

A role for AID in chromosome translocations between *c-myc* and the IgH variable region

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Chromosome translocations between oncogenes and the region spanning the immunoglobulin (Ig) heavy chain (*IgH*) variable (V), diversity (D), and joining (J) gene segments (Ig V-J_H region) are found in several mature B cell lymphomas in humans and mice. The breakpoints are frequently adjacent to the recombination signal sequences targeted by recombination activating genes 1 and 2 during antigen receptor assembly in pre-B cells, suggesting that these translocations might be the result of aberrant V(D)J recombination. However, in mature B cells undergoing activation-induced cytidine deaminase (AID)-dependent somatic hypermutation (SHM), duplications or deletions that would necessitate a double-strand break make up 6% of all the Ig V-J_H region-associated somatic mutations. Furthermore, DNA breaks can be detected at this locus in B cells undergoing SHM. To determine whether SHM might induce *c-myc* to Ig V-J_H translocations, we searched for such events in both interleukin (IL) 6 transgenic (*IL-6* tg) and *AID*^{-/-} *IL-6* tg mice. Here, we report that *AID* is required for *c-myc* to Ig V-J_H translocations induced by IL-6.

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Abbreviations used: AID, activation-induced cytidine deaminase; IgH, Ig heavy chain; Ig V-J_H, genomic region spanning the heavy chain V(D)J; RSS, recombination signal sequences; SHM, somatic hypermutation; tg, transgenic; V(D)J, variable, diversity, and joining.

Chromosome translocations are products of unresolved double-strand DNA breaks (1–4) and therefore occur frequently at Ig genes because these loci undergo programmed DNA damage during antigen receptor gene diversification. In developing T and B cells, RAG1 and RAG2 proteins produce double-strand breaks at recombination signal sequences (RSS) found adjacent to variable, diversity, and joining (V(D)J) gene segments (5, 6). These RSS are found in close proximity or within translocation breakpoints in numerous B cell lymphomas (for review see references 7 and 8).

In mature B cells, expression of activation-induced cytidine deaminase (AID) (9–11) leads to deamination of cytidine residues in Ig V-J_H and Ig switch regions resulting in U:G mismatches that are processed to produce somatic hypermutations (SHMs) and initiate class switch recombination (for review see references 12–14). Double-strand breaks are obligate intermediates in the class switch reaction, and translocations involving switch regions are frequently found in sporadic Burkitt's lymphoma, diffuse large B cell lymphoma, and multiple myeloma, suggesting that AID is responsible for the lesions that lead to such translocations (15–22).

Consistent with this idea, AID-induced breaks in the switch region activate the cellular DNA damage response machinery (23), and AID is essential for *c-myc* translocations to the Ig switch region in *IL-6* transgenic (tg) (24, 25). In addition, AID appears to target several oncogenes that are frequently mutated and often translocated to antibody genes in mature B cell malignancies (26–30). In agreement with these observations, deregulated expression of AID is associated with malignancy (31–34).

Double-strand breaks are not obligate intermediates in SHM of the Ig V-J_H (35). Nevertheless, duplications or deletions that would necessitate a double-strand break make up 6% of all the Ig V-J_H region-associated somatic mutations, and DNA breaks can be detected in this region in B cells undergoing mutation (36–42). In addition, endemic Burkitt's lymphoma, multiple myeloma, follicular lymphoma, and diffuse large B cell lymphoma contain mutated V genes as well as translocations to the Ig V-J_H or Ig V-J_L regions (for review see references 7, 8, and 43). This suggests that translocations in these malignancies may have occurred in mature B cells that express AID but not RAG1/2 (44), and that some Ig V-J_H region-associated

translocations are byproducts of lesions induced by AID during hypermutation. To ascertain the extent to which AID contributes to genomic instability at the *IgH* locus, we tested if AID is required for translocations between *c-myc* and the Ig V-J_H region in *IL-6* tg mice.

RESULTS

IL-6 tg mice develop hyperplastic lymph nodes that contain large numbers of class-switched plasmacytes, a portion of which express GL7 and CD138 (24, 45, 46). Plasmacytosis is believed to develop in these mice because IL-6 attenuates apoptosis and promotes proliferation and differentiation of late-stage B cells, allowing for the accumulation of translocations between *IgH* and *c-myc* (45). Although a majority of the *c-myc* translocation breakpoints are at the Ig switch region, a small fraction occur at the V-J_H region (46) and therefore resemble the translocations found in endemic Burkitt's lymphoma (for review see references 7 and 8). To determine

whether AID is required for translocations between the Ig V-J_H region and *c-myc*, we generated *AID*-deficient *IL-6* tg mice (*AID*^{-/-}*IL-6* tg) by breeding (24). *AID*^{-/-}*IL-6* tg mice developed lymph node hyperplasia and plasmacytosis with a slightly delayed onset compared with *IL-6* tg mice, and there was no detectable class switching in the *AID*^{-/-}*IL-6* tg mice (Fig. 1, A and B) (24).

To document translocations between the Ig V-J_H region and *c-myc*, we developed PCR assays for these events and examined cells from hyperplastic lymph nodes from *IL-6* tg and *AID*^{-/-}*IL-6* tg mice (Fig. 2 A). Southern blotting and DNA sequencing were used to verify candidate translocations (Figs. 2 and 3). Assaying four different lymph node pools per mouse for derivative 12 and derivative 15 translocations (Fig. 2 A), we identified 37 unique translocations in 14 *IL-6* tg mice, but none in 12 *AID*^{-/-}*IL-6* tg mice (P = 0.0025) (Fig. 2 C). Derivative 12 and 15 translocations were similar in both the number of translocations identified (21 and 16, respectively)

