The reciprocal translocation t(15;17)(q22;q21) is associated exclusively with acute promyelocytic leukemia (APL) and the promyelocytic blast crisis of chronic myeloid leukemia (CML). The translocation juxtaposes the promyelocytic leukemia (PML) gene on chromosome 15 and the retinoic acid receptor-α (RARA) gene on chromosome 17, resulting in the formation of a chimeric mRNA transcript. We describe a patient with the microgranular variant form of APL, with no detectable cytogenetic abnormality of either chromosomes 15 or 17, who nevertheless had juxtaposition of PML and RARA genes and expressed a chimeric transcript. Conventional cytogenetics showed the karyotype 46,XY,d-; with the correct culturing conditions, a chimeric transcript was formed. Fluorescent in situ hybridization (FISH) with probes for PML and RARA showed the juxtaposition on one chromosome 15 homolog. Both genes were also present on their normal homologs; in addition, part of the RARA gene was still present on the remaining chromosome 17. DNA analysis by Southern blotting, performed with a variety of probes including PML, RARA and retinoic acid receptor-β (RARβ), showed a rearrangement in PML. Reverse transcriptase-polymerase chain reaction (RT-PCR) confirmed the presence of hybrid transcripts of 276, 455 bp and 623 bp, from PML-RARA on the der(15) chromosome, consistent with alternate exon splicing of the long form of the transcript occurring in 50% to 60% of patients with APL. Our results show that APL patients with cytogenetically normal chromosomes 15 and 17 may, nevertheless, have involvement of both PML and RARA genes defining a subgroup of APL, t(15;17)-negative/PML-RARA-positive which is analogous to Philadelphia chromosome-negative/BCR-ABL-positive CML. In this case, the presence of chimeric transcripts suggests that treatment with all-trans RA may be warranted in APL, even in the absence of detectable cytogenetic change, showing the usefulness of RT-PCR or FISH to aid diagnosis.

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cultures were terminated with colcemid (final concentration, 0.1 µg/mL). The cells were suspended in 0.075 mol/L KCl for 15 minutes and fixed in 3:1 methanol:glacial acetic acid. Slides were banded by incubation in 2× SSC (1× SSC: 0.15 mol/L NaCl, 0.015 mol/L trisodium citrate) at 60°C for 1 hour, followed by a brief rinse in trypsin (0.05% in pH 6.8 buffer) and stained with 6% Giemsa.

**Table 1. Sequences of Oligonucleotide Primers and Probes**

<table>
<thead>
<tr>
<th>No.</th>
<th>3' to 5' Sequence</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CCGATGGCTCGAGAGTTTC</td>
<td>PML</td>
</tr>
<tr>
<td>2</td>
<td>CTCACAGGGCCGCTGCACT</td>
<td>RARA</td>
</tr>
<tr>
<td>3</td>
<td>TGGATCTGCGGGAAGAGCCCTGAG</td>
<td>RARA</td>
</tr>
<tr>
<td>A</td>
<td>TTCAAGGTCGCTGCTAGGA</td>
<td>PML exon 3</td>
</tr>
<tr>
<td>B</td>
<td>GCTATGGCTGTTGCTAGCT</td>
<td>PML exon 5</td>
</tr>
<tr>
<td>C</td>
<td>TCAAGGAGTGGACTGAGGG</td>
<td>PML exon 6</td>
</tr>
<tr>
<td>D</td>
<td>AAGCCTGAGGACTTGTCTGA</td>
<td>RARA exon IV</td>
</tr>
</tbody>
</table>

Slides were rinsed in a solution of 4× SSC, 0.05% Tween 20 (SSCT) at 37°C. They were then incubated in a series of solutions at 37°C for 30 minutes in the following order, with washes between in SSCT:

- 5% Marvel in SSCT; (1) 5% Marvel in SSCT; (2) avidin-fluorescein isothiocyanate (5 µg/mL in SSCT with 2% Marvel; Vector Laboratories, Peterborough, UK) for the paints or the same solution with the addition of anti-Digoxigenin mouse monoclonal antibody (0.2 µg/mL; Boehringer) for the single copy probes; (3) biotinylated antidig (5 µg/mL in SSCT with 2% Marvel; Vector) for the paints and the same solution with the addition of antinouse monoclonal-Texas Red (7.5 µg/mL; Vector) for the single copy probes; and (4) avidin-fluorescein isothiocyanate, as before. After dehydration through an ethanol series, the samples were counterstained with propidium iodide (1 µg/mL) or DAPI (0.5 µg/mL; both from Sigma, UK) as appropriate in Citifluor antifade mountant (Citifluor, Cranbury, UK).

