Integrated Genomic Profiling of Chronic Lymphocytic Leukemia Identifies Subtypes of Deletion 13q14

Peter Ouillette, 1 Harry Erba, 1 Lisa Kujawski, 1 Mark Kaminski, 1 Kerby Shedden, 2 and Sami N. Malek 1

1Department of Internal Medicine, Division of Hematology and Oncology and 2Department of Statistics, University of Michigan, Ann Arbor, Michigan

Abstract

Chronic lymphocytic leukemia (CLL) is a biologically heterogeneous illness with a variable clinical course. Loss of chromosomal material on chromosome 13 at cytoband 13q14 is the most frequent genetic abnormality in CLL, but the molecular aberrations underlying del13q14 in CLL remain incompletely characterized. We analyzed 171 CLL cases for loss of heterozygosity and subchromosomal copy loss on chromosome 13 in DNA from fluorescence-activated cell sorting–sorted CD19+ cells and paired buccal cells using the Affymetrix XbaI 50k SNP array platform. The resulting high-resolution genomic maps, together with array-based measurements of expression levels of RNA in CLL cases with and without del13q14 and quantitative PCR–based expression analysis of selected genes, support the following conclusions: (a) del13q14 is heterogeneous and composed of multiple subtypes, with deletion of Rb or the miR15a/miR16 loci serving as an important land mark, respectively; (b) del13q14 type Ia deletions are relatively uniform in length and extend from breakpoints close to the miR15a/miR16 cluster to a newly identified telomeric breakpoint cluster at the ~50.2 to 50.5 Mb physical position; (c) LATS2 RNA levels are ~2.6-fold lower in cases with del13q14 subtype I that do not delete Rb, as opposed to del13q14 subtype II or other ALL cases; (d) PHLP3 RNA is absent in ~50% of CLL cases with del13q14; and (e) ~15% of CLL cases display marked reductions in miR15a/miR16 expression that are often but not invariably associated with bi-allelic miR15a/miR16 loss. These data should aid future investigations into biological differences imparted on CLL by different del13q14 subtypes.

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Introduction

Chronic lymphocytic leukemia (CLL) is the most common form of adult leukemia in the Western world and is characterized by a highly variable clinical course (1). Genetic subtypes of CLL that display different biological and clinical properties have been identified (2–5).

Fluorescence in situ hybridization (FISH) has identified various chromosomal changes, including del13q14, in ~80% of patients with CLL, and the presence of specific chromosomal abnormalities has proved to be a prognostic indicator for disease progression and survival (6).

Loss of chromosomal material, including the genomic marker D13S319 on chromosome 13 (known as the deletion 13q14), occurs in ~50% of all CLL cases and multiple other cancers (7, 8). Efforts by multiple groups have identified candidate genes within an ~1 Mb stretch on chromosome 13 that have each been implicated in CLL del13q14 biology; nonetheless, mutations in these genes have not been identified and questions remain as to the validity of reducing the biology of del13q14 to a minimal deleted region or a single-gene mutation/expression event (8–19). Analysis of del13q14 is further complicated by an evolving understanding of resident gene structure and the discovery of complex noncoding RNAs (20).

Given the absence of mutations in genes within del13q14, haploinsufficiency has been proposed as a mechanism of action (21). However, independent experimental verification for such a mechanism has not yet been reported.

More recently, discovery of the deletion or reduced expression of two microRNAs miR15a and miR16 as part of del13q14 has been suggested as a unifying principle underlying del13q14 pathogenesis (22). Searches for miR15a/miR16 targets have identified Bcl-2 mRNA, and data have been presented in heterologous cell lines that suggest Bcl-2 mRNA regulation by these miRs (23).

Nonetheless, the general favorable outlook for patients with del13q14 remains difficult to reconcile with the postulated consequences of miR–locus deregulation/deletion, as patients with CLL and high Bcl-2 levels tend to have more aggressive disease (24).

Given the frequent occurrence of del13q14 in multiple cancers and given some of the abovementioned uncertainties surrounding its biology, we decided to analyze this lesion using high-resolution genomic mapping efforts.