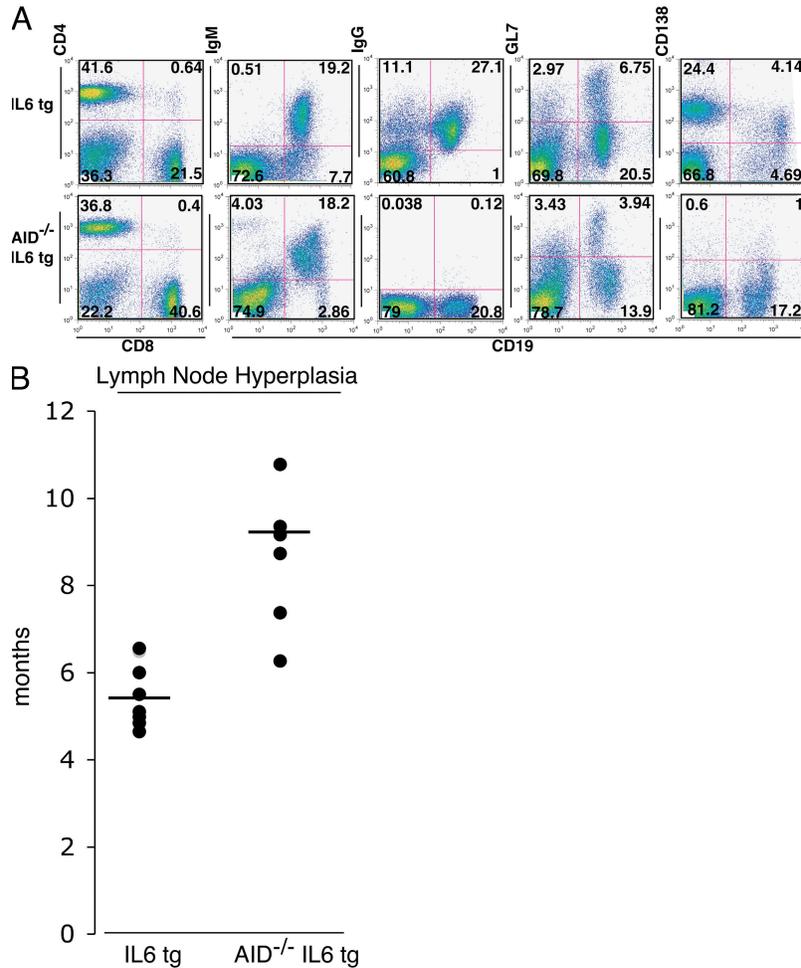


Figure 1. Characterization of *IL-6* tg and *AID*^{-/-} *IL-6* tg mice. (A) Flow cytometry analysis of cells from hyperplastic lymph nodes from *IL-6* tg and *AID*^{-/-}*IL-6* tg mice. Numbers indicate percentages of cells in a given quadrant. (B) AID accelerates the development of disease in *IL-6* tg mice. *IL-6* tg mice and *AID*^{-/-}*IL-6* tg mice were killed when they developed enlarged lymph nodes. The average time of death for *IL-6* tg was 5.5 mo (*n* = 8) and 9.2 mo for *AID*^{-/-}*IL-6* tg mice (*n* = 8; P = 0.0001476 using a two-tailed Student's *t* test assuming unequal variance). Each point represents one mouse, and the black bars indicate the average time of death.

as well as in their breakpoint distribution along the chromosome (Fig. 3), providing strong evidence that variable region translocations are reciprocal. As expected, *c-myc* to Ig switch region translocations were far more frequent (Fig. 2 B) (24, 46). We conclude that translocations between *c-myc* and the Ig V-J_H region are AID dependent in *IL-6* tg mice.

To gain further insight into the etiology of the identified translocations, we analyzed and mapped the breakpoints. Sequence analysis revealed that the majority of the breakpoints were in or around J_H segments, as commonly seen for oncogenic translocations in B cell non-Hodgkin's (Fig. 3) (for review see references 7 and 8). Junction sequences resembled those previously characterized for *c-myc* to Ig switch region translocations from *IL-6* tg mice (24) in that they involved either blunt ends or 1–3 nucleotide stretches of microhomology or nucleotide insertions (Tables I and II), implying that nonhomologous end joining resolves these breaks. Finally, the translocation breakpoints in *c-myc* were all in the first intron, which differs from those to the Ig switch region

in *IL-6* tg mice, where a majority of the breakpoints are in the first exon of *c-myc* (Fig. 3) (24).

Although there was no correlation between the position of the breakpoints and the RGYW motifs, which are the preferred targets of AID, the translocated Ig V-J_H region was somatically mutated at a frequency of $\sim 0.6 \times 10^{-3}$ mutations per basepair (Fig. 4). This rate of mutation is similar to that reported for the Ig V-J_H region in B cells undergoing hypermutation (47). Derivative 12 and 15 *IgH* sequences had a similar frequency of hypermutation, suggesting that SHM must have occurred before or during translocation. Interestingly, the overall position of the mutations mirrored the positions of the translocation breakpoints (compare Figs. 3 and 4), supporting the idea that regions prone to SHM are susceptible to translocations. Excluding nucleotide insertions at the breakpoint, the rate of mutation within 20 bp of either side of the translocation breakpoints was almost 10-fold higher (5.4×10^{-3}) than that seen overall for *IgH* in our translocations. This implies that *c-myc/IgH* translocations are

