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Philadelphia chromosome–like acute lymphoblastic leukemia (Ph-like ALL) is a high-risk ALL commonly associated with alterations that affect the tyrosine kinase pathway, tumor suppressors, and lymphoid transcription factors. Loss-of-function mutations in the gene-encoding adaptor protein LNK (also known as SH2B3) are found in Ph-like ALLs; however, it is not clear how LNK regulates normal B cell development or promotes leukemogenesis. Here, we have shown that combined loss of *Lnk* and tumor suppressors *Tp53* or *Ink4a/Arf* in mice triggers a highly aggressive and transplantable precursor B-ALL. *Tp53*−/−*Lnk*−/− B-ALLs displayed similar gene expression profiles to human Ph-like B-ALLs, supporting use of this model for preclinical and molecular studies. Preleukemic *Tp53*−/−*Lnk*−/− pro-B progenitors were hypersensitive to IL-7, exhibited marked self-renewal in vitro and in vivo, and were able to initiate B-ALL in transplant recipients. Mechanistically, we demonstrated that LNK regulates pro-B progenitor homeostasis by attenuating IL-7–stimulated JAK/STAT5 signaling via a direct interaction with phosphorylated JAK3. Moreover, JAK inhibitors were effective in prolonging survival of mice transplanted with *Lnk*−/−*Tp53*−/− leukemia. Additionally, synergistic administration of PI3K/mTOR and JAK inhibitors further abrogated leukemia development. Hence, our results suggest that LNK suppresses IL-7R/JAK/STAT signaling to restrict pro-/pre-B progenitor expansion and leukemia development, providing a pathogenic mechanism and a potential therapeutic approach for B-ALLs with *LNK* mutations.

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LNK/SH2B3 regulates IL-7 receptor signaling in normal and malignant B-progenitors

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Acute lymphoblastic leukemia (ALL) is the leading cause of cancer-related death in young people and commonly has a poor outcome in adults. Gene profiling and exome sequencing of clinically high-risk ALLs have led to the recent identification of the Philadelphia chromosome–like (Ph-like) ALL subtype (1–3). This subtype exhibits a gene expression profile similar to Ph-positive ALL and exhibits similar clinical behavior to Ph-positive ALL, but it lacks a BCR-ABL1 rearrangement. The Ph-like ALL subgroup comprises 10%–15% of pediatric ALL and is thus 3–4 times more common than Ph-positive ALL in children (4, 5). A recent large-scale genomic analysis on 1,725 patients with B cell precursor ALL (BCP-ALL) found that the prevalence of Ph-like ALL increases with age, from 10% among children with standard-risk ALL to 27% among young adults with ALL, and is associated with a poor outcome (6). Children and adults with Ph-like ALL have an extremely high risk of relapse and poor survival when treated with conventional chemotherapy.

Three major signaling pathways are found perturbed in high-risk ALLs, the TP53/RB pathway predominantly involving deletions of CDKN2A/CDKN2B, loss of function mutations/deletions of lymphoid transcription factors IKZF1 and PAX5, and tyrosine kinase activation lesions (6, 7). Most Ph-like ALL–associated mutations/deletions/translocations identified to date are known or predicted to activate oncogenic cytokine receptor signaling, particularly of JAK-associated pathways. Approximately half of Ph-like ALLs have CRLF2 (cytokine receptor-like factor 2) rearrangements resulting in overexpression of CRLF2, many of which have concomitant gain-of-function (GOF) alterations in JAK pathway–associated genes, including JAK1, JAK2, and IL7RA (IL-7 receptor α chain) (2, 8–12). IL-7 binds to IL-7Rα and γc chain to activate STAT5. The CRLF2 protein heterodimerizes with the IL-7Rα chain to create the thymic stromal lymphopoietin receptor (TSLPR) and binds its ligand, TSLP (13, 14). TSLP likely activates STAT5 through JAK2 (15–18). Constitutive activations of STAT5, S6, and/or ERK are induced in murine pro-B lymphoma Ba/F3 cell lines transduced with human ALL–specific JAK and/or IL7RA or CRLF2 mutations (8, 11, 12, 19–21).

The lymphocyte adaptor protein LNK (also called SH2B3) has emerged as a powerful and important negative regulator of cytokine signaling during hematopoiesis and B-lymphopoiesis. Lnk–/– mice exhibit a 3- to 5-fold elevation in wbc (22), increased prosurvival and immaturity B cells in the BM (23), and a marked expansion in the hematopoietic stem cell (HSC) pool (24, 25). Mechanistically, LNK attenuates cytokine signaling in multiple hematopoietic lineages. In the HSC compartment, LNK constrains HSC self-renewal largely through inhibition of thrombopoietin (TPO) and its receptor myeloproliferative leukemia protein–mediated (MPL/CD110-mediated) JAK2 activation (25–27). We previously reported that LNK directly interacts with JAK2 and that LNK deficiency potentiates JAK2 activation in HSCs (26). In the B cell

Introduction

Acute lymphoblastic leukemia (ALL) is the leading cause of cancer-related death in young people and commonly has a poor outcome in adults. Gene profiling and exome sequencing of clinically high-risk ALLs have led to the recent identification of the Philadelphia chromosome–like acute lymphoblastic leukemia (Ph-like ALL) is a high-risk ALL commonly associated with alterations that affect the tyrosine kinase pathway, tumor suppressors, and lymphoid transcription factors. Loss-of-function mutations in the gene-encoding adaptor protein LNK (also known as SH2B3) are found in Ph-like ALLs; however, it is not clear how LNK regulates normal B cell development or promotes leukemogenesis. Here, we have shown that combined loss of Lnk and tumor suppressors Tps5 or lnk4a/Arf in mice triggers a highly aggressive and transplantable precursor B-ALL. Tp53−/−Lnk−/− B-ALLs displayed similar gene expression profiles to human Ph-like B-ALLs, supporting use of this model for preclinical and molecular studies. Preleukemic Tp53−/−Lnk−/− pro-B progenitors were hypersensitive to IL-7, exhibited marked self-renewal in vitro and in vivo, and were able to initiate B-ALL in transplant recipients. Mechanistically, we demonstrated that LNK regulates pro-B progenitor homeostasis by attenuating IL-7–stimulated JAK/STAT5 signaling via a direct interaction with phosphorylated JAK3. Moreover, JAK inhibitors were effective in prolonging survival of mice transplanted with Lnk−/−Tp53−/− leukemia. Additionally, synergistic administration of PI3K/mTOR and JAK inhibitors further abrogated leukemia development. Hence, our results suggest that LNK suppresses IL-7R/JAK/STAT signaling to restrict pro-/pre-B progenitor expansion and leukemia development, providing a pathogenic mechanism and a potential therapeutic approach for B-ALLs with LNK mutations.

