TCL1 Oncogene Activation in Preleukemic T Cells From a Case of Ataxia-Telangiectasia

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The TCL1 oncogene on human chromosome 14q32.1 is involved in chromosome translocations (t(14;14)(q11;q32.1) and t(7;14)(q35;q2.1)) and inversions (inv(14)(q11;q32.1)) with TCRβ loci in T-cell leukemias, such as T-prolymphocytic (T-PLL). It is also involved in T-acute and -chronic leukemias arising in cases of ataxia-telangiectasia (AT), an immunodeficiency syndrome. Similar chromosomal rearrangements occur also in the clonally expanded T cells in AT patients before the appearance of the overt leukemia. We have analyzed the expression of TCL1 mRNA and protein in peripheral blood lymphocytes (PBLs) from four AT cases and from healthy controls. We found that the TCL1 gene was overexpressed in the PBLs of an AT patient with a large clonal T-cell population exhibiting the t(14;14) translocation but not in the lymphocytes of the other cases. Fluorescence in situ hybridization of the TCL1 genomic locus to lymphocyte metaphases from the AT patient with the T-cell clonal expansion showed that the breakpoint of the t(14;14) translocation lies within the TCL1 locus and is accompanied by an inverted duplication of the distal part of chromosome 14. These data indicate that TCL1 is activated in preleukemic clonal cells as a consequence of chromosome translocation involving sequences from the TCR locus at 14q11. Deregression of TCL1 is the first event in the initiation of malignancy in these types of leukemias and represents a potential tool for clinical evaluation.

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The Development of human cancer is thought to be a multistep process that entails a progressively more aggressive phenotype through the evolution of cellular subsets with increasing numbers of genetic alterations. The identification of steps that are necessary for the full manifestation of leukemia and lymphoma is also a multistep process. In hematopoietic tumors, cytogenetic alterations such as chromosomal translocations and inversions are quite common. These chromosomal aberrations directly involve genes responsible for malignant transformation, but development of leukemias and lymphomas is also a multistep process. It has been shown, for example, that follicular lymphoma (a low-grade malignancy) with BCL2 rearrangement can progress to a more aggressive form of tumor by acquiring a MYC gene rearrangement; another example is the clinical transition from chronic to acute phase in chronic myelogenous leukemia, in which p53 mutations and deletions are observed in 20% to 30% of the cases of blast crisis.

An excellent model for studying tumor progression is represented by T-cell leukemias arising in patients with ataxia-telangiectasia (AT), an immunodeficiency syndrome associated with genomic instability, deficient DNA repair, cerebellar ataxia, and oculocutaneous telangiectasias. These patients are prone to cancer (10%), especially of the hematopoietic lineage, with a 70- to 250-fold increase in the probability of developing lymphocytic leukemia and lymphoma, particularly in childhood. In contrast to the general population, in which B-cell leukemias are predominant, leukemias of T-cell phenotype are particularly frequent in the AT population. In these patients, the presence of clonal T-cell expansions has been observed before the onset of full-blown leukemia (reviewed by Kirsh). These expansions are of two types. The first type of expansions is characterized by translocations and inversions (t(7;7)(p15;q35), inv(7)(p15;q35), (7;14)(q35;q11), and (t;7;14)(p15;q11)) that usually involve rearrangements among T-cell receptor genes and are not associated with neoplasia. The second type of expansions, which is observed in 7% of 10% of all AT cases, involves the clonal expansion of cells carrying either the t(14;14)(q11;32.1) translocation or inv(14)(q11;q32.1) inversion, or more rarely t(X;14)(q28;q11). In these cases, cells tend to expand in the peripheral blood with time until they represent 90% to 100% of all circulating lymphocytes and invariably progress to a frank leukemia. Chromosomal translocations in the latter cases involve on one side the TCRβ locus on chromosome 14q11 and, on the other side, either the TCL1 gene on 14q32.1 or the MTCPl/6.1b gene on Xq28. These two genes have recently been cloned and, interestingly, show a high degree of homology to each other. We have recently shown that the TCL1 gene is normally expressed in lymphoid cells as well as in cases of T-prolymphocytic leukemia (T-PLL), a very aggressive type of mature T-cell proliferation accompanied by rearrangements at 14q32 in 80% of the cases. Interestingly, it has been reported that some of the full-blown leukemias
arising in AT or, in one case, a preleukemic clonal expansion have morphologic features similar to those of T-PLLs.\(^{17}\)

To examine the role of the TCL1 gene and gene product in clonal AT expansions, we have studied peripheral blood cells from an AT case exhibiting a clonal expansion of T cells (60% of peripheral blood lymphocytes [PBLs]) with t(14;14)(q11;q32.1) chromosome translocation. Comparison of these PBLs to PBLs derived from three other AT patients without cytogenetic evidence of clonal expansion in the peripheral blood and with a normal healthy control shows that TCL1 gene is deregulated only in the preleukemic cells carrying the chromosomal translocation.