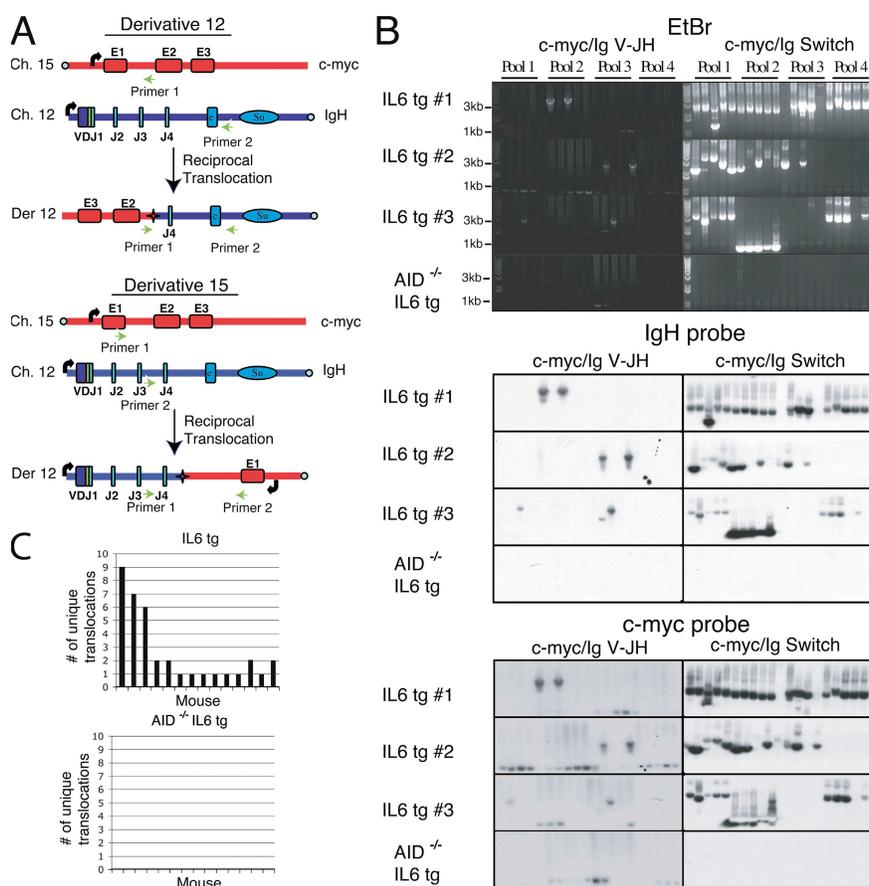


Figure 2. C-myc to Ig V-J_H region. (A) Diagram of translocation assay for detecting derivative 12 and 15 chromosomal translocations from *c-myc* to the Ig V-J_H region. Primer set 1 is indicated in the diagram for derivative 12 (see Materials and methods). The circles at the end of each chromosome represent the centromere. (B) Comparison of *c-myc* translocations to the IgH V-J_H versus switch region. Representative PCRs from three *IL-6* tg and one *AID*^{-/-}*IL-6* tg mouse. Primer set 1 was used to detect translocations to the variable region. Each lane represents amplification products from 10^5 cells. The ethidium bromide–stained gels at the top were probed for *c-myc*, stripped, and then probed for IgH to verify translocations. (C) Graph shows the number of unique *c-myc* to Ig V-J_H region translocations identified in 14 *IL-6* tg mice. No translocations were identified in the same analysis of 12 *AID*^{-/-}*IL-6* tg mice ($P = 0.00284$ using a two-tailed Student's *t* test assuming unequal variance.).

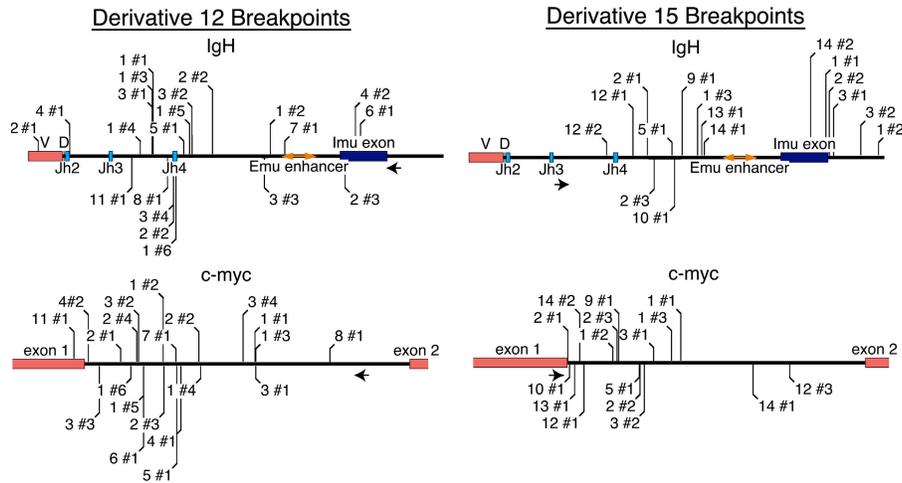


Figure 3. Translocation breakpoints. Diagram of translocation breakpoints from *c-myc* to the Ig V-J_H region. Only primer set 1 is indicated for derivative 12 (see Materials and methods). The translocations are annotated as the mouse number followed by the translocation number for that mouse. For example, "2 #2" is mouse 2 translocation number two amplified from that mouse.

resolved through error-prone repair, or that translocation breakpoints occur at or immediately adjacent to hypermutated sequences. Discounting mutations within 20 bp of the breakpoint, we identified three mutations in *c-myc*, resulting in a mutation rate that is above background ($\sim 0.2 \times 10^{-3}$) but approximately threefold lower than the rate observed for *IgH* (Fig. 4). These results suggest that *c-myc* translocations to

the Ig V-J_H region in *IL-6* tg mice occur during or after Ig V-J_H region SHM (28, 47, 48).

DISCUSSION

Molecular characterization of translocations found in lymphomas showed that in addition to Ig switch regions, many breakpoints are near RSS, suggesting a role for aberrant V(D)J

Table I. Derivative 12

Translocation	IgH	Jnc	c-myc
4 #2	GAGTGTCTCTCAACCACCA	A	GATCTGGTGGTCTTCCCTG
2 #3	GAATACTCAGAAAGTGGTCT		CTTTGCGTTGGGAGCGAG
3 #3	TAAACTTTAAGTAATGTC	<i>t</i>	TTAGGACAGCTTTCTTCCA
2 #4	CTTTATTCTAAAACTGAA		CGGCCGGTTGGACATTATTG
1 #2	TTAAAAGTCAGTCTGAATA	G	ATTACCTTTTGC GTTGGGA
1 #3	CCCCTGGACCCCTCTTAGT		AGGGAAGACGCCCTGCACCC
3 #1	CCTGGACCCCTCTTAGT		AGGGAAGACGCCCTGCAC
1 #5	GACAGTTTATTCCCAATT	CT	TTGAGGGGCAAACCGGGAG
4 #1	GTTGTAAGGACTCACCTGAG	G	CATTCTGACAGCCTGGG
3 #2	CAGCCGGTCCCTCAGGGAC		TTGGACATTCTTGCTTTGCTAt
1 #1	CCCCTGGACCCCTCTAAGT		AGGGAAGACGCCCTGCAC
1 #6	GGAGACGGTGACTGAGGT		TCCCAGGTTACTATGGGC
5 #1	GTCTGCAATGTTCAGAAAAC	T	AAATTCAGCTTGGTGCAAT
1 #4	CCCTAATTCTACAAGATC		TTTTGGCTTTAAAAATAGTG
2 #2	GTTCTTGACCCCGAAGTC		AAGAAGTTGCTATTTTGGCT
6 #1	CACAGAGCATGTGGACTGGC	TT	AATTGATATGTGCCTTTG
7 #1	CCAAATAGCCTTGCCACATG		GGGCATTTAAATTCAGCTT
8 #1	ATACCCGACAAAACCCGAC	<i>t</i>	CTTCTCCTTCAGGTGGCGC
2 #1	GCCTTGACGACAGCTTCAC		ATGACAGAGGAAAGGGGAAG
3 #4	CTTGACCCAGTAtTCCATAG		GAAGACTCGCGTGAGTCGTGA
11 #1	CCTTCTCATACTCAGgTCT		CCTGAAAAGAGCTCCTCGAGC

Junction sequences are those that cannot be definitively assigned to *c-myc* or IgH. Lower case letters indicate mutations, and insertions are in italics. The translocations are annotated as the mouse number followed by the translocation number for that mouse. For example "2 #2" is mouse 2 translocation number two amplified from that mouse. Jnc., junction.