Conflict of interest: The authors have declared that no conflict of interest exists.
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lineage, LNK is thought to dampen stem cell factor (SCF) and its receptor c-KIT, IL-7/IL-7R, and FLT3 function (22, 23, 28); however, LNK-mediated signaling in B cells has not been fully examined. Neither is it known which JAK family members are regulated by LNK in lymphoid cells. Recently, somatic deletion/mutations in LNK (also known as SH2B3) were found in various B-ALLs and T-ALLs in children (2, 6, 29, 30). A recent sequencing effort identified kinase-activating alterations in 91% of Ph-like ALL patients. Chromosomal rearrangements involving ABL, JAK2, and CRLF2 and sequence mutations involving FLT3, IL-7R, or SH2B3 are most common (6). Specifically, 9 of 154 patients of pediatric and young adult Ph-like B-ALLs have mutations in SH2B3 (5.8%) (6). Furthermore, genetic loss of LNK contributes to pediatric ALL development (30), underscoring the importance of LNK in ALLs. However, the mechanisms by which it impacts ALL initiation or progression remain poorly understood.

In this report, we investigated mechanisms by which LNK regulates normal B cell and B-ALL development. We developed a B-ALL mouse model that resembles human Ph-like B-ALLs in a gene expression signature. Mechanistically, we found that LNK suppresses normal B progenitor cell and B-ALL development through downregulating IL-7–mediated JAK/STAT signaling. We also explored therapeutic strategies using this mouse model of B-ALL. Together, our studies enhance our understanding of Ph-like B-ALLs and provide insight into therapeutic strategies.

Results

**LNK synergizes with TP53 and INK4A/ARF in suppressing B-ALL development in mice.** We previously reported that Lnk−/− mice spontaneously develop chronic myelogenous leukemia–like (CML-like) myeloproliferative neoplasms (MPNs) upon aging (31). Furthermore, following the natural progression of these mice, we found that most Lnk−/− mice died of monocytic tumors around 1.5 years, while about 5% developed B-ALL at 2 years of age (Tables 1 and 2). Lnk−/− mice develop B-ALL at low penetrance and long latency, suggesting the need for cooperating events. To explore genetic interactions that could cooperate with Lnk deficiency in the development of ALL, we generated mice harboring mutations for both Lnk and tumor suppressors Tp53 or Inka4a/Arf. Tp53 is associated with poor diagnosis in many subtypes of B-ALL (32, 33). The human gene locus that encodes Inka4a/Arf, CDKN2A/CDKN2B, is highly mutated in Ph-like ALL, a subtype of high-risk ALL with poor prognosis (6, 7). We found that loss of 1 or 2 alleles of Lnk increased cancer-associated mortality in a gene dose–dependent manner when placed on Tp53 heterozygous or homozygous background, respectively (Figure 1A, with the statistical analysis shown in Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI81468DS1). Notably, Tp53−/− Lnk−/− mice died of B-ALL at almost 100% penetrance by 4 months, while mice deficient for Tp53 alone died of T-lymphoma or sarcoma after 6 months of age, as previously reported (refs. 34–36, Figure 1C, and Table 1). Similarly, Lnk deficiency exacerbated cancer-associated mortality on Inka4a/Arf heterozygous or homozygous background (Figure 1B, with the statistical analysis shown in Supplemental Table 2) and markedly increased the incidence of B-ALL in Inka4a/Arf−/− Lnk−/− mice (Figure 1D and Table 2). The B-ALL blasts filled the BM cavity and peripheral blood (PB) and infiltrated into spleen, lymph nodes, thymus, and— in some mice— liver, lung, and kidney (Figure 1E and data not shown). Further phenotyping of Tp53−/− Lnk−/− and Inka4a/Arf−/− Lnk−/− B-ALL cells revealed that they were precancer B-ALLs as determined by cell surface expression for B progenitor markers, CD19+IgM−CD43+IL-7R−AA4.1+Kit+ and aberrant downregulation of B220 (Figure 2A and Supplemental Figure 1). We transplanted a graded dose of sorted B-ALL blasts into sublethally irradiated mice, and the results showed that mice transplanted with as low as 300 B-ALL blasts succumbed in 1 month, indicating that Tp53−/− Lnk−/− and Inka4a/Arf−/− Lnk−/− B-ALLs are highly aggressive and transplantable malignancies (Figure 2, B and D), with leukemia-initiating cells at a frequency about approximately 1 in 200 (Figure 2, C and E). Our data thus establish that LNK synergizes with tumor suppressor TP53 and INK4A/ARF in suppressing B-ALL development in mice.

**Lnk loss of heterozygosity in B-ALLs.** It is important to note that about half of Tp53−/− Lnk−/− mice developed B-ALL, while the others developed T-lymphoma (Table 1). To determine Lnk loss-of-heterozygosity (LOH) status in these tumors, we assessed if the B-ALL cells from Tp53−/− Lnk−/− mice had lost the WT allele of Lnk using purified B-ALL cells, along with cells of myeloid, T lineages, and mature B lineages in the same animals. While myeloid and T cells, as well as normal mature CD19+B220−B cells, exhibited the germline genotype Tp53−/− Lnk−/−, B blasts were homozygous for Lnk in this genetic background (Figure 2).
Lnk deficiency synergizes with loss of tumor suppressors TP53 and INK4A/ARF to promote B-ALL. (A and B) Kaplan-Meier curves show the survival of p53/Lnk (n = 42–74 mice per group) (A) or Ink4aArf/Lnk (n = 12–40 mice per group) (B) mutant mice. Log-rank t tests are shown in Supplemental Tables 1 and 2. (C and D) The bar graphs depict the tumor incidences of p53/Lnk (C) or Ink4aArf/Lnk (D) mutant mice. n numbers are labeled on top of the bars. (E) Histology of p53−/−Lnk−/− B-ALLs are shown as Wright-Giemsa staining of BM cytospins (left, ×600 magnification), H&E staining of BM sections (middle, ×200), and IHC with anti-B220 antibodies (right, ×100).