Herein, we report the results of a large CLL profiling study with focused analysis of deletion 13q14 using 50k Affymetrix SNP microarrays (25) resulting in the identification of subtypes of del13q14 based on anatomic and functional criteria. Furthermore, we report that ~15% of CLL cases display marked reductions in miR15a/miR16 expression that are often but not invariably associated with bi-allelic miR15a/miR16 loss (26).

SNP array data were integrated with expression data and led to the discovery of differential expression of LAT52 in del13q14 subtypes. Finally, expression of PHLP3 was lower and often undetectable in del13q14 CLL cases as opposed to other FISH-based genomic CLL subgroups (27).

Materials and Methods

Patients

Between January 2005 and July 2007, 179 CLL patients evaluated at the University of Michigan Comprehensive Cancer Center were enrolled onto this study. Eligibility criteria required a diagnosis of CLL based on the...
National Cancer Institute Working Group Guidelines (28). We validated that the diagnostic criteria were met for all subjects through review of both laboratory (complete blood count with differential) and pathology (flow cytometry, bone marrow biopsy/aspirate, lymph node biopsy) reports dated at the time of diagnosis. Eligible patients needed to have an absolute lymphocytosis (>5,000 mature lymphocytes/µL), and lymphocytes needed to express CD19, CD23, slg (weak), and CD5 in the absence of pan–T-cell markers. Five patients enrolled on the study were excluded from analysis (diagnosis: large cell lymphoma, marginal zone lymphoma, small lymphocytic lymphoma, Crohn's disease, and CLL with concurrent acute myelogenous leukemia). Three posttreatment patient samples gave insufficient DNA for analysis and thus were excluded from analysis. The study was approved by the University of Michigan Institutional Review Board (IRBMED 2004-0962), and written informed consent was obtained from all patients before enrollment. All analyses were performed on samples obtained during initial enrollment. Follow-up times were calculated from enrollment dates to clinical data analysis date (September 2007). Disease durations at enrollment were calculated from diagnosis dates to enrollment dates.

**Cell Isolation**

Cell purification. Peripheral blood mononuclear cells from CLL patients were isolated by Ficoll-Paque gradient centrifugation (GE Healthcare), aliquoted into FCS with 10% DMSO, and cryopreserved in liquid nitrogen. Cryopreserved peripheral blood mononuclear cells from CLL patients were washed and then treated with anti-human CD3 (Miltenyi Biotec 130-050-201) per manufacturer's recommendations. Cell suspensions were run through Miltenyi MACS separation LS columns (130-042-401) to negatively enrich for CD19+ B cells. This resulted in >95% CD19+-positive cells.

**Genomic Southern Blotting**

Cryopreserved peripheral blood mononuclear cells derived from CLL patients were washed and then treated with anti-human CD3 (Miltenyi Biotec 130-050-101) and anti-human CD14 microbeads (Miltenyi Biotec 130-050-201) per manufacturer's recommendations. Cell suspensions were run through Miltenyi MACS separation LS columns (130-042-801) to negatively enrich for CD19+ B cells. This resulted in >95% CD19+-positive cells.

Genomic DNA was prepared using digestion of cell pellets with proteinase K at 20 µg/mL in 100 mmol/L Tris, 50 mmol/L EDTA, 50 mmol/L NaCl, and 1% SDS at 56°C. DNA was digested and prepared for Southern analysis using standard protocols. Probes for genomic Southern analysis were generated from SNP chips posthybridization via scanners at the University of Michigan Microarray Core Facility and imported into the Affymetrix GCOS and GDAS software suites. dChip used native Affymetrix CEL files and text formatted .CHP files from GDAS to generate copy number heatmap displays (29).

The loss of heterozygosity (LOH) tool was used to display SNPs with LOH between paired tumor samples and buccal DNA (30).

**Array Data Analysis**

Affymetrix data files were generated from SNP chips posthybridization via scanners at the University of Michigan Microarray Core Facility and imported into the Affymetrix GCOS and GDAS software suites. dChip used native Affymetrix CEL files and text formatted .CHP files from GDAS to generate copy number heatmap displays (29).