Table II. Derivative 15

Translocation	IgH	Jnc	c-myc
2 #1	AGGCTCATTGAGGGAcATG		GTTTCCAACGCCCAAAGAA
2 #3	AGTTGGAGATTTTCAGTTTT-AG		TCCAACCGGCCGGGTCAG
9 #1	GAGAGCTGTCTTAGTGATTG	<i>t</i>	AAGAATGTCCAACCGGCCG
14 #2	AGGTCTGAGACCAGGCTGCT	<i>aaaaat</i>	CGGCCGCTACATTCAAGACG
12 #2	ATGTCTGAGTTGCCAGGGGT	G	GCGCCGCTCGCTCGGCCCC
5 #1	TAAAACCTCATTGTTGGAAG		ATCCCTTCTCCAAAGACCTCA
3 #2	AATTATTCA:TTAAGTGAT		CTTCTCGCTCCCAAACGCAAA
2 #2	TCCGAAACCAGGCACCGC	AAA	AGGTAATCCCTTCTCCAA
12 #1	GAAGTTGGGAAATAAACTGTC		GAtGAAAGACTGTCTTAACCG
13 #1	GTCCAAAATTTTTGTCAATC	A	AtACAGGGAAAGACCACCAG
10 #1	TTGCTGTCTAGAGAGGCTG	G	CTTACCGGGTTTCCAACGC
1 #1	GAACAATCCACACAAAGACT	C	TAAATTTACTACGATCAC
1 #2	GAAGGAATTTAAATTGGAAG	C	CATAGTAACCTCGGGAACCC
1 #3	ACTTTAAAATGTGAGAGGG	TT	AAAAGGCTCAGGGACGGGT
3 #1	GCCACAGCTGTGGCTGCTGCT		GCTGAAATTTAAATGCCTCT
14 #1	TCAATTTGAGGTCTGTTTGT		AtAGCTCAGTCTCCGGCTATC

Junction sequences are those that cannot be definitively assigned to c-myc or IgH. Lower case letters indicate mutations, and insertions are in italics. The translocations are annotated as the mouse number followed by the translocation number for that mouse. For example "2 #2" is mouse 2 translocation number two amplified from that mouse. Jnc., junction.

recombination in their etiology. This idea is supported by experiments in mice deficient in DNA damage response and apoptosis pathways that develop spontaneous lymphomas harboring oncogenic translocations involving the *TCR* or *IgH* locus (1, 2, 49–53). For example, ataxia telangiectasia mutated mice (*ATM*^{-/-}) develop thymic lymphomas with *TCR* gene translocations (54–58). These translocations can be ascribed to V(D)J recombination because they fail to occur in the absence of RAG expression (51, 53). Similarly, mice deficient in p53 and nonhomologous end joining factors or histone H2AX develop RAG-dependent translocations that lead to pro-B cell lymphomas (1, 2, 49, 50, 52, 59–63).

However, some translocation breakpoints in proximity of RSS are found in mature B cell tumors, such as endemic Burkitt's lymphoma, diffuse large B cell lymphoma, and multiple myeloma (for review see references 7, 8, and 43). These translocations are believed to arise during or after the germinal center reaction because the Ig genes involved in the translocations are usually somatically mutated (7). Nevertheless, they could be mediated by V(D)J recombination if RAG1/2 were reexpressed in the germinal center. An alternative possibility is that the translocations to the Ig V-J_H region in mature B cells are byproducts of double-strand DNA breaks created by AID during SHM.

Although double-strand breaks are not obligate intermediates in SHM, a measurable fraction of all Ig hypermutations involve deletions or insertions that require repair of double-strand breaks (36, 37). A region spanning 1–2 kbp downstream of Ig V_H genes undergoes somatic mutation at a rate of 10⁻³ per basepair per generation in germinal center B cells (for review see reference 12) (47). Given the large numbers

of B cells in the germinal center and their rapid rates of division, AID-induced double-strand breaks in the Ig V-J_H region are not infrequent events (36–39). However, to date

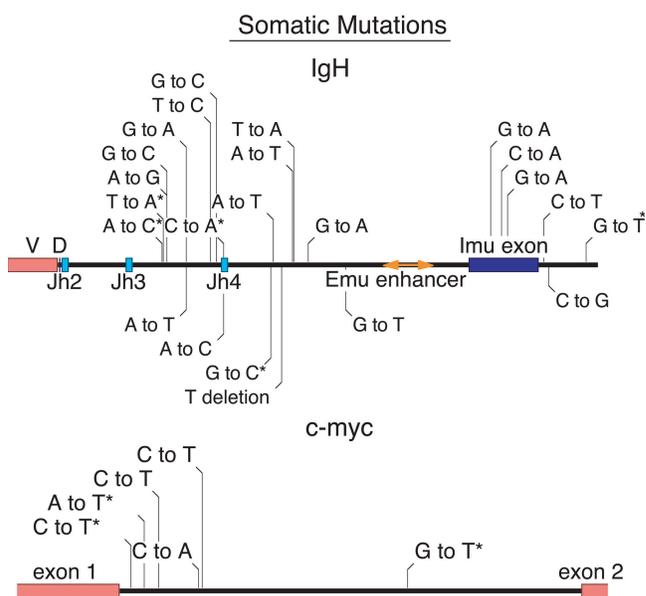


Figure 4. Somatic mutations in translocated IgH. Analysis of 32,654 bp of IgH sequence from c-myc/IgH translocations identified 20 different mutations (mutation frequency = 0.61×10^{-3}), excluding the two mutations found within 4 nts of breakpoints. Excluding the three mutations within 3 nts of the breakpoint, analysis of 16,960 bp of c-myc identified three different mutations (mutation frequency = 0.18×10^{-3}). The overall mutation rate within 20 nts of a breakpoint on either side of the translocation was 5.4×10^{-3} . Asterisks indicate mutations within 20 nts of a breakpoint.

there has been no direct evidence for the role of AID-dependent Ig V-J_H region breaks in chromosome rearrangement.