Lnk deficiency synergizes with loss of tumor suppressors TP53 and INK4A/ARF to promote B-ALL. Of note, some mice transplanted with Tp53−/−Lnk−/− cells developed B-ALL along with T-lymphoma in the thymus (data not shown), suggesting that Lnk deficiency does not switch tumor types or suppress T-lymphoma; rather, it promotes B-ALL development. We next transplanted purified pro-B cells from preleukemic Tp53−/−Lnk−/− mice and found that, indeed, Tp53−/−Lnk−/− pro-B progenitors were able to initiate B-ALL (Figure 3C). Tp53−/−Lnk−/− B-ALLs resemble human Ph-like B-ALLs. To determine if Lnk−/−p53−/− B-ALLs exhibit similar molecular features to human B-ALL, we performed genome-wide expression profiling. We compared Lnk−/−p53−/− B blasts to pro-B/pre-B (B220−Ly-6M Nk1.1 Ly6C CD43−CD44−AA4.1−CD19−) cells isolated from WT, Lnk−/−, p53−/−, and preleukemic Lnk−/−p53−/− mice. Remarkably, gene set enrichment analysis (GSEA) (37) revealed that Lnk−/−p53−/− B blasts specifically exhibit gene signatures of human Ph-like B-ALL (ref. 6 and Figure 3D) and R8 subgroup of B-ALL with poor prognosis (3) but not other R1-R7 types (data not shown).

Tp53−/−Lnk−/− pro-B progenitors initiate B-ALL. To investigate the mechanisms by which Tp53/Lnk deficiency promotes B-ALL development, we set out to examine BM progenitor cells from young Tp53−/−Lnk−/− mice before any signs of malignancy, here referred to as preleukemic mice. We isolated LSK cells from young WT, Tp53−/−, Lnk−/−, and Tp53−/−Lnk−/− mice and transplanted 1,000 LSKs along with isogenic BM competitors into lethally irradiated recipients. All mice transplanted with preleukemic Tp53−/−Lnk−/− LSK cells succumbed to B-ALL within 3 months, while Tp53−/−transplanted mice died significantly later with T-lymphoma (Figure 3B). This result indicates that TP53/LNK suppresses B-ALL development in a cell-autonomous manner. Of note, some mice transplanted with Tp53−/−Lnk−/− cells developed B-ALL along with T-lymphoma in the thymus (data not shown), suggesting that Lnk deficiency does not switch tumor types or suppress T-lymphoma; rather, it promotes B-ALL development. We next transplanted purified pro-B cells from preleukemic Tp53−/−Lnk−/− mice and found that, indeed, Tp53−/−Lnk−/− pro-B progenitors were able to initiate B-ALL (Figure 3C).
LNK controls normal B cell and B-ALL development independently of the Mpl pathway or its effects in HSCs. We and others previously established that LNK regulates HSC homeostasis and self-renewal largely through limiting the TPO/MPL/JAK2 pathway (25–27). To determine if LNK plays a cell-autonomous role in B cells or if the B cell expansion is secondary to the HSC phenotype, we examined B cell development in Mpl−/−Lnk−/− mice. We found that Mpl−/−Lnk−/− mice exhibited reduced HSC number (Figure 4A), similar to Mpl−/− mice as we reported previously (26). In contrast, Mpl−/−Lnk−/− mice showed an expansion in B cells similarly to that in Lnk−/− mice (Figure 4B). Moreover, Tp53−/−Mpl−/−Lnk−/− triple-nullizygous mice developed B-ALL around 3 months with 100% penetrance and, interestingly, faster than Tp53−/− Lnk−/− double-nullizygous mice (Figure 4C), indicating that LNK controls normal B cell and B-ALL development independently of the MPL/JAK2 pathway or its effects in HSCs.

LNK regulates pro-B and pre-B homeostasis. We thus focused our study on the role of LNK in committed lymphoid progenitors, in particular B progenitors. We determined the numbers of lymphoid-primed multipotential progenitors (LMPP) (38), CLPs (39), pre–pro-B progenitors, pro-B, and pre-B cells in WT and Lnk−/− mice at both young and old ages using well-established cell surface markers by flow cytometry (40, 41). Our results suggest that Lnk deficiency did not affect LMPP, CLP, or pre-/pro-B progenitor numbers at the young age, nor did it affect the decline of these early lymphoid progenitors upon aging (Figure 5A and Supplemental Figure 3). Rather, pro-B cells were the earliest B progenitor stage elevated in Lnk−/− mice, and cells of later developmental stages — e.g., pre-B and immature B cells — were also correspondingly increased in the BM (Figure 5, B and C). Importantly, whereas WT pro-B cells declined upon aging (40, 42), Lnk−/− pro-B cells accumulated (Figure 5B), suggesting LNK also regulates pro-B cell aging. Moreover, we found that pro-B cells in young preleukemic Tp53−/−Lnk−/− mice were markedly increased in comparison with WT and single KO mice (Figure 5D). Thus, LNK regulates pro-B cell homeostasis and aging, and synergistic loss of Lnk and Tp53 leads to a further expansion of pro-B progenitors.