### MATERIALS AND METHODS

**Patient samples and purification of T cells.** Lymphocytes from four patients with AT and a healthy donor were analyzed in this study. AT94-1 is a 16-year-old girl with classical AT. The first karyotypic analysis of her lymphocytes was performed in 1986 and showed 4% clonal cells carrying a t(14;14)(q11;q32.1). This abnormality increased to 60% and has remained stable at this frequency in the last two semianual observations.\(^{17,18}\) The white blood cell count was 6,220/mL, with lymphocytes ranging around 14.4%. The phenotype of these PBLs at the time of these studies was: CD45+ (98%), CD4+ (16%), CD8+ (25%), TCR\(\delta\)P (10%), CD56+ (1%), and TCR\(\gamma\)C (1%).

T cells from AT94-1 and from a normal donor were enriched by adhering B cells and monocytes to a nylon-wool column at 37°C for 60 minutes and T-enriched cells were collected in the eluted fraction. After purification, T cells from normal control and AT94-1 represented approximately 77%, with the remaining cells being CD3+CD56+ (natural killer cells) and less than 1% being CD19+ (B cells).

The other three patients were classical AT cases without cytogenetically evident clonal expansions.

**Cytochrome c and fluorescence in situ hybridization (FISH).** Chromosome preparations were obtained using standard methods from 72-hour lymphocyte phytohemagglutinin-stimulated cultures of AT patients. Analysis of spontaneous chromosome rearrangements was performed on at least 30 G-banded metaphases.

For FISH analysis, the cosmid clones pPLC-1 and pPLC-4 were isolated by screening a human placental genomic library using probes B0.9 and pE/S.\(^{18}\) The pPLC-4 cosmid contains a genomic fragment corresponding to the region from pE/S to the region 40 kb centromeric to pE/S (Fig 1D). The TCL1 gene, and pPLC-1 cosmid are located about 120 and 250 kb centromeric to the end of the pPLC-4 cosmid, respectively.\(^{18}\) For in situ hybridization, pPLC-1 or pPLC-4 was labeled with biotin-16-dUTP or digoxigenin-11-dUTP, respectively, using a nick-translation kit (Bethesda Research Laboratories, Gaithersburg, MD). The hybridization mixture contained 200 ng each of both labeled probes, pPLC-1 and pPLC-4, as well as 10 \(\mu\)g of sonicated salmon sperm DNA, 10 \(\mu\)g of Escherichia coli tRNA, and 350 ng of human Cot-1 DNA (Bethesda Research Laboratory) in 10 \(\mu\)L of 50% formamide, 50 mmol/L phosphate, 10% dextran sulfate, 2X SSC, pH 7.0. Before hybridization, the mixture was denatured at 75°C for 5 minutes, quickly chilled, and incubated at 37°C for 30 minutes to compete for repetitive sequences in the probe. After overnight hybridization, the slides were washed for 20 minutes in 50% formamide, 2X SSC, pH 7.0 at 37°C, followed by two 15-minute washes in 2X SSC, and finally rinsed in 4X SSC at room temperature. Fluorescein isothiocyanate (FITC)-conjugated avidin and anti-digoxigenin tagged with rhodamine (Boehringer Mannheim, Mannheim, Germany) were used for the detection of biotinylated pPLC-1 and digoxigenin-labeled pPLC-4. The chromo-