AID induces *c-myc* translocations to the Ig switch region by a mechanism that resembles class switching in that formation of the initial lesion requires cytidine deamination and uracil removal from DNA (25). However, resolution of the lesion proceeds by distinct pathways for switching and translocation (25). Factors that act in cis to promote switch region synapsis, such as 53BP1 and H2AX, have no impact on *c-myc* to Ig switch translocations despite their effects on genomic stability (25, 64). In contrast, factors that transmit damage signals to the nucleus, such as p53, do not appear to affect switching but are essential in suppressing Ig switch translocations, possibly by promoting the death of cells that overexpress *c-myc* (65, 66).

We have shown that mature B cells in *IL-6* tg mice develop translocations involving *c-myc* and the Ig V-J_H region and that they are AID dependent. These rearrangements closely resemble those found in endemic Burkitt's lymphoma, multiple myeloma, and diffuse large B cell lymphoma in that both of the translocated genes are hypermutated (for review see references 7 and 8). Ig V-J_H regions are direct targets of AID, which is likely to produce the DNA double-strand break intermediates in the translocation reaction. Although translocated *c-myc* was also mutated, germline *c-myc* is not thought to be a target for AID (28), and *c-myc* mutation was substantially lower than the Ig partner. We speculate that *c-myc* mutation may have occurred after the translocation when it was under the control of Ig regulatory elements (28, 48, 67, 68).

The higher level of mutation we found proximal to the translocation breakpoints is analogous to what is observed for switch region junctions (69). However, the mutation breakpoints proximal to the *c-myc* to Ig V-J_H region translocations are not RGYW hotspot biased and differ from breakpoint distal mutations in that they are not enriched for transitions. This suggests that the higher mutation frequency within 20 nts of the junction is the result of error-prone repair by non-homologous end joining, whereas many of the mutations further away from the breakpoint are AID induced.

We conclude that translocations involving the Ig V-J_H region of the Ig locus can be attributed to lesions produced by AID.

MATERIALS AND METHODS

DNA preparation and PCR. Hyperplastic lymph nodes from individual male and female *IL-6* tg (14) and *AID*^{-/-}*IL-6* tg (12) mice were combined into four pools. Total DNA was prepared from 2 × 10⁷ cells for each pool. 0.5 × 10⁶ cells from each of the four pools for 12 different mice was assayed for derivative 12 translocations by PCR using primer set 1 and 2.5 × 10⁶ cells using primer set 2 (see below). For derivative 15 translocations, 0.5 × 10⁶ cells from each of the four pools from 12 different mice was amplified using set 3 (see below).

For derivative 12 translocations from *c-myc* to the IgH variable region, we performed nested PCR (Long Expand PCR system; Roche) using the following primers: primer set 1: first round with 5-GCAATGACT-GAAGACTCAGTCCCTCTTAAG-3 (*IgH*) and ACTTAGCCCTGC-AGACGCCAGGAATCGCC (*c-myc*), followed by nested PCR with

TACCATTGCGGTGCTGGTTTCGGAGAGG (*IgH*) and TTGGCT-TCAGAGGCTGAGGGAGGCGACTG (*c-myc*); primer set 2: first round with GTGCCCACTCCACTCTTTGTCCCTATGC (*IgH*) and GAAA-TAAAAGGGGAGGGGGTGTCAAATAATAAGAG (*c-myc*), followed by nested PCR with ATCATCCAGGGACTCCACCAACACCATCAC (*IgH*) and CCTCCCTTCTACTACTTAAACCGCGACGCCAC (*c-myc*). 500 ng DNA (10⁵ cells) was amplified in each 20 μl first-round PCR reaction; 1 μl of the first reaction was template for the nested PCR reaction. PCR conditions for the first round were 94°C for the first 2 min, followed by 10 cycles of 94°C for 30 s, 61°C for 30 s, and 68°C for 7 min, followed by 19 cycles of 94°C for 30 s, 61°C for 30 s, 68°C for 7 min plus 20 s/cycle. The conditions for the nested PCR were as follows: 94°C for 15 s, 61°C for 30 s, 68°C for 4 min, followed by 15 cycles of 94°C for 30 s, 61°C for 30 s, 68°C for 4 min plus 20 s/cycle. The combined total number of cycles of amplification was 45.

Conditions for amplification of derivative 15 translocations from *c-myc* to the *IgH* variable region were the same as those for derivative 12, with the exception of a 2-min extension time in the first-round PCR and a 1-min extension time in the nested PCR. Amplification of derivative 15 translocations was performed using the following primers: primer set 3: GTTGAGACATGGGTCTGGGTACAGGGAC (*IgH*) and ATCAGCGGCC-GCAACCCTCGCCGCCGC (*c-myc*), followed by a nested PCR reaction with CTCTGCTGCTGGTCTGTGGTGACATTAG (*IgH*) and GAAG-CTGGATTTCCTTTGGGCGTTGG (*c-myc*).

For amplification of derivative 12 *c-myc* to switch region translocations, primers described previously (24) were used following the PCR conditions described above for primer set 1.

All animal experiments were performed in accordance with the rules and regulations of The Rockefeller University Institutional Laboratory of Animal Care and Use committee.

Southern blot analysis. PCR products from primer set 1 were separated on 0.8% agarose gels and denatured for 15 min in 0.4 M NaOH before transfer to nylon membranes and probing with P32 radiolabeled primers. The *IgH* probe sequence is GGTGGCAGAAGCCACAACCATAACATTCCCA, and the *c-myc* probe sequence is GCGCCTCGGCTCTTAGCAGACTGTAT.

Sequencing. The PCR reactions were separated on 0.8% agarose gels, and the bands were gel extracted using the QIAGEN gel extraction kit according to the manufacturer's instructions and sent for direct sequencing. Translocations were sequenced with the nested PCR primers. If the translocation breakpoint was not identified with the first round of sequencing, we designed new primers for sequencing to walk along the translocation until we reached the breakpoint.

Sequence analysis. PCR products were sent directly for sequencing without cloning so that we could discount the error rate of the polymerase in our analysis. Mutations that arose during early PCR cycles could be identified by chromatogram analysis by the presence of more than one base signal for the same nucleotide. Such nucleotides were discounted from our analysis. All sequenced translocations were aligned using both SeqMan from DNA Star and the Codon Code Aligner software. Overlapping traces from all the translocation sequences allowed for distinction between real mutations and single nucleotide polymorphisms. In the case of *c-myc*, we also amplified and sequenced the first intron from the *IL-6* tg mouse to verify that the *c-myc* mutations identified were not single nucleotide polymorphisms.

FACS analysis. FACS analysis was conducted as described previously (24). All antibodies were from BD Biosciences.

