Cell Fate Decisions: The Role of Transcription Factors in Early B-cell Development and Leukemia

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ABSTRACT B cells are an integral part of the adaptive immune system and regulate innate immunity. Derived from hematopoietic stem cells, B cells mature through a series of cell fate decisions. Complex transcriptional circuits form and dissipate dynamically during these lineage restrictions. Genomic aberrations of involved transcription factors underlie various B-cell disorders. Acquired somatic aberrations are associated with cancer, whereas germline variations predispose to both malignant and nonmalignant diseases. We review the opposing role of transcription factors during B-cell development in health and disease. We focus on early B-cell leukemia and discuss novel causative gene–environment cooperation and their implications for precision medicine. Childhood leukemia is frequently initiated during fetal hematopoiesis. Clinical silent preleukemic clones are detectable in cord blood of a large number of healthy newborns. These predisposing alterations cooperate with environmental factors to trigger leukemia onset. Understanding of the underlying principles is a prerequisite for the development of measures to prevent leukemia in children.

INTRODUCTION

B cells are white blood cells of the lymphocyte subtype. They play an essential role in humoral immunity of the adaptive immune system by secretion of antibodies (1). An antibody response is elicited against a specific antigen when unique B-cell receptors (BCR) expressed on the cell surface of B cells recognize and bind the antigen (1). In addition, B cells produce cytokines, present antigens, and function as regulators of the second branch of the immune system, innate immunity (2). All mature blood cells, including B cells, are generated by hematopoietic stem cells (HSC) and differentiate through the serial action of transcription factors (TF) that determine their cell fate at specific decision-making stages during development (1). B cells arise in the bone marrow of mammals, and their development is tightly regulated. Disturbances of B-cell development can cause diseases ranging from benign lymphoproliferation to malignant leukemia and lymphoma (1). Therefore, a key to understanding these diseases is to unravel physiologic B-cell development. Recent studies have revealed a growing number of genetic alterations affecting B-cell TFs that directly cause or predispose individuals to B-cell acute lymphoblastic leukemia (B-ALL) development (3, 4). These novel insights have revised the way we view early B-cell development. Here, we review these recent findings and how they advance our understanding of early B-cell development and associated disease.

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TRANSCRIPTIONAL AND EPIGENETIC REGULATION DETERMINES NORMAL EARLY B-CELL DEVELOPMENT

Early B-cell Differentiation

Pluripotent stem cells give rise to multiple cell types during development. The differentiation process is tightly regulated by lineage-specific TFs and epigenetic modification resulting in stepwise lineage commitment, differentiation, and lineage-specific gene expression (5). The B-cell differentiation process can be subdivided into distinct stages based on the expression of cell-surface markers and the differentiation potential of