**Genomic Profiling and CLL 13q14 Subtypes**

A novel oligonucleotide platform, the 50k SNP chip, was introduced in 2004 by Affymetrix. Selected technical characteristics of the 50k SNP chips are a total combined number of ~58,000 SNPs, a median intermarker distance of ~16 kb, a mean intermarker distance of 47 kb, and average heterozygosity of 0.29.

A 50k SNP chip-based analysis using DNA purified from FACS-sorted CD19+ or CD3+ cells or buccal swabs was done as described (31).

**Preparation of Sample DNA for Hybridization to Affymetrix 50kXbaI Mapping Arrays and Assay Characteristics**

A novel oligonucleotide platform, the 50k SNP chip, was introduced in 2004 by Affymetrix. Selected technical characteristics of the 50k SNP chips are a total combined number of ~58,000 SNPs, a median intermarker distance of ~16 kb, a mean intermarker distance of 47 kb, and average heterozygosity of 0.29.

A 50k SNP chip-based analysis using DNA purified from FACS-sorted CD19+ or CD3+ cells or buccal swabs was done as described (31).

**Preparation of CLL-Derived Amplified RNA for Hybridization to Affymetrix Human 133 2.0 Plus Arrays**

Twenty CD19+ selected CLL samples were sorted to purity using a high-speed FACSAria (Becton Dickinson) sorter.

**Determination of Immunoglobulin Heavy Chain Variable Gene Mutation Status**

Determination of immunoglobulin heavy chain variable gene (IgVH) mutation status was done as described (31).

**Detection of Percentage of ZAP-70–Positive Cells Using Multivariable Fluorescence-Activated Cell Sorting Analysis**

Determination of percentage of ZAP-70–positive cells using multivariable fluorescence-activated cell sorting (FACS) analysis was done as described (31).

**Fluorescence In Situ Hybridization**

FISH was performed for all patient samples at the Mayo Clinic as a routine clinical test with the following published chromosomal target regions: 6cen (D6Z1), 6q23.3 (c-myb locus), 11cen (D11Z1), 11q13 (CCND1-XT), 11q22.3 (ATM), 12cen (D12Z3), 12q15 (MDM2), 13q4 (LAMPI), 14q32 (IGH-XT), 17cen (D17Z1), 17p13.1 (p53).
Measurement of Gene Expression Using Quantitative PCR

RNA was prepared from 2 to 4 x 10⁶ FACS-sorted CD19⁺ cells from 165 CLL cases using the Trizol reagent and resuspended in 100 µL DEPC-treated water. Complementary DNA (20 µL) was made from −50 ng of RNA using the Superscript III first strand synthesis kit (Invitrogen) and random priming.

Complementary DNA for microRNA reverse transcriptase quantitative PCR (Q-PCR) was made from −5 ng of RNA using the TaqMan microRNA reverse transcription kit (Applied Biosystems) and RNA-specific primers. Primers and TaqMan-based probes were purchased from Applied Biosystems (primers-on-demand). Primer/probe mixtures included LATS2 (Hs00324396_m1), PHLPP (Hs01597866_m1), LPP1 (Hs00299515_m1), DFN15 (Hs00189346_m1), SERPINE2 (Hs00299953_m1), ARHGAP20 (Hs00826991_m1), cytochrome B5 (Hs00157217_m1), AQP3 (Hs00185020_m1), SLA2 (Hs0026078_m1), GAPD (Hu GAPD), PGK1 (Hu PGK1), miR16 (Tmol/L 391), miR15a (RT 389), RNU43 (TM 1095), and RNU49 (TM 1005).

Duplicate amplification reactions included primers/probes, TaqMan 2× Universal PCR Master Mix, No AmpErase UNG, and 1 µL of cDNA in a 20-µL reaction volume. Reactions were done on an ABI 7900HT machine. Normalization of relative copy number estimates for RNA species of interest was done with the C_t values for GAPD or PGK1 as reference (C_t mean gene of interest − C_t mean GAPD or PGK1). Comparisons between CLL subgroups were performed through subtraction of means of normalized C_t values.

