Detection of Minimal Residual Disease in B Lymphoblastic Leukemia by High-Throughput Sequencing of IGH

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Abstract

Purpose: High-throughput sequencing (HTS) of immunoglobulin heavy-chain genes (IGH) in unselected clinical samples for minimal residual disease (MRD) in B lymphoblastic leukemia (B-ALL) has not been tested. As current MRD-detecting methods such as flow cytometry or patient-specific qPCR are complex or difficult to standardize in the clinical laboratory, sequencing may enhance clinical prognostication.

Experimental Design: We sequenced IGH in paired pretreatment and day 29 post-treatment samples using residual material from consecutive, unselected samples from the Children’s Oncology Group AALL0932 trial to measure MRD as compared with flow cytometry. We assessed the impact of ongoing recombination at IGH on MRD detection in post-treatment samples. Finally, we evaluated a subset of cases with discordant MRD results between flow cytometry and sequencing.

Results: We found clonal IGH rearrangements in 92 of 98 pretreatment patient samples. Furthermore, while ongoing recombination of IGH was evident, index clones typically prevailed in MRD-positive post-treatment samples, suggesting that clonal evolution at IGH does not contribute substantively to tumor fitness. MRD was detected by sequencing in all flow cytometry–positive cases with no false-negative results. In addition, in a subset of patients, MRD was detected by sequencing, but not by flow cytometry, including a fraction with MRD levels within the sensitivity of flow cytometry. We provide data that suggest that this discordance in some patients may be due to the phenotypic maturation of the transformed cell.

Conclusion: Our results provide strong support for HTS of IGH to enhance clinical prognostication in B-ALL. Clin Cancer Res; 20(17); 4540–8. ©2014 AACR.
Translational Relevance
This study evaluates the potential for high-throughput sequencing (HTS) of the immunoglobulin heavy-chain gene, IGH, to detect minimal residual disease (MRD) in patients with acute precursor B lymphoblastic leukemia (B-ALL). We show that MRD can be readily detected by sequencing with no false-negative results—contrast compared with flow cytometry—by using unselected, consecutive paired pretreatment and day 29 post-treatment samples from patients enrolled in Children’s Oncology Group ALL0932 trial. As prior work exploring next-generation sequencing in B-ALL included only patients with prior confirmed evidence of a clonal IGH rearrangement, our results show that sequencing of IGH alone is broadly applicable for unselected patients with B-ALL. Furthermore, we measure IGH repertoire during therapy and show that ongoing recombination at IGH does not contribute to enhanced tumor fitness that represents day 29 relapse. We contend that the enhanced specificity of HTS of IGH for MRD detection should greatly improve patient prognostication.

Materials and Methods
Clinical samples
Clinical samples (pretreatment: peripheral blood or bone marrow aspirate; and day 29 post-treatment: bone marrow aspirates) were collected from 99 individuals with informed consent by local clinicians, as part of enrollment into COG Study AALL0932 (registered as #NCT01190930; ref. 13). All patients had a diagnosis of B-ALL established locally, and then COG-coded pre- and post-treatment samples were submitted to the University of Washington Hematopathology Laboratory for routine flow cytometry analysis for MRD. Samples were not otherwise preselected, such as on the basis of having prior evidence of a clonal IGH gene rearrangement (11).

Flow cytometry
Multiparametric flow cytometry was performed at the University of Washington as part of the routine evaluation for MRD (14). Samples were labeled with the antibody combinations: CD20 FITC, CD10 PE, CD38 PerCP-Cy5.5, CD19 PE-Cy7, CD58 APC, and CD45 APC-H7 and CD9 FITC, CD13/CD33 PE, CD34 PerCP-Cy5.5, CD19 PE-Cy7, CD10 APC, and CD45 APC-H7, and processed using NH4Cl + 0.25% formaldehyde for red cell lysis with >750,000 events acquired on a Becton-Dickinson LSRII. Clusters of events differing from normal B-cell maturation were defined as MRD by B.L. Wood, and quantified relative to total mononuclear cells and total nucleated cells. Data were analyzed using Woodlist software version 2.7 (in-house software written by B.L. Wood; equivalent software is commercially available; ref. 14).