Lnk/Tp53 deficiency promotes B progenitor cell self-renewal and superior responses to IL-7. Since Tp53−/−Lnk−/− blasts bear surface markers resembling pro- and pre-B progenitors, we next assessed the self-renewal ability of pro-B cells (CD19+ B220+ IgM CD43+ AA4.1+) using serial replating assays. While WT or Lnk−/− pro-B cells did not replate in the presence of IL-7 and SCF, Tp53−/− and preleukemic Tp53−/−Lnk−/− pro-B cells replated for over 5 rounds (Figure 6A). Importantly, Tp53−/−Lnk−/− pro-B cells showed enhanced sensitivity to IL-7 compared with Tp53−/− cells in generating increased numbers of colonies (Figure 6B) and colonies with bigger sizes (Figure 6C). In liquid culture, Tp53−/−Lnk−/− pro-B cells expanded at a much faster rate and for a more extended period of time compared with Tp53−/− cells or cells of all other genotypes (Figure 6D). We further assessed pro-B progenitor proliferation and differentiation in vivo using adoptive transfers. At 3 weeks after BMT, we found that Tp53−/−Lnk−/− pro-B cells gave rise to markedly higher B cell reconstitution in host spleens compared with WT or single KO mice (Figure 6E), indicating that synergistic loss of Lnk and Tp53 enhances B cell expansion in vivo. Thus, our data suggested that Tp53/Lnk deficiency promotes B progenitor self-renewal and superior responses to IL-7.

Tp53−/−Lnk−/− mice survive over 400 days, we do not have enough mouse numbers to quantify tumor spectrum in these mice.

| Tumor spectrum and frequencies in Ink4aArflnk mutant mice are shown. Frequency of the tumor incidence is shown in the table, while the number of positive mice/total number of mice examined is shown in parentheses. Myeloid leukemia includes monocytic tumors. One mouse also had sarcoma. One mouse also had T-lymphoma. Since Ink4aArf−/− mice survive over 400 days, we do not have enough mouse numbers to quantify tumor spectrum in these mice. |
|---|---|---|---|---|
| Ink4aArf−/− | Sarcoma | Myeloid leukemia | B-ALL | B-ALL/Myeloid leukemia |
| Lnk−/− | 27.3% (3/11) | 72.7% (8/11) | 9.1% (1/11) | |
| Ink4aArf−/−Lnk−/− | 66.7% (4/6) | 33.3% (2/6) | | |
| Ink4aArf−/−Lnk+/− | 14.3% (3/21) | 19% (4/21) | 66.7% (14/21) | 4.8% (1/21) |
| Ink4aArf+/−Lnk+/− | 18.2% (2/11) | 81.8% (9/11) | | |
| Ink4aArf+/−Lnk−/− | 5.3% (1/19) | 68.4% (13/19) | 10.5% (2/19) | 15.8% (3/19) |
| Lnk−/− | 50% (18/36) | 3% (1/36) | 3% (1/36) | |
attesting the importance of Lnk-controlled JAK/STAT signaling in B progenitor homeostasis. While the preleukemic Lnk–/–p53–/– pro-B cells displayed slightly increased pSTAT5 intensity, the leukemic blasts showed markedly increased pSTAT5 upon IL-7 stimulation (Figure 7, B and D). This is manifested at both the 

Figure 2. p53–Lnk– and Ink4a/Arf–Lnk– B-ALLs are transplantable and have high leukemia-initiating cell frequencies. (A) Representative flow cytometric plots of p53–Lnk– and Ink4a/Arf–Lnk– mice with B-ALL, along with WT controls, are shown. (B and D) Kaplan–Meier curves show the survival of mice transplanted with a graded dose of B-ALL cells from p53–Lnk– (B) or Ink4a/Arf–Lnk– (D) mice. (C and E) The graph shows the limiting dilution analysis of mice transplanted with B-ALLs from various p53–Lnk– (C) or Ink4a/Arf–Lnk– (E) mice. n = 5 mice per dose. Different color lines represent different cell dosages injected in B and D. Different color lines represent different donor mice in C and E. The black horizontal dashed lines indicate 37% negative points, and the vertical lines that intersect with the horizontal lines mark the frequency. Estimated leukemia-initiating cell frequencies are shown for each donor.

tantly, Lnk–, but not p53–, pro-B cells exhibited enhanced response to IL-7 in activating STAT5 (56% vs. 35%), indicating Lnk deficiency promotes IL-7-mediated JAK/STAT signaling (Figure 7, B and C). Preleukemic Lnk–p53– pro-B cells showed similar percentage of pSTAT5+ cells compared with Lnk– pro-B,
level of amplitude (mean fluorescence intensity [MFI]) and the percentage of cells responded. Of note, we found that preleukemic Lnk–/–p53–/– B progenitors showed a slight increase, and leukemic blasts displayed a marked elevation in basal pSTAT5 activation (Figure 7E). Consistently, Leukemic Lnk–/–p53–/– blasts showed both basal and IL-7–induced activation of JAK1 and JAK3 but not JAK2 (Figure 7F). Altogether, our data indicate that the synergistic effects of Lnk and p53 loss result in enhanced IL-7/JAK/STAT signaling and B progenitor cell transformation.

**LNK interacts with phosphorylated JAK3.** We previously reported that the LNK SH2 domain directly interacts with phosphorylated JAK2 (pY813) upon TPO stimulation in HSPCs (26); however, how LNK interacts with the lymphoid signaling pathway has not been explored. Neither was it known which JAK family members were regulated by LNK in the IL-7R pathway, since IL-7R activates JAK1 and JAK3 but not JAK2 (Figure 7F). Altogether, our data indicate that the synergistic effects of Lnk and p53 loss result in enhanced IL-7/JAK/STAT signaling and B progenitor cell transformation.