Similar efficacies of amplification of target genes using primers for LATS2, PHLPP, GAPD and PGK1 or miR16, and RNU49 were verified using 2-fold serial dilutions of cDNA made from cell line–derived RNA over a range of 256-fold dilutions. Data were analyzed using least square regression analysis.

Statistical analysis was done using two-sample t statistics. PCR cycle times x were converted to abundance units via the transform x−1,500 × 2⁻⁸. These values were subsequently transformed to logarithmic abundance units via the transform x−log(x + 1)/log(2). The resulting values were approximately symmetrically distributed.

Duplicate amplification reactions for microRNAs included primers/probes, TaqMan 2× Universal PCR Master Mix, No AmpErase UNG, and 1.35 µL of cDNA in a 20-µL reaction volume. Normalization of relative copy

Figure 1. Combined copy number and LOH analysis identifies copy-neutral LOH and significant anatomic variation of del13q14 in CLL. Text files generated through use of the Affymetrix program Copy Number Tool for all patients were imported into the LOH tool, and all individual positions of LOH between buccal DNA and paired tumor DNA were graphed as a blue tick mark across the length of the chromosomes. Copy number estimates for all SNP positions for all patients were generated through dChipSNP as described and displayed across the length of the chromosomes. Copy losses are displayed with blue colors, copy gains with red colors. The physical position of SNPs is not linear along the displayed portions of the chromosome. A, LOH display for chromosome 13. Each row represents one patient. Vertical solid lines, 10-Mb intervals. The location of the commonly used FISH probe spanning the genomic marker D13S319 at 49.6 Mb physical position is marked with a vertical arrow. B, copy number display for chromosome 13. The estimated copy numbers for all SNP positions for CLL 10 are displayed along the entire chromosome below the chromosome 13 display. Red line, 2N state; red double arrows, CLL patients with copy-neutral LOH (CLLs 12, 13, 51, 70, and 97).
number estimates for RNA species of interest was done with the Ct values for the RNU43 or RNU49 as reference (Ct mean gene of interest / Ct mean RNU43 or RNU49). Comparisons between CLL subgroups were performed through subtractions of means of normalized Ct values.

Results

Patient characteristics. Characteristics of the 171 patients analyzed are detailed in Supplementary Tables S1 to S4. Information of familial clustering of the studied cases was not available.

Combined high-resolution LOH and copy number analysis of del13q14 in CLL. 50k SNP array data from 171 patients were analyzed for LOH and subchromosomal copy loss on chromosome 13. Comparative analysis of SNP array–derived detection of del13q14 using copy number analysis compared with clinical FISH results showed strong agreement between both methods: FISH detected 91 of 171 (53%) overall del13q14 incidence and 77 of 171 cases (45%) with >25% of cells involved. SNP arrays detected 82 of 171 del13q14 incidence (48%). SNP arrays detected 74 of 77 (96%) of all CLL cases which were >25% FISH positive and 82 of 91 (90%) of all CLL cases which were FISH positive.

In Fig. 1, we display horizontally LOH data (A) for all patients for chromosome 13 together with heatmap displays of paired copy number estimates (B). This analysis identified four cases (red arrows) with extensive LOH on chromosome 13 but copy loss restricted to a small area at ~13q14.3 (~49.6 Mb physical position) and one case without any LOH-associated copy loss (uniparental disomy).

Combined analysis for LOH and copy loss furthermore revealed significant del13q14 lesion length heterogeneity, as well as potential clustering into discrete subtypes, prompting investigation into anatomic and functional differences.

Identification of multiple distinct anatomic subtypes of del13q14 in CLL. Inspection of chromosomal copy number displays for del13q14 at higher resolution led to the characterization of del13q14 subtypes based on anatomic criteria (Fig. 2A–C). In Fig. 2A, we display from left to right all profiled CLL cases according to del13q14 lesion length. In Fig. 2B, we display a “zoomed-in” view of the epicenter of these deletions centered on the clinically important genomic FISH probe D13S319. In Fig. 2C, we display genomic copy number estimates [red vertical lines flanked by copy number estimates (0, 1, or 2 copies)] based on comparative genomic Southern blotting.