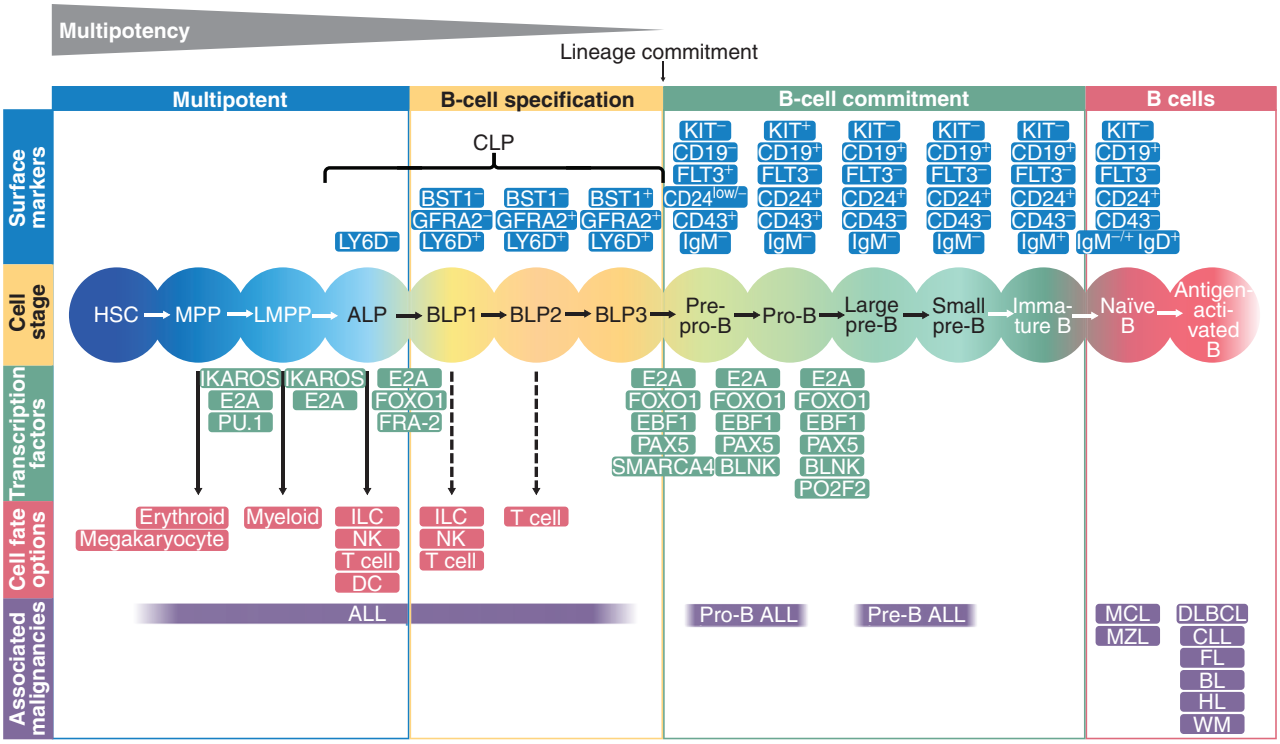

Figure 1. Transcriptional regulation determines normal B-cell development. A global network of regulatory circuits and epigenetic factors drives differentiation of HSCs through B-cell lymphopoiesis. The first stages of B-cell development are marked by multipotent cell types that can also develop in very different hematopoietic cell types. Potential other developmental paths are given in red boxes. The most important TFs that drive the differentiation from one progenitor to another are presented in green between the developmental stages. Surface markers are given in blue and hematopoietic malignancies associated with the cell stage in purple. The multipotent cells are succeeded by BLPs that are already primed toward becoming B cells but still have other lymphoid options. The BLP stages are characterized by the expression of the surface proteins BST1 and GFRA2. After full lineage commitment, BLP3 develop into pro-B cells. The TFs E2A, EBF1, and PAX5, in combination with several epigenetic factors, play central roles in the B-cell fate decision. ALL, acute lymphoblastic leukemia; BL, Burkitt lymphoma; CLL, chronic lymphocytic leukemia; DLBCL, diffuse large B-cell lymphoma; FL, follicular center cell lymphoma; HL, Hodgkin lymphoma; MCL, mantle cell lymphoma; MZL, marginal zone B-cell lymphoma; WM, Waldenström macroglobulinemia.

the cells (Fig. 1). As a first step, HSCs lose their self-renewal capacity. They begin to express the surface marker tyrosine kinase receptor Flt3 and transition to multipotent progenitors (MPP; ref. 6). MPPs that have lymphoid and myeloid potential, but retain only limited potential to differentiate along the erythroid and megakaryocyte lineage, are referred to as lymphoid-primed MPPs (LMPP; ref. 7). LMPPs are the precursors to the common lymphoid progenitors (CLP) that give rise to B cells, natural killer (NK) cells, dendritic cells (DC), innate lymphoid cells (ILC), and T cells and retain only a low myeloid potential (8). CLPs are subdivided into Ly6D (lymphocyte antigen 6 complex, locus D)-negative, all-lymphoid progenitors (ALP) and B-cell–biased lymphoid progenitors (BLP) that express Ly6D on the cell surface (9). ALPs retain the potential to differentiate into T cells, B cells, NK cells, and DCs, whereas BLPs are restricted to the B lineage. It has recently been shown in mice that BLPs can be further separated into three subsets (BLP1–3) according to the expression of the cell-surface proteins GFRA2 (GDNF Family Receptor Alpha 2) and BST1 (bone marrow stroma cell antigen 1; ref. 10). BLP1 ($Ly6D^+GFRA2^-BST1^-$) and BLP2 ($Ly6D^+GFRA2^+BST1^-$) retain the potential to differentiate into T cells and/or NK cells, whereas BLP3 ($Ly6D^+GFRA2^+BST1^+$) loses this potential. BLP3s finally give rise to fully committed pro-B cells that can be identified by expression of CD19.

Networks of Transcription and Epigenetic Factors Drive Early B-cell Differentiation

The contribution of specific TFs to the B-cell differentiation process has been previously reviewed thoroughly (11, 12). Briefly, current knowledge on the regulation of B-cell development is mainly based on studies in mice, and it is not clear whether the same statements also hold true for human B-cell development. Specification to the B-lymphoid lineage is initiated at the MPP to LMPP differentiation stage and regulated by three main TFs: PU.1 [purine-rich (PU) sequence binding factor], Ikaros (Ikzf1), and E2A (Tcf3). Likewise, there is strong cooperation between E2A, EBF1, and PAX5 in the commitment of cells to the B-cell lineage. In the absence of PAX5, B-cell development is arrested at the pro–B-cell stage (13) and commitment to the B-cell lineage is lacking (Fig. 1). These cells are capable of differentiating into multiple hematopoietic lineages, including T cells, NK cells, and myeloid cells (14, 15). Similar capacities for multilineage differentiation were reported in E2A-deficient progenitors

and EBF1-deficient progenitors (15, 16). These progenitors express myeloid, ILC, and T-cell lineage genes and retain the potential to differentiate into these lineages. In contrast, ectopic expression of E2A or EBF1 restricts their alternative differentiation potential and promotes B-cell fate specification (16).