**JAK inhibitors are effective in vivo and against Lnk–/–p53–/– leukemic blasts.** Our signaling studies suggest that LNK-regulated IL-7R/JAK/STAT signaling plays important roles in normal and

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**Figure 3.** p53–/–Lnk–/– pro-B progenitors initiate B-ALL, and Lnk–/–p53–/– B leukemic blasts resemble human Ph-like ALL. (A) LOH of the Lnk allele in p53–/–Lnk–/– mice. B-ALL blasts and normal myeloid, T cells, and mature B cells were purified by flow cytometric sorting (left panels), and subjected to PCR analysis of Lnk gene status (right panels). Various HSPC populations from p53–/–Lnk–/– mice were purified and subjected to PCR analysis for Lnk gene status (bottom right panel). LSK, HSPCs (Lin–Sca1+Kit+); LKS–, myeloid progenitors (Lin–Sca1+Kit+); CLPs, (Lin–IL-7R+Flt3+Kit–Sca1–). (B) Kaplan-Meier curves show the survival of mice transplanted with 1,000 LSK cells from 2-month-old Lnk–/–, p53–/–, or p53–/–Lnk–/– preleukemic mice. P value found using log-rank t test. n = 5 mice per group. (C) Kaplan-Meier curves show the survival of mice transplanted with 100,000 pro-B cells from young preleukemic p53–/–Lnk–/– mice. P value found using log-rank t test. n = 6 mice per group. (D) Enrichment plots of GSEA analysis using Lnk–/–p53–/– B leukemic blasts (4 samples) versus control B progenitors (1 sample) indicate that 3 WT, 3 Lnk–/–, 3 p53–/–, and 2 preleukemic p53–/–Lnk–/– mice) express data against Ph-like B-ALL gene signature from the previous publication (6). NES, normalized enrichment score; FDR, false discovery rate.
malignant B progenitors, which can be exploited for therapeutic purposes. This finding is corroborated with the results showing that JAK1/2 inhibitor ruxolitinib and JAK3/2 inhibitor tofacitinib inhibited STAT5 and ERK phosphorylation (Figure 9C and Supplemental Figure 6D). We tested a number of PI3K inhibitors, but not MEK inhibitors (selumetinib or trametinib), in combination with JAK inhibitors to further abrogate ALL cell growth. We found that PI3K inhibitors (NVP-BEZ235) synergized with ruxolitinib to abrogate ALL cell growth (Figure 9B and Supplemental Figure 6A). Inhibit-

Discussion

In this study, we aimed to unravel molecular mechanisms by which LNK controls B progenitor cell development and leukemic transformation and devise effective treatment strategies to eliminate leukemia cells with loss-of-function Lnk mutations. The work presented here provides new insights into LNK function in normal and malignant B progenitor cells. We demonstrated that LNK plays a pivotal role in prospero-B homeostasis and aging through regulating IL-7-mediated JAK/STAT signaling. Furthermore, LNK suppresses precursor B-ALL development in mice, and Lnk

Figure 4. LNK controls normal B cell and B-ALL development independently of Mpl pathway or its effects on HSCs. (A) Lnk–/–Mpl–/– double-null mice show decreased HSPC and myeloid progenitor compartments similar to Mpl–/– mice. LSK, Lin–Sca1–Kit– cell fraction that contains both HSCs and multipotential progenitors; CMP, common myeloid progenitor, Lin–Sca1–Kit–CD34–FcR–. **P < 0.01; ns, not significant, 2-tailed Student’s t test. n = 3–5 per group. (B) Lnk–/–Mpl–/– double-null mice show increased pre- and pro-B cell frequencies in the BM, similar to Lnk–/– mice. *P < 0.05; **P < 0.01; ns, not significant, 2-tailed Student’s t test. n = 3–4 per group. (C) p53–/–Lnk–/– triple-null mice develop aggressive B-ALL similarly to p53–/–Lnk–/–double-null mice. The left panel shows flow analysis of BM B-ALL cells in p53–/–Lnk–/– and p53–/–Lnk–/–Mpl–/– mice. P value found using log-rank t test. n = 6–12 mice per group.
Rearrangements involving ABL kinases, JAK2, and cytokine receptors and sequence mutations involving FLT3, IL7RA, or SH2B3 were most common (6). Our results show that LNK and TP53 or INK4A/ARF synergistically suppress B-ALL development in mice, implying that our mouse models are of clinical relevance. The superior responses to IL-7 and the hyperactivation of STAT5 pathway in Lnk–/–Tp53–/– B-ALLs are also consistent with the Ph-like high-risk B-ALL phenotype that is associated with dysregulated cytokine signaling. Furthermore, Lnk–/–Tp53–/– B-ALLs demonstrate a gene expression signature similar to Ph-like B-ALL but not other subtypes, strongly arguing for a role of LNK in this subtype of B-ALL with underlying aberrant cytokine signaling. Of note, 5 of 9 patients with LNK mutations also harbor IL7R mutations (6). Therefore, our findings showing that LNK interacts with phosphorylated JAK3 that is activated by IL-7R may shed light on the molecular mechanism for this unique clinical connection between LNK and IL-7R.

JAK/STAT signaling pathway aberration is found in over 50% of Ph-like ALL. Whole-genome or whole-exome sequencing identified patients with mutations in multiple genes within the kinase signaling pathway, with evidence of subclonality in a majority of patients tested (6). Mutations in FLT3, IL7R, JAK1, JAK2, JAK3, NF1, NRAS, and PTPN11 were subclonal, and several cases harbored multiple subclonal mutations in the same pathway, indicating the presence of multiple subclones with distinct mutations activating JAK/STAT and/or RAS signaling. Interestingly, the mutant allele frequency (MAF) of SH2B3 is very high at 0.9, implicating a proliferative advantage of the ALL clone that harbor the mutant SH2B3 allele (6). This is consistent with our data showing that LOH in LNK is evident Lnk+/–Tp53–/– B-ALLs, but not in T-lymphomas. Together, these data suggest a pivotal role for Lnk in the transformation/progression of B-ALL development.