HTS
Sequencing CDR3 regions. IGH CDR3 regions were amplified and sequenced from 400 ng of pretreatment and 6 μg of day 29, post-treatment DNA samples, or in a subset of cases using all available extracted DNA. Amplification and sequencing of IGH CDR3 regions was carried out using the clonoSEQ platform (Adaptive Biotechnologies), in which a set of multiplexed forward primers matching V and D gene segment sequences are combined with a set of reverse primers matching J gene segment sequences to amplify both mature VDJ and immature DJ IGH rearrangements. Sequencing was performed starting from the J gene segment and extending 87 bp into the CDR3 region. Sequences for IGH CDR3 regions were delineated according to criteria established by the International ImMunoGeneTics collaboration with a standard algorithm to identify V, D, and J gene segments (15, 16). Rearranged CDR3 sequences were classified as nonproductive if insertions or deletions were identified that resulted in frameshifts or premature stop codons.

Identifying CDR3 sequences and defining clonality. DNA from bone marrow isolated from 9 healthy individuals was used to amplify IGH sequences using the same protocol as the day 29, post-treatment B-ALL samples. The frequency of the most common IGH gene rearrangement from the marrow aspirate of these individuals averaged 0.08% ± 0.04%
of total nucleated cells (mean ± SD; Supplementary Fig. S1). For this study, a very conservative definition of a neoplastic clone was chosen as representing a minimum of 10% of nucleated cells. For samples in which the two most common IGH sequences were of comparable frequency, biallelic rearrangement was assumed with both sequences considered to represent the lymphoblast clone. In day 29 post-treatment samples, MRD was identified by searching for CDR3 sequences that identically matched the clonal sequence defined in pretreatment samples, requiring a complete (87 bp) match. Both the presence and the frequency of the MRD clone relative to the total IGH repertoire and total nucleated cells were determined. To determine if the clonal CDR3 sequences identified were specific, all post-treatment samples were screened for the presence and frequency of all identified pretreatment IGH CDR3 clones.

**Use of a synthetic template to minimize bias in multiplexed PCR.** Because accurate quantification of lymphoblast clones for MRD detection is critical, we developed an approach to ensure minimal bias in multiplex PCR (17). Briefly, each potential VDJ rearrangement of the IGH locus contains one of nine J segments, one of 27 D segments, and one of 124 V segments, many of which have disparate nucleotide sequences. To amplify all possible VDJ combinations, we used a single tube, multiplex PCR assay with 84 V and 15 D forward and 9 J reverse primers. To remove potential PCR bias, every possible V–J and D–J pair was chemically synthesized as a template with specific barcodes (17). These templates were engineered so as to be recognizable as nonbiologic and have universal 3′ and 5′ ends to permit amplification with universal primers and subsequent quantification by HTS. This synthetic immune system can then be used to calibrate the multiplex PCR assay. Iteratively, the multiplex pool of templates is amplified and sequenced with our IGH V/D- and J-specific primers, and the primer concentrations are adjusted to rebalance PCR amplification (Supplementary Fig. S2). Once the multiplex primer mixture amplifies each V and J template nearly equivalently, residual bias is removed computationally.

**Quantifying the fraction of B cells in bone marrow or blood.** The clonoSEQ assay amplifies and sequences rearranged IGH molecules. We quantify the amount of DNA input into the assay and convert this to the equivalent total number of nucleated cells, assuming approximately 6.4 pg genomic DNA per diploid cell. clonoSEQ then amplifies and sequences the molecules with rearranged IGH. Because the clonoSEQ assay includes analysis of DJ rearrangements, most B cells produce two sequences, one of which is a complete VDJ rearrangement and the other either a VDJ or an incomplete DJ rearrangement. To estimate the number of starting templates with IGH rearrangements that were in the sample, the average number of sequence reads for each starting template was measured. Synthetic control templates are also spiked at limiting dilution into each sample such that each template may be present at most as a single copy. One then can compute the average number of reads for each sequenced spiked synthetic template. The total number of B cells sequenced is then derived as the total number of sequencing reads divided by this computed average reads per template (fold-coverage), further divided by two, because there are two alleles per B cell. The total fraction of B cells in the mixture is this number of B cells divided by the total number of input cells as determined by DNA input quantity. This method is precise across a large range of initial B cell fractions (Supplementary Fig. S3).