This anatomic clustering allowed us to propose the following schema for del13q14 lesions.
(a) Type I lesions (60% of all del13q14 lesions) do not include Rb and almost always terminate in a genomic region at \( \sim 50.2 \) to 50.5 Mb that we, here, term the major 13q14 telomeric breakpoint cluster \( (M13q14TBC) \) (Fig. 2C). Within the group of 13q14 type I deletions, one can further identify a majority subset of cases (del13q14 type Ia) with breaks in close proximity to rs9316482 and, therefore, close to the \( \text{miR}16/15a \) locus.

Southern analysis on selected del13q14 type Ia cases (Fig. 2C) confirmed that chromosomal breaks occur within a tight genomic region (between 49.45 and 49.55 Mb). Breakpoint analysis further identified cases with bi-allelic loss of the \( \text{miR} \) cluster (physical position at \( \sim 49.52 \) Mb), as well as cases with one retained \( \text{miR} \) cluster copy (Fig. 2C). In addition, type Ia lesions were identified in multiple CLL cases coexisting on the second chromosome with larger 13q14 deletions.

(b) Type II lesions (40% of all del13q14 lesions) include Rb and, in many cases, extend many Mb past Rb toward the centromere. A subset of type II lesions at the telomeric end terminate in the \( M13q14TBC \).

This analysis reliably identified only 2 of 171 CLL cases with deletions shorter than del13q14 type Ia lesions, implying that removal of \( \sim 0.8 \) Mb of chromosomal material from \( \sim 49.5 \) to \( \sim 50.5 \) Mb is required for the biology of del13q14 type Ia lesions (10, 12, 15, 16, 18, 19, 36).

Finally, we note that the clustering of breaks could result in fusion genes in a small subset of CLL cases involving (a) \( \text{DLEU2} \) or either \( \text{GUCY1B2} \) or (b) \( \text{RFP2} \)/\( \text{DLEU5} \) and \( \text{FLJ11712} \).

**Clinical characteristics associated with del13q14 subtypes.**

Of the 171 CLL cases analyzed, 134 were from patients that were untreated at enrollment. Of these 134 patients, 14% had a del13q14 type II, 34% had a del13q14 type I, and 52% lacked a del13q14. The ratio of del13q14 type II to del13q14 type I deletions was 19:46 (0.41). ZAP-70 was positive in 32%, 30%, and 54% of the patients with del13q14 type II, del13q14 type I, or no del13q14, respectively. IgVH genes were unmutated in 32%, 37%, and 46% of patients with del13q14 type II, del13q14 type I, or no del13q14, respectively (Supplementary Tables S2 and S3A,B; Table 1).

Patients with del13q14 type II showed significantly higher Rai stage at enrollment (\( P = 0.02 \); linear-by-linear \( \chi^2 \) test; ref. 37) compared with patients with either del13q14 type I or no del13q14 (mean Rai stage of 1.42, 0.91, and 0.78, respectively). Overall survival data were not mature enough for correlative analysis.

Thirty-seven patients were pretreated at enrollment. Of these 37 patients, 32% had a del13q14 type II, 14% had a del13q14 type I, and 54% lacked a del13q14. The ratio of del13q14 type II to del13q14 type I deletions was 12.5 (2.4; Supplementary Tables S3A,B and S4; Table 1). Interestingly, compared with previously untreated patients, del13q14 type II lesions were significantly enriched and del13q14 type I lesions significantly depleted in the previously treated group of patients (\( P = 0.001 \)).

Finally, of the 46 untreated patients with del13q14 type I, 14 cases displayed copy number estimates of \( <1 \) (range, 0.23–0.98; mean, 0.6), whereas 32 cases displayed estimates equal to or \( >1 \) (range, 1.0–1.41; mean, 1.17). The Rai stage at enrollment was not significantly different (\( P = 0.37 \)) for these cases (mean Rai stage of 1.1 versus 0.8, respectively).