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REFERENCES

- Zhu, C., K.D. Mills, D.O. Ferguson, C. Lee, J. Manis, J. Fleming, Y. Gao, C.C. Morton, and F.W. Alt. 2002. Unrepaired DNA breaks in p53-deficient cells lead to oncogenic gene amplification subsequent to translocations. *Cell*. 109:811–821.
- Difilippantonio, M.J., S. Petersen, H.T. Chen, R. Johnson, M. Jasin, R. Kanaar, T. Ried, and A. Nussenzweig. 2002. Evidence for replicative repair of DNA double-strand breaks leading to oncogenic translocation and gene amplification. *J. Exp. Med.* 196:469–480.
- Richardson, C., and M. Jasin. 2000. Frequent chromosomal translocations induced by DNA double-strand breaks. *Nature*. 405:697–700.
- Franco, S., F.W. Alt, and J.P. Manis. 2006. Pathways that suppress programmed DNA breaks from progressing to chromosomal breaks and translocations. *DNA Repair (Amst.)*. 5:1030–1041.
- Schatz, D.G., M.A. Oettinger, and D. Baltimore. 1989. The V(D)J recombination activating gene, RAG-1. *Cell*. 59:1035–1048.
- Oettinger, M.A., D.G. Schatz, C. Gorka, and D. Baltimore. 1990. RAG-1 and RAG-2, adjacent genes that synergistically activate V(D)J recombination. *Science*. 248:1517–1523.
- Shaffer, A.L., A. Rosenwald, and L.M. Staudt. 2002. Lymphoid malignancies: the dark side of B-cell differentiation. *Nat. Rev. Immunol.* 2:920–932.
- Kuppers, R., and R. Dalla-Favera. 2001. Mechanisms of chromosomal translocations in B cell lymphomas. *Oncogene*. 20:5580–5594.
- Muramatsu, M., K. Kinoshita, S. Fagarasan, S. Yamada, Y. Shinkai, and T. Honjo. 2000. Class switch recombination and hypermutation require activation-induced cytidine deaminase (AID), a potential RNA editing enzyme. *Cell*. 102:553–563.
- Revy, P., T. Muto, Y. Levy, F. Geissmann, A. Plebani, O. Sanal, N. Catalan, M. Forveille, R. Dufourcq-Labeau, A. Gennery, et al. 2000. Activation-induced cytidine deaminase (AID) deficiency causes the autosomal recessive form of the Hyper-IgM syndrome (HIGM2). *Cell*. 102:565–575.
- Muramatsu, M., V.S. Sankaranand, S. Anant, M. Sugai, K. Kinoshita, N.O. Davidson, and T. Honjo. 1999. Specific expression of activation-induced cytidine deaminase (AID), a novel member of the RNA-editing deaminase family in germinal center B cells. *J. Biol. Chem.* 274:18470–18476.
- Barreto, V.M., A.R. Ramiro, and M.C. Nussenzweig. 2005. Activation-induced deaminase: controversies and open questions. *Trends Immunol.* 26:90–96.
- Neuberger, M.S., R.S. Harris, J. Di Noia, and S.K. Petersen-Mahrt. 2003. Immunity through DNA deamination. *Trends Biochem. Sci.* 28:305–312.
- Honjo, T., H. Nagaoka, R. Shinkura, and M. Muramatsu. 2005. AID to overcome the limitations of genomic information. *Nat. Immunol.* 6:655–661.
- Adams, J.M., S. Gerondakis, E. Webb, J. Mitchell, O. Bernard, and S. Cory. 1982. Transcriptionally active DNA region that rearranges frequently in murine lymphoid tumors. *Proc. Natl. Acad. Sci. USA*. 79:6966–6970.
- Crews, S., R. Barth, L. Hood, J. Prehn, and K. Calame. 1982. Mouse c-myc oncogene is located on chromosome 15 and translocated to chromosome 12 in plasmacytomas. *Science*. 218:1319–1321.
- Dalla-Favera, R., S. Martinotti, R.C. Gallo, J. Erikson, and C.M. Croce. 1983. Translocation and rearrangements of the c-myc oncogene locus in human undifferentiated B-cell lymphomas. *Science*. 219:963–967.
- Erikson, J., A. ar-Rushdi, H.L. Drwina, P.C. Nowell, and C.M. Croce. 1983. Transcriptional activation of the translocated c-myc oncogene in burkitt lymphoma. *Proc. Natl. Acad. Sci. USA*. 80:820–824.
- Hamlyn, P.H., and T.H. Rabbitts. 1983. Translocation joins c-myc and immunoglobulin gamma 1 genes in a Burkitt lymphoma revealing a third exon in the c-myc oncogene. *Nature*. 304:135–139.
- Marcu, K.B., L.J. Harris, L.W. Stanton, J. Erikson, R. Watt, and C.M. Croce. 1983. Transcriptionally active c-myc oncogene is contained within NIARD, a DNA sequence associated with chromosome translocations in B-cell neoplasia. *Proc. Natl. Acad. Sci. USA*. 80:519–523.