**Identifying evolved IGH clonotypes.** To detect ongoing recombination at the IGH locus (so-called clonal evolution), we applied the algorithm proposed by Gawad and colleagues (12). Briefly, this approach defines evolved clonotypes of IGH as those that (i) share an identical JH sequence with the index clone, (ii) share at least six bases of identical NDN sequence with the index clone (starting from the J-segment boundary, with D-segment matches collapsed to two effective NDN bases), and (iii) are annotated with a different VH gene than the index clone (12). We verified the specificity of this approach using cross-patient comparisons and find that among clones that share a JH sequence, only 0.005% were considered “evolved” in other patients, as compared with 60.9% of H1-matching clones within the same patient, confirming that this algorithm has a low false-positive rate (12).

**Results**

Using unselected, consecutive residual material derived from 99 paired pre- and day 29 post-treatment B-ALL samples from patients enrolled in the COG AALL0932, we sequenced the complementarity-determining region 3 (CDR3) of IGH using the equivalent of approximately 300,000 genomes for pretreatment samples and 1,000,000 genomes for day 29 post-treatment samples. One case unexpectedly failed at the outset with inadequate DNA from the extraction of the pretreatment sample and was excluded from further consideration. The pretreatment sequencing analysis permitted us to define for 91 of 98 patients the unique, recombined IGH gene sequences (V–DJ complete rearrangements > 10%), representing the patient’s clonal, neoplastic B lymphoblasts (Table 1, Fig. 1A). The remaining 7 patients without a B lymphoblast clone with a complete IGH rearrangement of 10% or higher of total cells in the bone marrow were studied individually. One patient had a large B lymphoblast clone with two D–J rearrangements, but no complete V–DJ IGH rearrangements. A second patient had a clone comprising approximately 4% of nucleated cells in the bone marrow, which still represents a statistically significant expansion compared with healthy donors (Supplementary Fig. S1), and this value agreed with the corresponding flow cytometry result. The remaining 5 patient samples did not have an identifiable clonal IGH sequence at diagnosis, defined as that comprising more than 10% among total nucleated cells of a complete (V–I) or incomplete D–J IGH sequence, and were not considered further herein. By flow cytometry, these 5 cases did not have a distinguishing or common pretreatment immunophenotype (Supplementary Fig. S4,
Supplementary Table S1). Thus, of 98 unselected samples, 92 cases at diagnosis had a clonal IGH complete or incomplete DJ rearrangement meeting our definition of a clonal B-cell population comprising more than 10% of total cells, with one additional case having a clonal IGH rearrangement at 4%, matching flow cytometry.

A total of eighty-four samples were examined with an assay designed to amplify V–DJ and D–J rearrangements. Fifty-eight of these samples had at least two IGH sequences with frequencies higher than 10%; 26 had two clonal IGH above 10% and the third most frequent clone at least 10-fold smaller than the second most frequent, providing the potential to improve specificity for this assay by post-treatment tracking of both alleles. The use of a synthetic IGH immune system in which templates of all VH and JH primer pairs are used to adjust primer concentrations minimizes multiplexed PCR bias. Among these 84 patients, incomplete D–J rearrangements with a frequency of at least 10% were observed in 22 samples, one of which showed no evidence of any V(D)J clone expansion (thus making the 92 samples in which we find a clonal IGH rearrangement; Table 1).

With knowledge of the index IGH CDR3 sequences of the patient’s clonal population in the pretreatment samples (Fig. 1A), we examined the potential for HTS to identify the same sequence at day 29 after treatment and compared these findings with results obtained by multiparametric flow cytometry (mpFC) performed as part of the COG trial (Fig. 1B). In those patients with biallelic IGH rearrangements, quantified MRD for the two alleles was highly correlated (Fig. 2). HTS to detect the patient’s original clonal IGH sequences in day 29 post-treatment samples revealed three subgroups of patients in this cohort: (i) those for whom MRD was not detected by either HTS or mpFC, 40 cases; (ii) those for whom MRD was detected only by HTS but not mpFC, 28 cases; and (iii) those in which MRD was detected by both HTS and mpFC, 23 cases (Fig. 1B). Importantly, there were no cases (false-negative results) for which MRD was detected only by mpFC, but not by HTS of IGH. For the 28 cases for which HTS did and mpFC did not detect MRD, the MRD was, on average, 10- to 100-fold lower than for the 23 cases for which both mpFC and HTS detected MRD (median, 8.0 × 10−6 vs. 1.4 × 10−5; P = 7.0 × 10−5 by two-tailed U test; Fig. 1B). As a conservative estimate, there was approximately a 10-fold increase in the lower detection limit for MRD detection by HTS as compared with mpFC. Tracking of IGH clones could be improved by following both rearranged alleles in tumors that had evidence of biallelic rearrangement (Fig. 2). However, for the purposes of subsequent comparisons between flow cytometry and sequencing, tracking of only a single dominant sequence was performed.