A subset of CLL cases display very low miR16/miR15a cluster expression. We proceeded to analyze the expression of

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**Table 1. Summary table of molecular and clinical characteristics of del13q14 subtypes**

<table>
<thead>
<tr>
<th>SNP array-based</th>
<th>del13q14 type la bi-allelic</th>
<th>del13q14 type ia mono-allelic</th>
<th>del13q14 type lb</th>
<th>del13q14 type II</th>
<th>Non-del13q14</th>
</tr>
</thead>
<tbody>
<tr>
<td>13q14 Anatomy (Definition)</td>
<td>Centromere break (rs9316482)</td>
<td>Centromere break (rs9316482)</td>
<td>Centromere does not include Rb</td>
<td>Centromere variable but includes Rb</td>
<td>N/A</td>
</tr>
<tr>
<td>Lesions incidence (untreated patients)</td>
<td>34% (all type I)</td>
<td>34% (all type I)</td>
<td>34% (all type I)</td>
<td>14%</td>
<td>52%</td>
</tr>
<tr>
<td>Lesions incidence (pretreated patients)</td>
<td>14% (all type I)</td>
<td>14% (all type I)</td>
<td>14% (all type I)</td>
<td>32%</td>
<td>54%</td>
</tr>
<tr>
<td>Bcl2 expression</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>PHPP expression</td>
<td>Absent in &gt;50% of cases</td>
<td>Absent in &gt;50% of cases</td>
<td>Absent in &gt;50% of cases</td>
<td>Absent in &gt;50% of cases</td>
<td>Moderate</td>
</tr>
<tr>
<td>miR16/miR15a expression Associated with prior therapies</td>
<td>Very low</td>
<td>Variable</td>
<td>Variable</td>
<td>Yes, highly enriched</td>
<td>Variable</td>
</tr>
<tr>
<td>Mean Rai stage at enrollment</td>
<td>1.1</td>
<td>0.8</td>
<td>0.8</td>
<td>1.42 (( P = 0.02 ))</td>
<td>0.78</td>
</tr>
<tr>
<td>% ZAP-70 positive cases</td>
<td>30% (all type I)</td>
<td>30% (all type I)</td>
<td>30% (all type I)</td>
<td>32%</td>
<td>54%</td>
</tr>
<tr>
<td>% Unmutated IgVH genes cases</td>
<td>37% (all type I)</td>
<td>37% (all type I)</td>
<td>37% (all type I)</td>
<td>32%</td>
<td>46%</td>
</tr>
</tbody>
</table>
miR16 and miR15a using Q-PCR in ~95% of the 171 CLL cases studied (Supplementary Table S5). Measurements were normalized to expression of two unrelated microRNAs, RNU43 (on chromosome 22q13.1) and RNU49 (on chromosome 17p11.2). Expression of RNU49 and RNU43 was detected in all CLL cases at relatively uniform levels. The correlation coefficient (with 95% confidence interval) between measurements of RNU49 Ct mean versus RNU43 Ct mean was high at 0.61 (0.51–0.70).

The range of the normalized expression values for both miR16 and miR15a across this large cohort of CLL cases was wide: range ΔCt miR16-RNU43 of 1.7 to 7.4, 10th percentile to 90th percentile of -0.3 to -5.8 (corresponding to a 45-fold expression difference) and range ΔCt miR15-RNU43 of 9.4 to -2.2, 10th percentile to 90th percentile of -5.7 to 0.0 (corresponding to a 52-fold expression difference).

We proceeded to compare relative expression levels of miR16 and miR15a in two mutually exclusive CLL subgroups: cases with and without del13q14 by FISH. Mean expression values of both miRs were modestly lower (miR16 = 1.2-fold/1.7-fold and miR15a = 1.4-fold/2-fold for RNU49/RNU43 normalization, respectively) in the del13q14 subgroup as opposed to non-del13q14 CLL cases.

Subsequently, we ranked all CLL cases according to chromosomal copy number estimates for a 0.4 Mb chromosomal region between rs9316484 (centromeric to the miR16/15a locus) and rs3118650 (telomeric to the miR16/15a locus). We calculated mean normalized expression values for miR16 and miR15a for the 22 (13%) CLL cases with more extensive chromosomal loss (range, 0.23–0.98; mean, 0.6) and the remaining 141 (87%) CLL cases with less extensive or no loss (range, 1.0–2.32; mean, 1.64).