More precise, time-resolved analysis of TF expression patterns underlying the B-cell lineage commitment were recently shown using inducible systems for *EBF1* expression and *E2A* inhibition (17, 18). Miyai and colleagues overexpressed an Id3–ER (estrogen receptor) fusion protein, whose nuclear translocation is induced by 4-hydroxytamoxifen (4-OHT) in hematopoietic stem and progenitor cells (17). In the presence of 4-OHT, E2A activity is repressed and B-cell development arrested at the MPP stage. These progenitor cells were named induced leukocyte stem (iLS) cells, because they retained the potential to differentiate into T, B, or myeloid lineage. B-cell differentiation of iLS cells was induced upon withdrawal of 4-OHT and regaining of E2A activity. Time-resolved analysis showed that the TF program was separated into three waves. Strikingly, TFs not specific to the B lineage, such as EGR1, NR4A2, and KLF4, were rapidly induced before the late onset of master regulators (including EBF1 and PAX5) in the third wave of commitment. Supporting this idea, Fra-2, a member of the activator protein 1 (AP-1) family belonging to the dimeric basic region-leucine zipper TFs, has been shown to be a critical regulator of FOXO1 in early B-cell differentiation (19). Many epigenetic regulators, such as SMARCA4, UHRF1, DNMT1, and EZH2 are also implicated in establishment of the B-cell fate. A similar hierarchy of transcriptional and epigenetic events was demonstrated in B-cell programming using EBF1 induction in developmentally arrested Ebf1$^{-/-}$ pre–pro-B cells (20) and in the differentiation of the Th cell 17 lineage (Th17; ref. 21), suggesting a general mode for differentiation of immune cells.

Chromatin Dynamics During B-cell Differentiation

Recent studies have indicated that the three-dimensional chromatin organization changes dramatically during B-cell development (20). TFs such as Pax5 are critical for the establishment of the B-cell lineage–specific genome structure. In uncommitted MPP cells, the transcriptionally inactive *EBF1* locus is located at the nuclear lamina. After differentiating to the pro–B-cell stage, *EBF1* relocates from the lamina to the inside of the nucleus to establish interactions associated with B lineage–specific transcriptional programs (20). These findings indicate that TFs fulfill a dual role in regulating lineage-specific gene expression programs and in establishing the three-dimensional genomic architecture during B-cell differentiation. However, it is still unclear how these processes are organized. Fundamental regulators of chromatin structure including CTCF (CCCTC-binding factor) and cohesin complexes may cooperate with TFs to regulate genome organization (22). Brahma-related gene-1 (Brg-1), a chromatin remodeler, is recruited to chromatin in B-cell progenitors and is critical for B-cell differentiation (23). Further studies are necessary to define regulating factors, control regions in the genome, and cell-type–specific genome structures.

GENETIC DYSREGULATION OF TFs INVOLVED IN EARLY B-CELL DEVELOPMENT CAUSES VARIOUS BENIGN AND MALIGNANT BLOOD DISORDERS

Genetic alterations of TFs involved in early B-cell development have been identified in a wide variety of blood disorders in humans (24) and add new, unexpected insights about B-cell development. Germline variants need to be compatible with embryogenesis and life in general. In some cases, *de novo* mutations are more severe or earlier in onset compared with transmitted ones. They can predispose to benign as well as malignant disorders. In contrast, acquired somatic variants have a more drastic effect on protein function and are restricted to malignant disease (ref. 24; Table 1).

Germline Variation

Inherited or *de novo* germline variants of a growing number of hematopoietic TFs (including *IKZF1, E2A/TCF3, PAX5*, and *ETV6*) have been associated with benign blood disorders and familial B-ALL or lymphoma (25–30).