As previously reported (11, 12), we also find widespread evidence of ongoing clonal evolution of IGH in these B-ALL samples, both in the pre- and MRD-positive post-treatment (Table 2). In post-treatment samples, the predominant clone in pretreatment samples was typically the most frequent clone. Clones consistent with VH replacement were found in 19 patients. In 1 patient, the only MRD detected was a single clone consistent with VH replacement at a level of approximately 1 in 1,000,000. The clinical significance of this low-level MRD is unclear. In the other 18 post-treatment MRD-positive cases with evidence of VH replacement, the dominant clone identified before treatment was also dominant after treatment. On average, 3.5% of total IGH rearrangements matched the dominant clone after treatment, whereas only 0.036% of IGH rearrangements were consistent with VH replacement of the major clone. Among pretreatment samples in which VH-replaced clones were detected, all VH-replaced clones together were 0.4% as large as the dominant clone on average (median). Among post-treatment samples, VH-replaced clones were on average 0.6% as large as the dominant clone. These trends are illustrated for a particular patient with MRD and a large number of VH-replaced

### Table 1. Summary of 99 consecutive patient cases

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failed initial DNA extraction</td>
<td>1</td>
</tr>
<tr>
<td>Adequate DNA</td>
<td>98</td>
</tr>
<tr>
<td>Pretreatment sequencing</td>
<td></td>
</tr>
<tr>
<td>Pretreatment clonal IGH (V–J)</td>
<td>91</td>
</tr>
<tr>
<td>Pretreatment clonal IGH (D–J) only</td>
<td>1</td>
</tr>
<tr>
<td>Pretreatment biallelic IGH</td>
<td>26</td>
</tr>
<tr>
<td>Post-treatment MRD</td>
<td></td>
</tr>
<tr>
<td>HTS+/mpFC+ post-treatment MRD</td>
<td>23</td>
</tr>
<tr>
<td>HTS+/mpFC− post-treatment MRD</td>
<td>28</td>
</tr>
<tr>
<td>HTS−/mpFC− post-treatment MRD</td>
<td>40</td>
</tr>
<tr>
<td>Eight additional mpFC-negative cases, triple flow cytometry–sorted for HTS</td>
<td></td>
</tr>
<tr>
<td>Evidence of clonal, pretreatment IGH in sorted mature B-cell fraction</td>
<td>1</td>
</tr>
<tr>
<td>No evidence of clonal, pretreatment IGH in sorted mature B-cell fraction in samples with adequate DNA</td>
<td>7</td>
</tr>
</tbody>
</table>

*a*Adequate DNA was only available to test for IGH D–J rearrangements (and therefore biallelic samples) in 84 of the 98 cases. Samples with three or more highly expanded IGH sequences were also not considered biallelic.
clonotypes in Supplementary Fig. S5. Taken together, these data indicate that generally there is little change in the relative proportions of the dominant clone and VH-replaced subclones through induction chemotherapy.

To evaluate the specificity of HTS for assessment of MRD, we evaluated the frequency of the specific clonal IGH sequence from each patient being present in the other 97 patient post-treatment samples at day 29. This estimate provides an assessment of the relative likelihood after treatment that B cells may by chance have the exact same clonal index IGH sequence. Prior analysis has reported that nonspecific amplification of IGH rearrangements in B-ALL may be dependent on the time point after therapy and also the gene segment and therefore the target rearrangement being considered (18). In our cohort, at the level of 1 cell in 100,000, nine shared sequences of 8,918 IGH comparisons (0.10%) in cross-patient comparisons were detected. This rate is slightly higher (0.72%) when clones at a frequency of 1 cell in 1,000,000 are considered. Of note, the level of these coincidental clones was lower by approximately one order of magnitude on average as compared with true MRD positives (i.e., index sequences found in the corresponding post-treatment samples, and not in cross-patient samples).