**RESULTS**

**Cytochrome c and fluorescence in situ hybridization (FISH).** The cytogenetic analysis by chromosome banding performed on...
Fig 1. In situ hybridization of cosmids clones (pPLC-1 and pPLC-4) flanking the TCL-1 locus derived from AT 94-1. The same chromosome is stained with the probes pPLC-1 (A), pPLC-4 (B), or both pPLC1 and pPLC4 (C) or were stained with Hoechst 33258 DNA dye (D). The large arrows and the triangle represent the position of each signal. (E) A schematic representation of this complex rearrangement. The large arrows and the triangle represent the signals illustrated in (A), (B), and (C). The dotted line is the breakpoint between 14q32 and 14q11 derived from the other 14 allele. The double arrow shows the extension of the area probably involved by the inverted duplication. On the upper left, the germline map of the TCL1 locus is given with the relative position of the probes pPLC1 and pPLC4 and of the TCL1 gene.
the lymphocytes of case AT94-1 shows that 51 of 84 (60%) metaphases analyzed carried a t(14;14) chromosomal translocation. The majority of metaphases (34/51) showed that this translocation was the only evident cytogenetic abnormality; in the remaining 17 metaphases additional rearrangements were also observed: two subclones were defined by an iso(21q) chromosome (4/51) and by a supernumerary C-like chromosome (4/51), presumably derived from a rearranged chromosome 22.

No evident clonal populations with rearrangements at 14q32 were observed in lymphocytes of the other AT cases.

To determine whether in AT 94-1 lymphocytes the DNA joined at the t(14;14) breakpoint involved the TCL1 locus, we conducted FISH analysis using probes close to the TCL1 breakpoint. Two cosmid clones, pPLC-1, localized about 120 kb centromeric to the TCL1 gene, and pPLC-4, localized about 250 kb telomeric to the TCL1 gene, were used (Fig 1). The biotinylated cosmid pPLC-I and digoxigenin-labeled pPLC-4 were simultaneously hybridized to AT lymphocyte metaphases. The signals from pPLC-I and pPLC-4 were visualized using FITC-conjugated streptavidin-and rhodamine-conjugated antidigoxigenin antibody, respectively.

The results of in situ hybridization experiments are shown in Fig 1. The hybridization of the pPLC-I probe showed the presence of two peaks of hybridization on the t(14;14) chromosome (one located slightly centromeric to the translocation breakpoint and the other located on the tip of long arm of the t(14;14); Fig 1A), whereas the signal of pPLC-4 showed three peaks of hybridization (one slightly centromeric to the breakpoint, one at the breakpoint site, and the third at the tip of the der 14; Fig 1B).

These results show that this rearrangement involves the TCL1 locus splitting the two probes, pPLC-1 and pPLC4, at the breakpoint site; furthermore, the orientation of the pPLC1 and pPLC4 at the junction is inverted with respect to the germline position (Fig 1E), because pPLC-4 localized telomeric to both TCL1 and pPLC-1. This result indicates that an inversion duplication event had also occurred in this chromosome.

As we have already described,18 this translocation, accompanied by an inverted duplication, will behave, in terms of juxtaposition of TCR elements (14q11) to the TCL1 gene, in a manner similar to that of the inv(14)(q11;q32.1) chromosome inversions. This inverted duplication event seems to be quite frequent on T-cell preleukemic and malignant clones, with a t(14;14) translocation in AT cases,11,19-21 and could result from chromosomal instability underlying the primary defect of AT.

TCL1 expression in AT and normal lymphocytes. Because the 14q32.1 breakpoint of case AT94-1 was, as expected, in the TCL1 locus, we investigated TCL1 expression in cells from this case to determine whether the expression was altered from that seen in normal PBLs. For this purpose, we performed semiquantitative PCR amplification of reverse-transcribed mRNAs derived from lymphocytes of AT 94-1, from three other AT cases without apparent clonal cells harboring a t(14;14) translocation, and from the Daudi cell line that expresses high levels of TCL1 protein.13 Reverse transcripts derived from RNAs of these cells were normalized, as described in the Materials and Methods, and were amplified by PCR with TCL1 and β-actin primers.

As shown in Fig 2, the level of TCL1 expression in AT 94-1 cells is much higher than the level of expression of TCL1 mRNA observed in the other three cases of AT. cDNAs derived from three healthy donors expressed levels of TCL1 comparable to those of the latter three AT cases (data not shown). The level of β-actin was also used for further control. β-Actin was amplified from the same amount of cDNA template used for TCL1 amplification independently for 10, 15, or 20 cycles to determine whether the amplification is in the linear phase, because the level of amplification of this gene reaches a plateau effect under the conditions used for TCL-1. Results obtained at 15 cycles (linear phase) for the housekeeping β-actin gene also confirmed the data of amplification observed for TCL1 primers (Fig 2).

