes (SRBC) were assayed as described.21,22

RESULTS

DNA samples extracted from ML1, ML2, and ML3 sublines and from human HL-60 promyelocytic leukemia, U937 and THP1 monocytic leukemia, and K562 erythroleukemia cells23 were digested with BamHI restriction endonuclease, separated by agarose gel electrophoresis and transferred to nitrocellulose filters. The resulting blots were hybridized to a 32P-labeled DNA probe specific for the constant region of the immunoglobulin heavy chain gene (Cμ).13 One germ-line band of approximately 17 kb was detected in all the myeloid cell lines tested (Fig 2). ML1, ML2, and ML3 cells showed an additional band of approximately 13.5 kb. Similarly, the joining (Jμ) segment12 of the μ-gene, detected after hybridization of HindIII-digested DNA from the cell lines with a 32P-labeled Jμ probe, resolved as a single 9-kb band in germline configuration in HL-60, U937, THP1, and K562 cells (Fig 3A). However, the Jμ segment was rearranged in ML1, ML2, and ML3 cells, as evidenced by a 9-kb germ-line band and a second band of 8 kb. Rearrangement of the Jμ segment was also detected when the DNA samples were digested with EcoRI restriction endonuclease (Fig 3B). In this case, we observed a 16-kb germline band and a second band of 12 kb, representing the rearranged Jμ segment. The rearrangement of both the Cμ gene and the Jμ segment suggests that, in ML cells, the target for malignant transformation was a cell that had completed the process of rearrangement of a heavy chain immunoglobulin gene. However, no μ-heavy chain immunoglobulin mRNA could be detected by mRNA dot blot (data not shown) under conditions that allow detection of approximately ten molecules per cell of specific mRNA.24

The Cα and the Cε genes were detected in a germ-line configuration in all the myelogenous leukemic cell

![Fig 1. Schematic representation of the human immunoglobulin gene probes used to detect germline and rearranged genes. (A) The 3.3-kb human Jμ region and the 1.2-kb Cμ, encoding the Cα, Cε, and Cμ fragments; (B) the 300-bp Cβ region; (C) the 8-kb Cα fragment containing the Ke Oζ Ke Oζ 'genes.

![Fig 2. Cμ-related sequences in DNA of human myeloid leukemic cell lines. BamHI-digested genomic DNA, prepared from HL-60, ML1, ML2, ML3, U937, THP1, and K562 cells, was electrophoresed, transferred to nitrocellulose paper, and hybridized to a 32P-labeled Cμ probe. All the cell DNA samples tested show a 17-kb germline band, whereas ML1, ML2, and ML3 DNA show an additional band of approximately 13.5 kb.

![Fig 3. Configuration of Jμ segment in human myeloid leukemia cell lines. DNA samples were digested with HindIII (A) and EcoRI (B) restriction endonucleases, electrophoresed, and hybridized to the 32P-labeled Jμ probe. (A) HL-60, U937, THP1, and K562 DNA show only a single germline band of 9 kb. ML1, ML2, and ML3 DNA show a rearranged configuration with a 9-kb germline and a rearranged 8-kb band; (B) similar results were obtained after EcoRI digestion of ML1, ML2, and ML3 DNA: 16-kb germline band and a 12-kb rearranged band.
Table 1. Characteristics of the Human Myeloid Leukemic Cell Line ML3

<table>
<thead>
<tr>
<th>Cytochemical and Immunologic Markers</th>
<th>Lineage Specificity</th>
<th>Percent Positive Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peroxidase*</td>
<td>Granulocytic</td>
<td>80</td>
</tr>
<tr>
<td>ASD chloroacetate esterase*</td>
<td>Granulocytic</td>
<td>60</td>
</tr>
<tr>
<td>R1B19</td>
<td>Granulocytic</td>
<td>95</td>
</tr>
<tr>
<td>S4.7</td>
<td>Myelomonocytic</td>
<td>95</td>
</tr>
<tr>
<td>LB3.45</td>
<td>Myelomonocytic</td>
<td>95</td>
</tr>
<tr>
<td>SK37.7</td>
<td>HLA-DR (a)</td>
<td>75</td>
</tr>
<tr>
<td>BA1</td>
<td>B subset</td>
<td>0</td>
</tr>
<tr>
<td>J5</td>
<td>CALLA</td>
<td>80</td>
</tr>
<tr>
<td>Membrane IgM*</td>
<td>B cell</td>
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</tr>
<tr>
<td>Cytoplasmic IgM*</td>
<td>pre-B cell</td>
<td>0</td>
</tr>
<tr>
<td>SRBC*</td>
<td>T cell</td>
<td>0</td>
</tr>
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*At least 200 cells were examined with the optical or fluorescent microscope. Values are the means of at least two separate experiments.