Of note then, 52 of 91 unselected patients had MRD clones at the level of 1 cell in a million or higher that was detectable by HTS of IGH alone, compared with only 23 cases of MRD positivity by flow cytometry (Fig. 1B). As many of the samples that were MRD negative by flow cytometry and MRD positive by HTS had levels of MRD within the expected range of detection of flow cytometry (~1 in 10,000 to 100,000), it is possible that flow cytometry may be missing relatively high-level MRD in a subset of patients. This could be due to post-treatment changes in the antigen expression resulting in immunophenotypic normalization (19). We, therefore, sought to determine if the detection of clonal sequences matching the original diagnostic samples could be derived from the mature B-cell fraction of samples. To test this hypothesis, we analyzed 10 additional, paired consecutive pre- and post-treatment B-ALL MRD samples for which residual material was available, and for which there was no evidence of MRD as determined by flow cytometry. This sample size was chosen
Discussion

Accurate risk stratification is important for the personalized treatment of patients with B-lineage acute lymphoblastic leukemia (2–5). Recent clinical studies have confirmed the importance of MRD in guiding patient care in both pediatric and adult B-ALL (9, 20). However, widespread implementation of diagnostic assays to accurately stratify patient risk in the clinical laboratory has been challenging. Each existing method of analyzing MRD, such as flow cytometry or qPCR, has its own drawbacks and technical challenges. Here, using a cohort of patient samples submitted to our institution for flow cytometric analysis of MRD, we confirm the broad potential of sequencing of IGH to permit highly specific molecular detection of clonality in nearly all-comers (91 of 98, ~93%) without the laborious requirement of individualized PCR or allele-specific oligonucleotide design, implicit in current molecular-based approaches for monitoring MRD (8, 21).

Although conventional practice has focused on identifying and following at least two clonal molecular markers for MRD detection (22), recent data from the AIEOP-BFM ALL 2000 study of pediatric and adolescent B-ALL suggests that patients with only one marker can be similarly stratified as they have outcome results quite similar to those patients followed by two markers (20). Specifically, of 3,184 patients, 454 had only one marker and event-free survival (EFS) results in this subset of patients was 5-year EFS of 94.1% for standard-risk (vs. 92.3% EFS for two markers) or 83.3% for intermediate-risk (77.6% for 2 markers; ref. 20). Thus, the ability to detect clonal IGH rearrangements in a large proportion of patients in our unselected cohort of B-ALL patients suggests that HTS of IGH should be, at the minimum, a viable strategy for MRD detection in many patients with B-ALL. Moreover, our data further support the analysis for both complete (VDJ) and incomplete (DJ) IGH rearrangements in B-ALL for MRD assessment, and highlight the potential utility of this approach to improve accuracy of quantification of MRD (Fig. 2). In addition, in patients with biallelic IGH rearrangements, tracking of both alleles can help to confirm the detection of MRD.

Prior work by Gawad and colleagues using next-generation sequencing has identified remarkable diversity in pretreatment diagnostic samples due to ongoing clonal evolution of IGH, with some tumors being composed of thousands of apparent subclones with respect to IGH and that seem to be derived from an ancestral clone due to a V_{\text{h}} replacement model (11, 12) or alternately, ongoing V(D)J recombination of a clone with incomplete DJ recombination. We similarly identify herein the evidence of ongoing recombination of IGH in pretreatment samples. However, in contrast with analysis by Gawad and colleagues, who did not evaluate the impact of this on MRD detection (12), we show here that clonal diversity as defined by evolved IGH clonotypes does not substantively change in day 29 post-treatment samples. Furthermore, in a MRD-positive, post-treatment sample, the dominant clone found at relapse by sequencing was identical to the dominant clone seen at

Figure 2. Comparison of clonal frequency of MRD in cases with presumed biallelic rearrangement of IGH versus mrFC. In samples with biallelic rearrangement, tracking of both alleles provides enhanced specificity for quantification of MRD. A total of 26 diagnostic samples generated clear evidence for biallelic rearrangements (exactly two dominant IGH sequences); in these samples, the frequency of each allele was tracked in post-treatment samples. In 10 samples, neither allele was observed after treatment. In 4 samples, only one allele was observed after treatment (at an average frequency of 1.2 x 10^{-5}). In the remaining 12 samples, both alleles were observed after treatment. The frequencies of the dominant and secondary alleles in post-treatment samples are charted. Post-treatment allele frequencies in biallelic samples are highly correlated (r^2 = 0.97).
ment sample in all cases. Furthermore, we do not believe by performing triple flow cytometry sorting and sequencing not flow cytometry (25), as we minimized these possibilities as shown in rare instances in which PCR detects MRD but MRD in a subset of cases for which flow cytometry evalu-