We then conducted immunostaining of T-cell-enriched PBLs from AT94-1 and from a normal donor using a rabbit polyclonal antiserum raised against TCL1 recombinant protein.15 After enrichment on a nylon-wool column, 77% of the cells were of T-cell origin, as demonstrated by staining with an anti-CD7 monoclonal antibody (data not shown).
Cytospins of the two samples were then stained with anti-TCL1 antiserum; 27% of the AT94-1 (Fig 3A) cells showed a strong cytoplasmic signal for the TCL1 protein, whereas less than 1% of the T-cell-enriched population from the normal donor (Fig 3B) showed positive signals. We also analyzed cytospins of unfractioned PBLs from another AT patient; only 0.8% of the cells stained positive (data not shown).

These results show overexpression of the TCL1 protein in cells carrying translocated TCL1. The discrepancy between the data obtained by immunostaining (27% of cells overexpressing TCL1) and the cytogenetic data [60% of metaphases with the t(14;14) translocation] could reflect either the lower sensitivity of the antibody or, alternatively, a more mitogenic responsiveness of the clonal cell population to PHA. It is well known that in this disease T cells may not respond very well to PHA; for this reason it could be possible that t(14;14) cells divide more frequent after a mitogenic stimulus. Therefore, it is possible that both explanations could account for protein expression results in AT94-1 lymphocytes.

**DISCUSSION**

AT represents a human model of a genetic disease leading to T-cell leukemia; because of the underlying genetic defect in these patients, there is a tendency for VDJ joining mis-
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takes and, consequently, chromosomal translocations with the TCR loci to the TCL1 locus or to the MTCP-1/C6.1b locus. Because these patients are routinely checked for chromosomal abnormalities, various examples of clonal expansions with a premalignant phenotype have been widely reported in the literature. These clones are invariably associated with t(14;14), t(X;14), or inv(14) chromosome translocations or inversions and expand over time to represent up to 100% of the T-cell population. These preleukemic cells consistently progress to an overt leukemic stage that usually resembles the one observed in T-PLL. Taking advantage of the recent molecular cloning of the TCL1 gene, we have shown that TCL1 is overexpressed at the RNA and protein level in one case of AT bearing 60% of clonal T cells with a t(14;14)(q11.2;q32.1) with the breakpoint in the TCL1 locus compared with other AT cases and normal healthy individuals without apparent clonal populations of T cells. These results indicate a pivotal role for TCL1 in the initiation of malignant transformation of these T-cell leukemias.

As a consequence of the translocation event, regulatory elements, such as enhancers of the TCRα gene, move in proximity of the TCL1 gene, probably dysregulating its expression. It seems that TCL1 deregulation confers a proliferative advantage to T cells; whether this is due to an increase in cell survival or to a mitogenic stimulus is currently under investigation and will remain unknown until the function of this gene is ascertained. However, these results suggest that the TCL1 product acts in an inducer of T-cell expansion. This situation can last for many years, and additional changes may be required for a full malignant transformation. This last situation is apparent in vivo in T-PLLs in which the t(14;14) translocation or the inv(14) inversions are involved in 75% of the cases and in which other cytogenetically abnormalities, such as iso 8q or iso 20, are also consistently present. These other rearrangements or other genetic events could play a secondary role in tumor progression.

Sherrington et al. have recently studied similar cases of clonal expansion in two cases carrying a t(14;14) and a t(X;14) translocation. By means of densitometric studies on serial samples using probes detecting a rearrangement band at the TCL1 locus and the TCRβ locus, they have shown that cells containing the translocation are oligoclonal with respect to TCRβ in the preleukemic stage and β-clonality was established at the time of the leukemia. In the present report, we have not analyzed this aspect, but the presence of several other small clones at cytogenetic analysis could suggest the possibility of different oligoclonal populations within the t(14;14) clone, indicating, in agreement with these investigators, that rearrangements at the TCL1 locus can occur at a very early stage during ontogeny of the immune system. This hypothesis is also substantiated by the presence, near the breakpoint of molecularly cloned cases, of elements such as heptamer-nonamer sequences and of N-region, indicating that such events may take place during VDJ rearrangement of T-cell receptor genes.

It has been reported in the literature that at least 10% of these patients will, over time, develop a clonal T-cell population in their peripheral blood that can comprise 100% of the peripheral T-cell metaphases karyotypically analyzed. Availability of antibodies and molecular diagnostics based on TCL1 RT-PCR could help to detect and to monitor these leukemias from their early stages. These data also raise the possibility of alternative approaches for treating these early stages in AT patients that, as is widely known, are particularly difficult to treat using conventional cytostatic therapy. Innovative therapies aimed at the TCL1 gene or at its product may result in the purging of leukemic cells.

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