- Stanton, L.W., R. Watt, and K.B. Marcu. 1983. Translocation, breakage and truncated transcripts of c-myc oncogene in murine plasmacytomas. *Nature*. 303:401–406.
- Taub, R., I. Kirsch, C. Morton, G. Lenoir, D. Swan, S. Tronick, S. Aaronson, and P. Leder. 1982. Translocation of the c-myc gene into the immunoglobulin heavy chain locus in human Burkitt lymphoma and murine plasmacytoma cells. *Proc. Natl. Acad. Sci. USA*. 79:7837–7841.
- Petersen, S., R. Casellas, B. Reina-San-Martin, H.T. Chen, M.J. Difilippantonio, P.C. Wilson, L. Hanitsch, A. Celeste, M. Muramatsu, D.R. Pilch, et al. 2001. AID is required to initiate Nbs1/gamma-H2AX focus formation and mutations at sites of class switching. *Nature*. 414:660–665.
- Ramiro, A.R., M. Jankovic, T. Eisenreich, S. Difilippantonio, S. Chen-Kiang, M. Muramatsu, T. Honjo, A. Nussenzweig, and M.C. Nussenzweig. 2004. AID is required for c-myc/IgH chromosome translocations in vivo. *Cell*. 118:431–438.
- Ramiro, A.R., M. Jankovic, E. Callen, S. Difilippantonio, H.T. Chen, K.M. McBride, T.R. Eisenreich, J. Chen, R.A. Dickens, S.W. Lowe, et al. 2006. Role of genomic instability and p53 in AID-induced c-myc-IgH translocations. *Nature*. 440:105–109.
- Pasqualucci, L., P. Neumeister, T. Goossens, G. Nanjangud, R.S. Chaganti, R. Kuppers, and R. Dalla-Favera. 2001. Hypermutation of multiple proto-oncogenes in B-cell diffuse large-cell lymphomas. *Nature*. 412:341–346.
- Pasqualucci, L., A. Migliazza, N. Fracchiolla, C. William, A. Neri, L. Baldini, R.S. Chaganti, U. Klein, R. Kuppers, K. Rajewsky, and R. Dalla-Favera. 1998. BCL-6 mutations in normal germinal center B cells: evidence of somatic hypermutation acting outside Ig loci. *Proc. Natl. Acad. Sci. USA*. 95:11816–11821.
- Shen, H.M., A. Peters, B. Baron, X. Zhu, and U. Storb. 1998. Mutation of BCL-6 gene in normal B cells by the process of somatic hypermutation of Ig genes. *Science*. 280:1750–1752.
- Gordon, M.S., C.M. Kanegai, J.R. Doerr, and R. Wall. 2003. Somatic hypermutation of the B cell receptor genes B29 (Igbeta, CD79b) and mb1 (Ialpha, CD79a). *Proc. Natl. Acad. Sci. USA*. 100:4126–4131.
- Muschen, M., D. Re, B. Jungnickel, V. Diehl, K. Rajewsky, and R. Kuppers. 2000. Somatic mutation of the CD95 gene in human B cells as a side-effect of the germinal center reaction. *J. Exp. Med.* 192:1833–1840.
- Kotani, A., N. Kakazu, T. Tsuruyama, I.M. Okazaki, M. Muramatsu, K. Kinoshita, H. Nagaoka, D. Yabe, and T. Honjo. 2007. Activation-induced cytidine deaminase (AID) promotes B cell lymphomagenesis in Emu-cmyc transgenic mice. *Proc. Natl. Acad. Sci. USA*. 104:1616–1620.
- Okazaki, I.M., H. Hiai, N. Kakazu, S. Yamada, M. Muramatsu, K. Kinoshita, and T. Honjo. 2003. Constitutive expression of AID leads to tumorigenesis. *J. Exp. Med.* 197:1173–1181.
- Matsumoto, Y., H. Marusawa, K. Kinoshita, Y. Endo, T. Kou, T. Morisawa, T. Azuma, I.M. Okazaki, T. Honjo, and T. Chiba. 2007. Helicobacter pylori infection triggers aberrant expression of activation-induced cytidine deaminase in gastric epithelium. *Nat. Med.* 13:470–476.
- Endo, Y., H. Marusawa, K. Kinoshita, T. Morisawa, T. Sakurai, I.M. Okazaki, K. Watashi, K. Shimotohno, T. Honjo, and T. Chiba. 2007. Expression of activation-induced cytidine deaminase in human hepatocytes via NF-kappaB signaling. *Oncogene*. In press.
- Petersen-Mahrt, S.K., R.S. Harris, and M.S. Neuberger. 2002. AID mutates E. coli suggesting a DNA deamination mechanism for antibody diversification. *Nature*. 418:99–103.
- Goossens, T., U. Klein, and R. Kuppers. 1998. Frequent occurrence of deletions and duplications during somatic hypermutation: implications for oncogene translocations and heavy chain disease. *Proc. Natl. Acad. Sci. USA*. 95:2463–2468.
- Wilson, P.C., O. de Bouteiller, Y.J. Liu, K. Potter, J. Banchereau, J.D. Capra, and V. Pascual. 1998. Somatic hypermutation introduces insertions and deletions into immunoglobulin V genes. *J. Exp. Med.* 187:59–70.
- Sale, J.E., and M.S. Neuberger. 1998. TdT-accessible breaks are scattered over the immunoglobulin V domain in a constitutively hypermutating B cell line. *Immunity*. 9:859–869.