Slides were examined using a Zeiss Axioplan microscope (Carl Zeiss [Oberkochem] Ltd, Welwyn Garden City, UK), equipped with appropriate filters for fluorescence, and photographed directly, or images were collected through a Photometrics CCD camera (Photometrics, Tucson, AZ) to a computer using Digital Scientific software (Digital Scientific, Cambridge, UK).

**Southern blotting.** High molecular weight DNA was extracted from a mononuclear fraction of peripheral blood at diagnosis by standard techniques and digested with the restriction enzymes, BamHI, EcoRI, HindIII, Sac 1 and Bgl II. Southern blotting and probe labeling were performed as previously described. Probes used in this study included, for the PML gene, a mixture of M4 and M12, which are PCR-amplified cDNAs containing the sequences between bases 49 through 117 (coding for exon 1 and 5' UTR) and 931 through 1739 (coding for exons 4 through 6) from the cDNA sequence of NB4; for RARA, a 1.3-kb Xba I genomic fragment, containing sequences from the human homolog of mouse exon 3 that encodes the unique A region of the RARA isoform; for RARβ (RARβ), a mixture of RARβ genomic sequences containing the human homolog of mouse exon 1 that encodes the unique A domain of RARB, and the human homolog of mouse exon 3 that codes for the unique A domain of RARB; and for c-mos a 2.5-kb human placental fragment containing the c-mos gene.

**RT-PCR.** RNA was extracted using the one-step guanidinium thiocyanate-phenolchloroform method. Reverse transcription was performed using 2.5 µg total RNA, 100 ng oligonucleotide primer 3 from Table i and 200 U of Mo-MLV reverse transcriptase (BRL), under conditions recommended by the supplier. Subsequently, one round of 35 cycles of PCR was performed using primers 1 and 2 from Table 1. Cycling times and conditions were as previously...

**Fig 1. Karyotype of patient 46,XY,der(3)t(3;8)(p25;q12) is shown. The arrow indicates the chromosome 8-derived portion of the der(3) chromosome.
Fig 2. FISH analysis of metaphase chromosomes from this patient is shown. (A) A paint specific for chromosome 8 confirms trisomy for 8q on the der(3) chromosome. (B) A paint specific for chromosome 15 shows two apparently normal homologs. (C) A paint specific for chromosome 17 shows two apparently normal homologs. (D) Probes specific for the PML gene (red), the RARA gene (green), and the centromere of chromosome 15 (green) are shown; small arrows show RARA in its normal position on chromosome 17; large arrow shows the juxtaposition of PML and RARA genes on one homolog of chromosome 15.

described. Negative controls were included at all stages, and the cell line NB4 that has the long form of PML-RARA transcript was used as a positive control. The PCR products were run on agarose gels and blotted onto filters that were examined with oligonucleotide probes for exon IV or RARA and exons 3, 5, and 6 of PML, as listed in Table 1.

RESULTS

Cytogenetics. The karyotype of this patient (Fig 1) was defined as 46,XY,der(3)(3:8)(p25;q12), arising from a translocation between 3p25 and 8q12 in addition to two normal copies of chromosome 8. This results in a net gain of material from chromosome 8 (trisomy, 8q12-24) and loss of material from the tip of 3p (monosomy, 3p26). Thirty-two metaphases were examined, and no evidence for any abnormality of either chromosome 15 or 17 was observed in any cells.

Molecular cytogenetics. To confirm the cytogenetic findings, FISH was performed on slides from the same culture as the cytogenetics, with paints specific for chromosomes 8, 15, and 17 (Fig 2A, B, and C, respectively). The paint for chromosome 8 confirmed that the material on the terminal portion of 3p was derived from chromosome 8. Analysis with chromosome 15-specific paint showed two
Fig 3. (A) Representative Southern blot shows results of probing for RARA and PML on DNA from N, normal control; 1, APL patient with t(15;17) showing rearrangements in both RARA and PML; and 2, patient in this study. (B) Schematic representation of normal PML and RARA genes. Restriction maps for B, BamHI; E, EcoRI; X, Xba I; H, HindIII; and K, Kpn I. Hatched boxes indicate exons; solid bars indicate probes used in Southern analysis.

intact copies of this chromosome. The slide painted with chromosome 17-specific probes also showed two apparently normal homologs. The standard t(15;17) is easily detected using these paints and conditions (unpublished observations, December 1992). Because of its distinctive morphology the der(3) chromosome was easily identifiable in the metaphase spreads hybridized with other paints, which served as a marker for the clone.