MRD in a subset of cases for which flow cytometry evalu-

similar in pre- and post-

treatment samples. These findings together suggest that within this early time frame, ongoing rearrangement at the IGH locus does not substantially alter the fitness of lymphoblast clones during induction chemotherapy. Additional studies at subsequent time points will need to be performed to further document how IGH repertoire may change over time, as several studies have shown that late relapsed clones can often be retrospectively identified in pretreatment samples (23). Nevertheless, our data provide the first picture of clonal IGH evolution through induction chemotherapy.

Similar to our findings in T-ALL (10), HTS can identify MRD in a subset of cases for which flow cytometry evaluation is negative. Indeed, in this cohort, 5 cases had MRD detected by HTS at a level of >1 cell in 10,000 that should have been detected by flow cytometry (Fig. 1B). To consider the possibility that these detected IGH sequences may be derived from cells with an altered immunophenotype, we examined an additional subset of eight cases that had detectable MRD by next-generation sequencing, but were negative by flow cytometry. Of these, 1 of the 8 patients had a clonal MRD sequence identified in the pretreatment sample that matched the patient’s index clone and was found within a triple flow cytometry–sorted B-cell fraction that appears to be immunophenotypically mature. Our finding of rare index IGH sequences within the mature B-cell fraction raises the possibility that in some patients, the finding of rare index sequences at the level that was seen in this patient at approximately 0.01%, even among the very rare examples of shared sequences. Our finding of antigenic shift is similar to that reported by Gawad and colleagues who showed in their diagnostic pediatric B-ALL samples that a portion of evolved clones may have substantial antigenic differences as compared with the index clone (12). Given that the malignant potential of a clone such as this with antigenic maturation is not known, its clinical import is undetermined despite its relatively high frequency in this patient.

The patient samples considered in this study were derived from the COG AALL0932 trial, from patients who were regarded as being generally low- to standard-risk for relapse. However, as shown in our findings, (Fig. 1B), many of these cases (51 of 92) have clonal sequences detectable by HTS but are flow cytometry negative. Although the clinical significance of these MRD levels below current diagnostic threshold of <0.01% is outside the scope of this study, the significance of these low-level sequences requires further study. It is likely that MRD positivity by sequencing will be clinically important for a subset of patients. Several studies support this claim. First, Paganin and colleagues show that detectable, but not quantifiable MRD below the level of \( < 10^{-4} \) had an intermediate EFS of 45% at 3 years versus patients who had MRD results that were either negative or outright positive at a level \( \geq 10^{-4} \) (26). The EFS for these patients were 73% and 19% for negative versus positive MRD, respectively. Second, Stow and colleagues showed in a study involving 455 clinical samples and using PCR analysis of MRD at one time point (day 46, at end of remission induction) that levels below the conventional clinical threshold of 0.01% were important for predicting relapse (27). In this work, patients in whom PCR was able to detect very low levels of MRD \((0.001% \text{ to } <0.01\%)\) had a 12.7% \(\pm 5.1\%\); SE) cumulative risk of relapse at 5 years compared with 5% \(\pm 1.5\%)\) for those below the MRD level of 0.01% \(P < 0.047\). Stow and colleagues (27) conclude that MRD positivity below the standard threshold of 0.01%
has prognostic significance for some patients, and that patients with low-level positivity by PCR should be closely monitored. Third, Pulsipher and colleagues (28) reported data showing that patients with pretreatment detectable MRD by deep sequencing of IGH had a significantly increased cumulative incidence of relapse when compared with those patients with no evidence of disease by sequencing (57% versus 4.4%; \( P = 0.008 \)) in a cohort of 64 COG patients who underwent total body irradiation-based myeloablative transplant for high-risk ALL in CR1 or CR2. Furthermore, although patients from this same cohort who were MRD negative based on flow cytometry had a cumulative risk of relapse of nearly 25%, by comparison, patients who were MRD negative by deep sequencing of IGH using the identical platform assay described herein had a cumulative risk of relapse of less than 5%. Finally, recent work comparing quantitative PCR-based methods versus flow cytometry for MRD detection in a cohort of 1,547 children with acute lymphoblastic leukemia enrolled into the AIEOP-BFM ALL 2000 trial has suggested that the outcome of patients with discordant MRD results between PCR-based methods and flow cytometry is likely to be different than for those cases for which MRD results are concordant between the two approaches (29). Therefore, low-level MRD detected by sequencing is likely to be meaningful for a subset of patients and suggests that these patients, at the very least, should be closely monitored.