Mean normalized expression values of both miR16 and miR15a were substantially lower (miR16 = 4.3-fold/3-fold and miR15a = 6.5-fold/4.9-fold for RNU49/RNU43 normalization, respectively) in the subgroup with more extensive del13q14 as opposed to the group with less extensive or no del13q14.

Upon removal of these 22 CLL cases (13%) with extensive del13q14 chromosomal loss from analysis, the relative miR16/15a expression levels for the remaining 141 (87%) cases (with del13q14 or without del13q14) were indistinguishable from all cases without del13q14.

Finally, we ranked all CLL cases by normalized miR16 or miR15a expression and analyzed the 41 (25%) cases with the lowest miR expression levels. This analysis disclosed 8 of 14 (miR15a/miR16) cases with no detectable alteration at 13q14 by either FISH or SNP array measurements, but low relative expression of the miR15a/miR16 genes, comparable in magnitude to CLL cases with extensive del13q14.

This combined data suggests that ~15% of CLL cases indeed have very low miR16/miR15a levels and that the majority of CLL cases (~85%) display a range of expression of these miRs that seems independent of the genetic background.

**miR16/miR15a levels do not predict Bcl2 levels in CLL.** Bcl-2 mRNA has been proposed as a physiologic target for miR15a and
miR16 in CLL. We therefore measured and compared expression levels of Bcl-2 using immunoblotting in FACS-sorted, highly pure CLL cells derived from CLL cases with or without del13q14 by both FISH and SNP arrays (average copy number estimates of 0.42 versus 2.1) and low versus high relative miR16/miR15a expression (ΔCt miR16-RNU43 = 0.1 versus −2.5, corresponding to a 6.1-fold expression difference and ΔCt miR15-RNU43 = 5.5 versus 2.8, corresponding to a 6.5-fold expression difference).

As can be seen in Fig. 3A-C, Bcl-2 levels, once normalized to Actin levels, were similar in both groups of CLL cases, prompting our interest in other genes deregulated as a consequence of del13q14.

**Identification of deregulated genes in CLL cases with del13q14 type I.** To identify genes deregulated in CLL cases with del13q14 type Ia, we selected 10 CLL cases each with and without del13q14 by both FISH and SNP arrays (average copy number estimates of 0.42 versus 2.1) and low versus high relative miR16/miR15a expression (ΔCt miR16-RNU43 = 0.1 versus −2.5, corresponding to a 6.1-fold expression difference and ΔCt miR15-RNU43 = 5.5 versus 2.8, corresponding to a 6.5-fold expression difference).

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del13q14 lesions and 0.001 (GAPD) and 0.0003 (PGK1) for comparison of type I and non-del13q14 cases using two sample $t$ testing.

**PHLPP expression is low or undetectable in ~50% of CLL cases with del13q14.** Q-PCR–based measurements of PHLPP expression in the 20 CLL cases profiled using the expression arrays detected low/absent expression in 8 of 10 of the del13q14 cases versus 3 of 10 of the reference cases (Supplementary Table S8).

Subsequently, PHLPP expression levels were measured in 164 CLL cases using Q-PCR, and data were normalized using PGK1 expression levels. CLL cases with a $CD19^+$ cells from 164 CLL cases.

RNA was prepared from FACS-sorted $f_{50\%}$ of CLL cases with del13q14. (Supplementary Table S10).

Correlative analysis of PHLPP expression by FISH categories discovered that ~50% of CLL cases with del13q14 did not express PHLPP (Fig. 5). The percentage of CLL cases that did not express PHLPP was 51% (isolated del13q14), 40% (normal FISH), 28% (complex FISH), 22% (isolated del1q or del17p), and 14% (isolated trisomy 12), respectively. Using a standard test of proportions, the difference between del13q14 and trisomy 12 cases for PHLPP expression was highly significant at $P = 0.01$, whereas a trend was observed for the comparison of del13q14 and complex FISH findings ($P = 0.14$).