39. Papavasiliou, F.N., and D.G. Schatz. 2000. Cell-cycle-regulated DNA double-stranded breaks in somatic hypermutation of immunoglobulin genes. *Nature*. 408:216–221.
40. Bross, L., M. Muramatsu, K. Kinoshita, T. Honjo, and H. Jacobs. 2002. DNA double-strand breaks: prior to but not sufficient in targeting hypermutation. *J. Exp. Med.* 195:1187–1192.
41. Papavasiliou, F.N., and D.G. Schatz. 2002. The activation-induced deaminase functions in a postcleavage step of the somatic hypermutation process. *J. Exp. Med.* 195:1193–1198.
42. Bross, L., and H. Jacobs. 2003. DNA double strand breaks occur independent of AID in hypermutating Ig genes. *Clin. Dev. Immunol.* 10:83–89.
43. Bergsagel, P.L., and W.M. Kuehl. 2001. Chromosome translocations in multiple myeloma. *Oncogene*. 20:5611–5622.
44. Yu, W., H. Nagaoka, M. Jankovic, Z. Misulovin, H. Suh, A. Rolink, F. Melchers, E. Meffre, and M.C. Nussenzweig. 1999. Continued RAG expression in late stages of B cell development and no apparent re-induction after immunization. *Nature*. 400:682–687.
45. Suematsu, S., T. Matsusaka, T. Matsuda, S. Ohno, J. Miyazaki, K. Yamamura, T. Hirano, and T. Kishimoto. 1992. Generation of plasmacytomas with the chromosomal translocation t(12;15) in interleukin 6 transgenic mice. *Proc. Natl. Acad. Sci. USA*. 89:232–235.
46. Kovalchuk, A.L., J.S. Kim, S.S. Park, A.E. Coleman, J.M. Ward, H.C. Morse III, T. Kishimoto, M. Potter, and S. Janz. 2002. IL-6 transgenic mouse model for extraosseous plasmacytoma. *Proc. Natl. Acad. Sci. USA*. 99:1509–1514.
47. McKean, D., K. Huppi, M. Bell, L. Staudt, W. Gerhard, and M. Weigert. 1984. Generation of antibody diversity in the immune response of BALB/c mice to influenza virus hemagglutinin. *Proc. Natl. Acad. Sci. USA*. 81:3180–3184.
48. Bemark, M., and M.S. Neuberger. 2000. The c-MYC allele that is translocated into the IgH locus undergoes constitutive hypermutation in a Burkitt's lymphoma line. *Oncogene*. 19:3404–3410.
49. Difilippantonio, M.J., J. Zhu, H.T. Chen, E. Meffre, M.C. Nussenzweig, E.E. Max, T. Ried, and A. Nussenzweig. 2000. DNA repair protein Ku80 suppresses chromosomal aberrations and malignant transformation. *Nature*. 404:510–514.
50. Gao, Y., D.O. Ferguson, W. Xie, J.P. Manis, J. Sekiguchi, K.M. Frank, J. Chaudhuri, J. Horner, R.A. DePinho, and F.W. Alt. 2000. Interplay of p53 and DNA-repair protein XRCC4 in tumorigenesis, genomic stability and development. *Nature*. 404:897–900.
51. Liao, M.J., and T. Van Dyke. 1999. Critical role for Atm in suppressing V(D)J recombination-driven thymic lymphoma. *Genes Dev.* 13:1246–1250.
52. Gladly, R.A., M.D. Taylor, C.J. Williams, I. Grandal, J. Karaskova, J.A. Squire, J.T. Rutka, C.J. Gidos, and J.S. Danks. 2003. The RAG-1/2 endonuclease causes genomic instability and controls CNS complications of lymphoblastic leukemia in p53/Prkdc-deficient mice. *Cancer Cell*. 3:37–50.
53. Petiniot, L.K., Z. Weaver, M. Vacchio, R. Shen, D. Wangsa, C. Barlow, M. Eckhaus, S.M. Steinberg, A. Wynshaw-Boris, T. Ried, and R.J. Hodes. 2002. RAG-mediated V(D)J recombination is not essential for tumorigenesis in Atm-deficient mice. *Mol. Cell. Biol.* 22:3174–3177.
54. Borghesani, P.R., F.W. Alt, A. Bottaro, L. Davidson, S. Aksoy, G.A. Rathbun, T.M. Roberts, W. Swat, R.A. Segal, and Y. Gu. 2000. Abnormal development of Purkinje cells and lymphocytes in Atm mutant mice. *Proc. Natl. Acad. Sci. USA*. 97:3336–3341.
55. Elson, A., Y. Wang, C.J. Daugherty, C.C. Morton, F. Zhou, J. Campos-Torres, and P. Leder. 1996. Pleiotropic defects in ataxia-telangiectasia protein-deficient mice. *Proc. Natl. Acad. Sci. USA*. 93:13084–13089.
56. Xu, Y., T. Ashley, E.E. Brainerd, R.T. Bronson, M.S. Meyn, and D. Baltimore. 1996. Targeted disruption of ATM leads to growth retardation, chromosomal fragmentation during meiosis, immune defects, and thymic lymphoma. *Genes Dev.* 10:2411–2422.
57. Barlow, C., S. Hirotsune, R. Paylor, M. Liyanage, M. Eckhaus, F. Collins, Y. Shiloh, J.N. Crawley, T. Ried, D. Tagle, and A. Wynshaw-Boris. 1996. Atm-deficient mice: a paradigm of ataxia telangiectasia. *Cell*. 86:159–171.
58. Liyanage, M., Z. Weaver, C. Barlow, A. Coleman, D.G. Pankratz, S. Anderson, A. Wynshaw-Boris, and T. Ried. 2000. Abnormal rearrangement within the alpha/delta T-cell receptor locus in lymphomas from Atm-deficient mice. *Blood*. 96:1940–1946.
59. Gidos, C.J., C.J. Williams, I. Grandal, G. Knowles, M.T. Huang, and J.S. Danks. 1996. V(D)J recombination activates a p53-dependent DNA damage checkpoint in scid lymphocyte precursors. *Genes Dev.* 10:2038–2054.
60. Nacht, M., A. Strasser, Y.R. Chan, A.W. Harris, M. Schlissel, R.T. Bronson, and T. Jacks. 1996. Mutations in the p53 and SCID genes cooperate in tumorigenesis. *Genes Dev.* 10:2055–2066.
61. Vanasse, G.J., J. Halbrook, S. Thomas, A. Burgess, M.F. Hoekstra, C.M. Distech, and D.M. Willerford. 1999. Genetic pathway to recurrent chromosome translocations in murine lymphoma involves V(D)J recombinase. *J. Clin. Invest.* 103:1669–1675.
62. Celeste, A., S. Petersen, P.J. Romanienko, O. Fernandez-Capetillo, H.T. Chen, O.A. Sedelnikova, B. Reina-San-Martin, V. Coppola, E. Meffre, M.J. Difilippantonio, et al. 2002. Genomic instability in mice lacking histone H2AX. *Science*. 296:922–927.
63. Bassing, C.H., H. Suh, D.O. Ferguson, K.F. Chua, J. Manis, M. Eckersdorff, M. Gleason, R. Bronson, C. Lee, and F.W. Alt. 2003. Histone H2AX: a dosage-dependent suppressor of oncogenic translocations and tumors. *Cell*. 114:359–370.
64. Franco, S., M. Gostissa, S. Zha, D.B. Lombard, M.M. Murphy, A.A. Zarrin, C. Yan, S. Tepsuporn, J.C. Morales, M.M. Adams, et al. 2006. H2AX prevents DNA breaks from progressing to chromosome breaks and translocations. *Mol. Cell*. 21:201–214.
65. Bartkova, J., N. Rezaei, M. Liontos, P. Karakaidos, D. Kletsas, N. Issaeva, L.V. Vassiliou, E. Kolettas, K. Niforou, V.C. Zoumpourlis, et al. 2006. Oncogene-induced senescence is part of the tumorigenesis barrier imposed by DNA damage checkpoints. *Nature*. 444:633–637.
66. Christophorou, M.A., I. Ringshausen, A.J. Finch, L.B. Swigart, and G.I. Evan. 2006. The pathological response to DNA damage does not contribute to p53-mediated tumour suppression. *Nature*. 443:214–217.
67. Rabbitts, T.H., A. Forster, P. Hamlyn, and R. Baer. 1984. Effect of somatic mutation within translocated c-myc genes in Burkitt's lymphoma. *Nature*. 309:592–597.
68. Taub, R., C. Moulding, J. Battey, W. Murphy, T. Vasicek, G.M. Lenoir, and P. Leder. 1984. Activation and somatic mutation of the translocated c-myc gene in burkitt lymphoma cells. *Cell*. 36:339–348.
69. Schrader, C.E., S.P. Bradley, J. Vardo, S.N. Mochegova, E. Flanagan, and J. Stavnezer. 2003. Mutations occur in the Ig Smu region but rarely in Sgamma regions prior to class switch recombination. *EMBO J.* 22:5893–5903.