Recently, a large-scale sequencing effort found that Ph-like precursor B-ALL increases in frequency from 10% among children to 27% among young adults with ALL and is associated with a poor outcome (6). Ph-like B-ALLs show aberrations in 3 categories of genes: kinase signaling pathways, lymphoid transcription factors such as IKZF1 and PAX5, and tumor suppressors, namely the INK4A/ARF/TP53/RF pathway (6, 7). Kinase-activating alterations are the signature and defining feature of Ph-like ALL, which are found in 91% of the cases. Our data, along with clinical data showing that LNK (or SH2B3) mutations occur in high-risk ALL patients and are likely associated with aberrant cytokine signaling besides JAK and receptors themselves, suggests that LNK is a bona fide tumor suppressor. Our B-ALL mouse model shows a similar gene expression signature to that of human Ph-like B-ALL, in which LNK, JAK2, IL7R, and CRLF2 mutations have been commonly identified, indicating that Lnk-deficient B-ALL mouse model is relevant to this subtype of B-ALL that is associated with poor prognosis. Thus, our studies provide mechanistic and therapeutic insight into the aberrant signaling transduction underlying Ph-like high-risk B-ALLs with LNK mutations.
Figure 6. \(p53^{-/-}Lnk^{-/-}\) progenitor cells show increased self-renewal and superior responses to IL-7 in vitro and in vivo. (A) The serial replating abilities of purified pro-B cells from mice of 4 different genotypes in the presence of IL-7 and SCF are shown. Representative graph of 5 independent experiments is shown. (B) The colony formation ability of \(p53^{-/-}\) or \(p53^{-/-}Lnk^{-/-}\) pro-B cells at the 4th replating in different concentrations of IL-7 along with 20 ng/ml SCF are shown. Representative graph of 4 independent experiments is shown. (C) Photomicrograph of colonies plated in methylcellulose in different cytokine conditions \((\times 40)\). (D) Log growth of purified pro-B cells cultured on OP-9 stromal cells supplemented with IL-7/SCF/Flt3L. Representatives of 4 independent experiments are shown. (E) \(p53^{-/-}Lnk^{-/-}\) progenitor cells show increased ability to generate B cells in vivo. pro-B cells \((1 \times 10^5)\) were purified from 2-month-old WT, \(Lnk^{-/-}\), \(p53^{-/-}\), or \(p53^{-/-}Lnk^{-/-}\) mice; mixed with \(3 \times 10^5\) competitor BM cells; and transplanted into lethally irradiated recipients. Chimerisms of donor-derived IgM\(^{+}\)IgD\(^{-}\) mature and IgM\(^{-}\)IgD\(^{+}\) immature B cells in the spleen of the transplanted mice are shown. \(n = 4-6\) mice per group. Representative results from 2 independent experiments are shown. **\(P < 0.01\); ***\(P < 0.001\), 2-tailed Students’ t test.
Figure 7. Lnk deficiency enhances IL-7–induced STAT5 activation. (A) Representative flow plots of healthy preleukemic and leukemic pS3/lnk−/− BM cells stained with of anti-B220 and intracellular IgM (µ-heavy chain, IgM) antibodies after fixation. (B) Combined B220 and intracellular IgM staining divide B cells into subpopulations at differentiation stages, which correlate with distinct IL-7 responsiveness. BM cells were starved, stimulated with or without IL-7, and subsequently fixed and stained as described in A, along with anti-pSTAT5 antibodies. Representative histograms of pSTAT5 signal for each population are shown. Dotted vertical lines indicate IL-7 control levels. Percentages of cells responded to IL-7 are indicated. P values are calculated from 2-tailed Student’s t test when compared with WT cells stimulated by IL-7. (C and D) The dot plots show the percentages of pSTAT5− cells (C) and the MFI of pSTAT5+ signals (D). (E) Lnk−/−pS3/− leukemic blasts show elevated basal activation of pSTAT5. Representative phosphoflow shows the activation status of basal-level pSTAT5 in BM B220−IgM− cells in comparison with leukemic cells after 1 hour of starvation. The dot plots show the quantification of relative MFI of phosphoflow signals. ∗P < 0.05; **P < 0.01; ***P < 0.001; ns, not significant. 2-tailed Students’ t test. n = 4–10 mice per group in all above experiments. (F) Lnk−/−pS3/− leukemic blasts were starved and stimulated with or without IL-7 for 20 minutes. Cell lysates were subjected to WB analysis with indicated antibodies to phospho- or total JAKs. (G) HEK293T cells were transfected with mock or JAK3, along with either human or mouse Flag-tagged Lnk expression constructs. Cell lysates were either precipitated with anti-Flag antibodies or directly and subjected to WB analysis with indicated antibodies. (H) BaF3/IL-7R cells were stably infected with retroviruses expressing either vector alone, or WT or R384E Lnk mutant. Cell growth in the presence of IL-7 was quantified daily and graphed.

LNK negatively regulates normal and malignant HSC expansion and self-renewal in part by restricting the TPO/MPL/JAK2 signaling pathway (25–27). LNK has been reported to interact with Kit and downregulate SCF signaling in BM-derived mast cells (BM-MCs) (23). LNK dysregulation has been found in MPNs and AMLs (43, 44), possibly due to its effects in MPL/JAK2 and KIT signaling pathways. A recent report showed that Lnk suppresses radiation resistance and radiation-induced B cell malignancies by inhibiting IL-11 signaling (45). IL-11 is critical for the ability of Lnk−/− HSPCs to recover from irradiation (IR) and become leukemic after a long latency. In contrast, our results demonstrate that LNK plays a direct role in B cell progenitors. It controls pro-B/pre-B homeostasis and aging by regulating IL-7–mediated JAK/STAT signaling. Furthermore, genetic studies suggest that the role of LNK in normal B cell and B-ALL development is independent of its effects in HSCs or early multipotential progenitors or CLPs, and it is independent of its role in the TPO/MPL/JAK2 pathway. This is further corroborated with our finding showing that pro-B cells from preleukemic mice are able to initiate B-ALL upon transplantation. Our studies thus implicate LNK as a regulator of IL-7R signaling in normal and malignant B progenitors.

Our data also suggest that Tp53 deficiency confers self-renewal ability in B progenitors, while Lnk deficiency confers cytokine hypersensitivity. The synergy between the loss of cytokine receptor signaling molecules and tumor suppressors is striking, and it is manifested by the fact that preleukemic B progenitors display enhanced self-renewal in vivo and in vitro and, further, enhanced basal and IL-7–stimulated STAT5 activation. Future investigation is warranted to elucidate the multiple underlying signaling pathways that function synergistically in ALLs.