An example of the result of applying the PML and RARA probes to metaphase spreads from this patient is shown in Fig 2D. The probes for both PML and RARA had been applied to normal male metaphase spreads to confirm that they mapped to the expected region (results not shown). Signal from the RARA probe was seen on both chromosomes 17 and on one copy of chromosome 15, with the signal coming to lie on top of one signal for PML that remains on chromosome 15 in both homologs. The probe for RARA encompasses the second intron, which is the site of translocation in most
reported cases of APL, therefore, it is not unusual, depending on the precise breakpoint, for this probe to show signal on both the translocated chromosomes 15 and 17.

**Southern blotting.** The gels probed with the RARA probe showed only normal bands on BamHI, EcoRI, HindIII, SacI, and BglII digests (examples are shown in Fig 3A); this is probably because the probe covers only a small portion of the second intron (shown in Fig 3B). These results show that any break in RARA must lie 5′ of the HindIII site in the second intron. Gels probed with PML showed rearranged bands with all enzyme digests (examples are shown in Fig 3A). Because RARB has been mapped to 3p24 and c-mos has been mapped to 8q11 close to the translocation breakpoints detected cytogenetically in this patient, we sought rearrangements of these genes by DNA blots, but none were detected (data not shown).

**RT-PCR.** The PCR for PML-RARA transcripts yielded three bands from this patient of 276 bp, 455 bp, and 623 bp. These were confirmed to be from PML and RARA by probing with oligonucleotide probes (Fig 4a) whose sequences are listed in Table 1 and whose position with respect to the exons of PML and RARA are shown in Fig 4b. All three bands hybridized to probes A and D from exon 3 of PML and exon IV of RARA, respectively; two of the bands hybridized to probes B and C from exons 5 and 6 of PML, respectively, which is consistent with alternative splicing of exon 5. However, the two longer transcripts were shorter than those in the control cell line, NB4, where the breakpoint in PML is known to be in intron 6, indicating that the breakpoint in this patient lies in exon 6. The patient in lane 1 has only a short form of the transcript consistent with a break in intron 3 of PML.

**DISCUSSION**

The translocation t(15;17)(q22;q21), or more specifically the fusion transcript PML-RARA, has not been reported in subtypes of acute myeloid leukemia other than APL and, therefore, may be used as a marker for this subtype of leukemia. In the present case, there was no cytogenetic evidence for involvement of either chromosomes 15 or 17, but there was an unusual translocation between chromosomes 3 and 8, all of which were confirmed by FISH with chromosome specific paints. FISH using cosmid probes for PML and RARA genes showed a break in the second intron of the RARA gene and an interstitial insertion of a portion of this gene juxtaposing it to the PML gene on one homolog of chromosome 15. This observation was confirmed both by Southern blotting, which showed rearrangement of the PML gene, and by RT-PCR, which showed the presence of a hybrid PML-RARA transcript.

Therefore, this patient defines a new cytogenetic subgroup of APL. This subgroup is composed of patients who are t(15;17) negative but PML-RARA-positive and is analogous to the Philadelphia chromosome-negative CML patients who, nevertheless, are BCR-ABL positive. Although the molecular consequences of this cytogenetically undetectable transposition appear to be identical to those observed in regular cases with t(15;17)(q22;q21), the molecular mechanisms underlying these events must differ; a further chromosome break distal to RARA must have occurred to allow for the transposition. The amount of chromosome-17 material inserted into chromosome 15 in this case is presently being studied. In cases of Philadelphia chromosome-negative/BCR-ABL-positive CML, the amount of DNA transferred can be substantial.

It is clear that, if the correct culturing conditions are used, cytogenetically detectable t(15;17) is present in the great majority of cases of both APL and the variant form. The incidence of this new subgroup of APL is not yet known. We are presently examining other cases of APL in which no t(15;17) was detected cytogenetically. A therapeutic consequence of the definition of this subgroup of APL might...
be that all-trans RA therapy should not be withheld on the basis of cytogentic alone unless supplemented by FISH and/or molecular investigations, because such cases may, nevertheless, have PML-RARA fusion. All-trans RA was not administered in the present case because of rapidly progressive disease. Whether all t(15;17)-negative PML-RARA-negative patients will follow such an unusual clinical course is not yet known.

ACKNOWLEDGMENT

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Interstitial insertion of retinoic acid receptor-alpha gene in acute promyelocytic leukemia with normal chromosomes 15 and 17

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