**Deletion 13q14 in CLL comprises multiple subtypes.** A summary of the distinct molecular and clinical characteristics of the newly identified del13q14 subtypes in CLL has been tabulated in Table 1.

**Discussion**

In this study, we describe the results of a high-resolution analysis of del13q14 in a large cohort of CLL patients using high-density SNP oligonucleotide arrays. SNP arrays offer an unbiased approach to the evaluation of entire cancer genomes through the assessment of allelic losses/gains and LOH (39–41).

A significant strength of this study is the use of sorted CD19$^+$ cells as substrates for all analyses, effectively eliminating confounding variables introduced by non–B cells.

SNP array analysis proved to be a highly sensitive and specific method for determining copy number losses at 13q14 in CLL based on comparison with FISH. Both methods, with few exceptions, detected the same cases.

Detailed anatomic analysis of del13q14 suggested to us the existence of distinct subtypes. Our initial suggestion for categorization classifies del13q14 lesions with Rb loss as type II (40% of del13q14 cases) and without such loss as type I (60% of del13q14 cases). Rb is a critical regulator of cell cycle progression and genomic stability, and loss of one or two alleles could differentially affect the biology of affected CLL cases (42, 43); further support for clustering del13q14 type I lesions as a separate group comes from expression analysis of LATS2, which we performed across this large CLL cohort.

LATS2 RNA levels were found to be low in CLL cases with del13q14 type I as opposed to type II cases or all other CLL cases without del13q14. Given that LATS2 has been implicated in cell cycle progression control, we surmise that Rb, LATS2, and possibly additional, unidentified regulators (in non-del13q14 cases) are regulating this process in different subsets of CLL (44, 45).

The mechanism of low LATS2 expression in CLL subtypes is not known; LATS2 lies outside of all 13q14 deletions. Possibilities include LATS2 promoter methylation, as described for other cancers, or an effect in trans of 13q14 resident genes on LATS2 expression (46, 47).

The discovery of differing LATS2 levels in CLL subtypes may also be of interest in the context of response to therapy or disease progression, as LATS2 has been shown to intersect with the Mdm2-p53 axis (48). This topic needs prospective analysis in well-defined CLL cohorts.

Further subdivision of del13q14 type I cases into type Ia and type Ib is suggested by the occurrence of deletions that appear of relatively uniform length (del13q14 type Ia) and that display centromeric breaks within the vicinity of the miR15a/miR16 cluster that we here term the major telomeric del13q14 breakpoint cluster. Bi-allelic del13q14 type Ia lesions were associated with marked reductions in miR15a/miR16 expression levels and
may exert effects on affected CLL cases through yet-to-be-identified miR15a/miR16 targets. In this context, it seems relevant that Bcl-2 levels were not correlated with miR15a/miR16 levels, providing a renewed impetus for searches for critical miR15a/miR16 targets (26).

Correlative analysis of surrogate clinical end points/variables by del13q14 subtype disclosed a higher Rai stage at study enrollment for del13q14 type II lesions, as opposed to del13q14 type I lesions. Furthermore, we detected a highly significant enrichment for del13q14 type II cases in previously treated as opposed to untreated CLL specimens. Whereas these data may portend that del13q14 type II is a marker for more aggressive CLL, only prospectively collected clinical data will allow for firm conclusions to be drawn regarding possible detrimental effects of del13q14 type II lesions on CLL outcome.

The novel discovery that ~50% of all CLL cases with del13q14 do not express PHLPP is of interest. PHLPP dephosphorylates activated AKT and low or absent PHLPP expression may allow for sustained AKT signaling after proper cell surface stimuli (49).

In summary, anatomic and functional data suggest that multiple genes are deregulated as part of various deletions on chromosome 13, including genes with properties that warrant reduction in actively dividing cancer cells (Rb, LAT2) and genes with the potential for more specialized functions (miR15a/miR16, RFP2, PHLPP and others; ref. 50).

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Peter Ouillette, Harry Erba, Lisa Kujawski, et al.


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