To decipher mechanisms underlying high-risk ALL requires a multifaceted approach to provide insights into the earliest stages of cellular transformation. Identification of signaling events specific to distinct stages of malignant transformation and progression will help delineate a new understanding of B-ALL development and point to potentially druggable pathways for intervention. In this report, we characterized the B cell compartment of freshly isolated and unfractionated BM cells via a phosphoflow strategy that combines surface B cell marker and intracellular IgM staining with phospho-specific antibodies to separate subpopulations of B progenitor cells with distinct cytokine responsiveness. We found that Lnk deficiency expands pro-B cells that are the most responsive to IL-7, and synergistic loss of Lnk and Tp53 results in an enhanced STAT5 activation in the preleukemic pro-B progenitors, indicating that LNK is a negative regulator for IL-7R–mediated JAK/SAT signaling that contributes to precursor B-ALL development. Fully transformed ALL blasts exhibited elevated activations of STAT5 at both basal conditions and upon stimulation. STAT5 is considered indispensable for maintenance of BCR-ABL-positive leukemia (46). Furthermore, overexpression of oncogenic STAT5 in the BM transplant models promotes B-ALL development in mice (47). Our signaling studies are translated into prolonged survival in Tp53−/−/lnk−/− B-ALL mice treated with JAK inhibition, supporting a previous report showing that the mice xenografted with human Lnk mutant B-ALLs are particularly sensitive to JAK inhibition (48).

Our work also uncovered an interaction between LNK and JAK3 that is activated by IL-7R. JAK3 and JAK1, but not JAK2, are activated in both normal B progenitors and B blasts. Thus, we believe that LNK interacts with JAK3 in B cell lineages, while it interacts with JAK2 in HSPCs. This finding is important, as LNK mutations co-occur with IL-7R mutations frequently (5 of 9), but not with CRLF2 rearrangement (1 of 9) or JAK2 mutations (0 of 9), in human Ph-like B-ALL (6). Although our results cannot exclude the possibility that LNK also plays a role in CRLF2/JAK2 mutant B-ALLs, our results point to distinct mechanisms for LNK in IL-7R-mediated signaling and proliferation in normal and malignant B progenitors. The co-occurrence of LNK and IL-7R mutations in human Ph-like ALLs also suggest JAK1/3 inhibitors would be effective in treating these patients to minimize the cytotoxic side effects of JAK2 inhibitors in suppressing hematopoiesis. Our biochemical studies found constitutive activation of multiple signaling pathways (e.g., STAT5, ERK, AKT, and S6), indicating that inhibition of these pathways simultaneously might be crucial. Indeed, we demonstrated that combined PI3K inhibition and JAK inhibition more potently suppressed B-ALL development in vivo and in vitro than single agents. Taken together, our studies enhance our understanding of the pathogenic mechanism underlying Ph-like B-ALLs with LNK mutations and will likely provide novel insights into therapeutic strategies.

Methods
Supplemental Methods are available online with this article.

Mice. Mpl−/− and Lnk−/− mice were provided by Frederic de Sauvage (49) (Genentech, South San Francisco, California, USA) and Tony Pawson (23) (Samuel Lunenfeld Research Institute, Toronto, Ontario, Canada), respectively. All mice were backcrossed onto the C57/BL6.
Ruxolitinib and/or anti-BP1 antibodies and sorted on FACS Aria. Pro-B cells (B220+CD19+CD43+AA4.1 + IgM –NK1.1–Ly6c–) were used for BMT or culture, as well as for RNA isolation for microarray. For phosphoflow analysis, freshly isolated BM cells were starved for 2 hours in DMEM medium (Invitrogen) supplemented with 0.5%BSA and either left unstimulated or stimulated with murine IL-7 for 10 minutes. Cells were immediately fixed with 2% ice-cold methanol. Cells were subsequently stained with anti-pSTAT5 (catalog 9351), anti-pAKT (catalog 4060), anti-pErk (catalog 4370), and anti-pS6 (catalog 4858) antibodies from Cell Signaling Technology, followed by staining with AlexaFluor 488-conjugate anti-rabbit IgG secondary antibodies, PE-conjugated anti-B220, and APC-conjugated anti-IgM μ-chain and analysis on a BD FACS Canto II or Fortessa.

IP and WB analysis. B-ALL cells from Tp53−/−Lnk−/− mice were starved for 2 hours in DMEM medium (Invitrogen) plus 0.5% BSA with either vehicle control or a graded dose of inhibitors for 0.5 hours, then stimulated with IL-7 and SCF (PeproTech) for 20 minutes. Cell lysates were subjected to standard WB analysis. Antibodies against pJAK1 (catalog 3331), JAK1 (catalog 3332), pJAK2 (catalog 3776), JAK2 (catalog 3230), pJAK3 (catalog 5031), JAK3 (catalog 8863), pSTAT5 (catalog 9351), pERK (catalog 4370), ERK (catalog 9102), pAKT (catalog 4060), AKT (catalog 9272), pS6 (catalog 4858), S6 (catalog 2317), p4EBP1 (catalog 2855) and 4EBP1 (catalog 9644), pSTAT5 (catalog 4322), pAKT (catalog 4060), and pERK (catalog 4370) were from purchased from Santa Cruz Biotechnology Inc. AlexaFluor 488-conjugate goat anti-rabbit IgG antibodies (catalog A-11034) were purchased from Molecular Probes.