Indeed, the increased sensitivity of MRD determination by HTS offers the opportunity to clinically assess for trends in MRD over time at time points when the level of disease may be beneath the detection limit of flow cytometry. Prior work has suggested that in patients with B-ALL, there is an inverse correlation between the level of MRD detected versus time to late relapse (29). Data from the AIEOP-BFM ALL 2000 study further support these findings, as patients with high MRD levels at day 33, but no MRD detected by molecular analysis at day 78 had a decreased 5-year cumulative relapse incidence of 20.7% versus 40.7% in patients who were positive for MRD at day 78, but had persistent MRD at a level less than 10\(^{-3}\). Additional work suggests that oftentimes, the clone that represents late relapse may be identified retrospectively in the index sample (20, 23, 29). Our studies demonstrate robust analytic ability to quantify IGH rearrangements (Supplementary Fig. S3).

In summary, we demonstrate the utility of HTS of IGH genes for the detection of MRD in B-ALL. Despite ongoing recombination of IGH, the analysis of IGH gene rearrangement permits robust identification of the neoplastic lymphoblastic population in a high proportion of unsampled cases. For cases in which no clonal IGH gene rearrangement was identified, evaluation of other loci, such as IGK, TRB, TRC, and TRD) genes may be helpful, as previously suggested by others and Faham and colleagues (11). Because HTS could greatly reduce the complexity associated with patient-specific molecular analysis of MRD and improve on observer variation in flow cytometry, it offers the potential to improve clinical prognostication in B-ALL. Further evaluation of sequencing-based MRD detection, however, must be confirmed in subsequent studies involving independent laboratories. However, the synthetic IGH templates that we use herein to ensure accurate and unbiased, multiplex PCR could be one approach to ensure standardized assay performance. Clinical laboratories adopting sequencing for MRD could use this synthetic immune system to confirm consistent test performance, permitting broad implementation of this technology.

In addition, it will be important to understand the clinical implications of cases in which relatively higher level of MRD was missed by flow cytometry but detected by sequencing. Although a limited observation, we show that clonal IGH index sequences in some patients can be identified within the immunophenotypically apparent mature B-cell subset, suggesting that some B lymphoblasts clones may undergo antigenic drift and/or maturation. The clinical significance of this finding merits further study and is underway.

**Disclosure of Potential Conflicts of Interest**

D. Wu reports receiving a commercial research grant from Adaptive Biotechnologies. R.O. Emerson, A. Sherwood, B. Howie, and I. Kirsch are employees of and have ownership interests (including patents) in Adaptive Biotechnologies. M. Rieder has ownership interest (including patents) in Adaptive Biotechnologies. C. Carlson and H. Robins have ownership interests (including patents) and are consultants/advisory board members for Adaptive Biotechnologies. No potential conflicts of interest were disclosed by the other authors.

**Authors’ Contributions**

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**Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.):** D. Wu, A. Sherwood, M.L. Loh, A. Angiolillo, M. Rieder, B.L. Wood

**Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis):** D. Wu, R.O. Emerson, A. Sherwood, B. Howie, I. Kirsch, C. Carlson, D. Williamson, H. Robins

**Writing, review, and/or revision of the manuscript:** D. Wu, R.O. Emerson, A. Sherwood, M.L. Loh, A. Angiolillo, J. Vogt, I. Kirsch, D. Williamson, B.L. Wood, H. Robins

**Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases):** D. Wu, A. Angiolillo, J. Vogt, M. Rieder

**Study supervision:** D. Wu, A. Angiolillo, B.L. Wood

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Detection of Minimal Residual Disease in B Lymphoblastic Leukemia by High-Throughput Sequencing of *IGH*

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