DISCUSSION

The ML1, ML2, and ML3 sublines were established from the peripheral blood of a patient with acute myelomonocytic leukemia. This leukemia arose two months after the patient underwent chemotherapy for a malignant lymphoma of pre-T cell type. A direct relationship between the T lymphoma cells of the patient and the myelogenous leukemia cells could not be established, since the karyotype of the lymphoma cells was diploid, while that of the myeloblastic leukemic cells was polyploid, with a unique marker chromosome. The leukemic sublines established in culture contained the same chromosomal abnormalities that were present in the leukemic cells of the patient. Therefore, the three sublines were considered to be of clonal origin and were not further recloned for these studies. Cells from these sublines exhibit myeloblastic and promyelocytic morphology and granulocytic lineage-specific immunologic and histochemical markers. They can be induced to differentiate in vitro into mature cells expressing several granulocyte- and monocyte-specific markers by treatment with the phorbol diester 12-O-tetradecanoyl-13-acetate, cytosine arabinoside, or dimethyl sulfoxide.

However, the ML cell line contains a rearrangement of the JH region of the immunoglobulin chain locus, but not of the light chain loci, which is a pattern observed in cells at an early stage of maturation along the B cell pathway, as in the REH common ALL cell line. Since several restriction enzymes were used in this study, the data support a recombination of the JH antigens, respectively. However, because CALLA is also expressed at low levels in granulocytic cells, its presence cannot be considered to be indicative of a pre-B marker. No cytoplasmic or membrane immunoglobulin or T cell markers were observed in ML3 cells.
region. A deletion with the intervening sequence can also be ruled out, because the different rearranged restriction fragments do not differ from their normal counterparts by the same amount. Since we were unable to detect an abnormal chromosome 14, we could rule out a chromosome translocation involving the heavy chain immunoglobulin locus.

Immunoglobulin gene rearrangement, common in cases of human B lymphomas, is a rare event in the case of T lymphoma. In fact, Korsmeyer et al. examined 12 cases of T cell lymphomas and found only one case (in the HSB2 cell line) in which Cμ and JH were rearranged.

The lack of available information about the conformation of the IgG genes in the T lymphoma cells of the patient from which the ML cells were derived precludes any definitive conclusion on whether or not the leukemia cells were derived from the malignant lymphoma T cells. This possibility cannot be ruled out in light of the case reported by Murphy et al., in which the direct transition from T leukemic cells to myeloid leukemia cells was observed following therapy. In any case, the observations reported here indicate that a recombination of the JH region does not restrict the commitment of a pluripotent cell to the lymphoid lineage, but still allows the cells to differentiate into cells with a myeloid phenotype. Since recombination of the JH region is usually lineage-specific, it is possible that lineage infidelity is observed only in those types of leukemias in which the target for the malignant transformation process is a very immature stem cell. The findings of lineage infidelity in the K562 line could be explained by the fact that K562 cells derive from a patient with chronic myelogenous leukemia, a type of leukemia that has been shown to originate from pluripotent stem cells. Recent reports indicate that myeloblastic leukemia cells freshly obtained from patients with chronic myelogenous leukemia in blastic crisis had immunoglobulin gene rearrangement in the case of lymphoid but not myeloid blastic crisis. It will be of interest, however, to determine whether or not other AML cells, freshly obtained from patients, contain immunoglobulin gene rearrangements.

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