Flow cytometry for cell surface markers, phosphoflow analysis, and cell sorting. For cell surface-flow cytometric analysis, cells were harvested from blood, BM, spleen, thymus, lymph nodes, and livers and stained with fluorochrome-conjugated antibodies to different cell markers for phenotypic analysis. For isolation of pro-B cells, BM samples were first depleted of lineage-positive cells using Biotin-conjugate anti-Ter119, anti-Mac-1, anti-Gr-1, anti-CD4, anti-CD5, and anti-CD8a antibodies, followed by removal with Dynabeads (Invitrogen). The cells remaining after depletion were labeled with fluorochrome-conjugated anti-B220, anti-CD19, anti-CD43, anti-IgM μ-chain, anti-NK1.1, anti-Ly6c, anti-A4.1, and/or anti-BPI antibodies and sorted on FACS Aria. Pro-B cells

Figure 8. Lnk−/−p53−/− leukemic cells are sensitive to JAK inhibitors. (A) JAK1/2 inhibitor ruxolitinib (left) and JAK3/2 inhibitor tofacitinib (right) inhibited leukemic Lnk−/−p53−/− B-ALL colony growth in a dose-dependent manner. Colony numbers are shown. (B) Cohort of mice transplanted with Lnk−/−p53−/− B-ALLs were treated either with vehicle alone or ruxolitinib (60 mg/kg) daily 10 days after transplant. Kaplan-Meier survival curves are shown. P value found using log-rank test. n = 9–10 mice per group. (C and D) Cohort of mice transplanted with Lnk−/−p53−/− B-ALLs were treated either with vehicle alone or ruxolitinib (60 mg/kg) daily for 10 days. The total donor leukemia percentage in the spleen (C) and spleen weight and images (D) are shown.
Figure 9. Synergistic inhibition of Lnk−/−p53−/− leukemic cell growth with JAK and PI3K/mTOR inhibitors. (A) Lnk−/−p53−/− leukemic blasts show elevated basal activation of pAKT, pS6, and pERK. Representative phosphoflow shows the activation status of indicated proteins in BM B220−ICμmed cells in comparison with leukemic cells after 1 hour of starvation. The dot plots show relative MFI of phosphoflow signals. n = 5–10. *P < 0.05; **P < 0.01; ***P < 0.001, 2-tailed Student’s t test. n = 5–10 mice per group. (B) Growth response curves for B-ALL cells treated with various concentrations of JAK and PI3K inhibitors. Lnk−/−p53−/− leukemic blasts were cultured in liquid culture supplemented with SCF and IL-7 in the presence of different concentrations of inhibitors, as indicated. Live cell numbers after 3 days of culture were determined by MTT absorbance. Representative results from 3 independent B-ALLs. (C) WB analyses for effector proteins of the STAT5, ERK, and PI3K/AKT pathways. Lnk−/−p53−/− leukemic blasts were stimulated with SCF and IL-7 for 20 minutes in the absence or presence of pretreatment with different concentrations of inhibitors. Cells were lysed, and the protein lysates were subjected to WB analysis with indicated antibodies. (D) Cohort of mice transplanted with Lnk−/−p53−/− B-ALLs were treated either with vehicle alone, ruxolitinib (JAKi), BEZ (PI3Ki), or combined 12 days after transplant. Kaplan-Meier survival curves are shown. Log-rank t test, *P < 0.001; **P < 0.001; drug treatment groups compared with vehicle group. *P < 0.01; **P < 0.005, single drug treatment groups compared with combined drug treatment group. n = 7–9 mice per group. (E and F) Cohort of mice transplanted with Lnk−/−p53−/− B-ALLs were treated either with vehicle alone or ruxolitinib, BEZ, or combined daily for 10 days. The spleen weight along with the spleen images (E), and the donor leukemia percentage in the BM (F, left) and the spleen (F, right) are shown. *P < 0.05; **P < 0.01; ***P < 0.001, 2-tailed Students’ t test. n = 4 mice per group.
For in vivo studies, BEZ235 was purchased from LC Laboratories and metinib, trametinib, and other PI3K inhibitors were from Selleckchem. Mice were analyzed for donor-derived fractions of myeloid, T cell, and B cell lineages with markers as indicated using flow cytometry.

**Drug treatments in vitro and in vivo.** For in vitro studies, ruxolitinib was purchased from LC Laboratories, while tofacitinib, BEZ235, selumetinib, trametinib, and other PI3K inhibitors were from Selleckchem. In vivo studies, BEZ235 was purchased from LC Laboratories and ruxolitinib from Medkoo. All mice were injected with 3,000 leukemic blasts from Lnk−/−P53−/− B-ALLs BM with or without receiving 5.5 Gy sublethal IR. Similar results were obtained with or without IR. Ten or 12 days after injection, the mice were randomly divided into 2 (vehicle, ruxolitinib) or 4 (vehicle, ruxolitinib, BEZ235, and ruxolitinib/BEZ235) treatments with cohorts of 7–10 mice per group for survival curves. The mice were treated with vehicle only or 60 mg/kg body weight ruxolitinib dissolved in PEG300/5%Glucose in water (v/v, 1:3) or 45 mg/kg BEZ235 in 10% 1-methyl-2-pyrrolidone/90% PEG 300 — or both ruxolitinib and BEZ235, by daily oral gavage — until the mice developed hind limb paralysis or became moribund. For spleen weight, donor peripheral blood was counted, immunophenotyped by flow cytometry, and reseeded in triplicate. Colonies were analyzed with 2 × 104 freshly isolated competitor cells and injected into lethally irradiated recipient mice (split dose of 10 Gy). Two weeks to 6 months after transplantation, complete blood count (CBC) was measured using a Hemavet 950 (Drew Scientific), and hematocrits were measured on a hematocrit centrifuge (Micro-MB, IEC). PB, BM, and spleen cells from transplanted mice were analyzed for donor-derived fractions of myeloid, T cell, and B cell lineages with markers as indicated using flow cytometry.

**Statistics.** For all the experiments described, 2-tailed Student’s t tests were performed with the data from 1 experiment with triplicates or from pooled data of 3–10 independent experiments. Graphs are presented as mean ± SEM. Statistical analysis of Kaplan-Meier survival curves were performed with log-rank tests using Prism (Graphpad Software Inc.). P values less than 0.05 were considered statistically significant.

**Study approval.** The animal studies were carried out in strict accordance with the recommendations in the Guide for the Care and Use of Laboratory Animals of the NIH. The protocol is approved by the Institutional Animal Care and Use Committee of the Children’s Hospital of Philadelphia (2015-7-781).

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