IKZF1 is a key regulator of both lymphoid and myeloid differentiation and implicated in proliferation restriction. Transmitted germline *IKZF1* mutations were recently linked to common variable immunodeficiency syndrome (CVID; ref. 31). CVID is a frequent but genetically heterogeneous primary immunodeficiency (incidence of 1:50,000–1:25,000) clinically characterized by recurrent infections, due to markedly decreased numbers of isotype-switched mature B cells and corresponding low levels of serum IgG-type antibodies (and commonly also IgM and/or IgA). The CVID subtype caused by *IKZF1* mutations presented with B-cell immune deficiency, autoimmunity, and susceptibility to B-ALL. *IKZF1* comprises an N-terminal DNA-binding domain (DBD) and a C-terminal dimerization domain. Several isoforms have been described. IKZF1 mainly functions as a transcriptional repressor and binds to DNA as a homo- or heterodimer associating with its own isoforms or other family members [IKZF2 (HELIOS), IKZF3 (AIOLOS), or IKZF4 (EOS)] at pericentromeric heterochromatin regions. The identified CVID-associated mutations included mostly loss-of-function deletions and missense mutations affecting the DBD. They acted by haploinsufficiency. In addition, *de novo* germline mutations of *IKZF1* DBD were reported that were autosomal dominant and acted in a dominant-negative manner. They were associated with early-onset combined immunodeficiency presenting with severe defects of both the innate and adaptive immune system (32). Besides low numbers of B cells and associated dysgammaglobulinemia, these variants caused multi-lineage abnormalities, including myeloid cells and lymphoid cells. Familial acute lymphoblastic leukemia (ALL) was observed in carriers with both *de novo* as well as transmitted loss-of-function *IKZF1* variants, and it is currently assumed that almost 1% of "sporadic" B-ALL cases might be due to underlying germline *IKZF1* mutations (26). These B-ALL–associated *IKZF1* germline variants are not restricted to specific functional domains; many of these variants have no effect on TF activity but strongly influence stem cell–like features and cell– and cell–stroma interaction,

Table 1. Genetic alterations of hematopoietic TFs predisposing to B-ALL development

Risk	Gene	Mutation type	Consequence	Tumor type
Low-penetrance susceptibility	*CEBPE*	Intronic SNP	Dysregulation	B-ALL
	GATA3	Intronic SNP	Dysregulation	Ph^+
	IKZF1	Intronic SNP, 3′UTR SNP	Dysregulation	B-ALL
	ERG			
	ARID5B	Intronic SNP	Dysregulation	Hyperdiploid
	IKZF3			
High-penetrance susceptibility	*ETV6*	Missense	Loss of function	
	IKZF1	Missense	Loss of function	
	PAX5	Missense	Lower transcriptional activity	
High-penetrance somatic variants	*ETV6*	Gene fusion	Transcriptional dysregulation	*ETV6–RUNX1*$^+$ pre-B-ALL
		CNA and/or missense	Loss of function	
	TCF3	Gene fusion	Transcriptional dysregulation	*TCF3–PBX1*$^+$ pre-B-ALL
	ZNF384	Gene fusion	Transcriptional dysregulation	
	MEF2D	Gene fusion	Transcriptional dysregulation	
	CEBPE	CNA and/or missense	Loss of function	
	GATA3	CNA and/or missense	Loss of function	
	IKZF1	CNA and/or missense	Loss of function	
	ERG	CNA and/or missense	Loss of function	
	PAX5	Gene fusions	Loss of function	
	IKZF3	CNA and/or missense	Loss of function	
	EBF1	CNA and/or missense	Loss of function	
	BTG1	CNA and/or missense	Loss of function	

Abbreviations: CNA, copy-number alteration; Ph, Philadelphia chromosome; UTR, unstranslated region.

and decrease drug responsiveness (26). Taken together, these studies identified *IKZF1* as an immune deficiency and leukemia predisposition gene.

B-cell development is impaired at the early LMPP stage in mice deficient in the TF *E2A/TCF3*. In humans, a recurrent heterozygous dominant-negative *de novo* mutation in E2A/TCF3 (E555K) was recently identified in patients presenting with profound reduction of $CD19^+$ B cells and agammaglobulinemia (33). B cells lacked a functional BCR, and differentiation was blocked at the common lymphoid precursor to pro–B-cell stage. However, some developmental progression along the B lineage takes place even in the complete absence of *E2A/TCF3*, as evidenced by a case with a homozygous nonsense *E2A/TCF3* mutation and with severe hypogammaglobulinemia combined with B-ALL that was recently described (34).

Pax5 is an essential regulator of B-cell development and absolutely required to exit the pro–B-cell stage. A rare *PAX5* germline variant (p.Gly183Ser) in the DBD associated with lower, but not lacking, transcriptional activity, was identified in three kindreds with susceptibility to B-ALL (25, 29). Leukemic cells displayed loss of hererozygosity by structural variations on chromosome 9p and retention of only the mutant variant. Consistently, sporadic ALL cases with combined 9p loss and somatic *PAX5* variants affecting Gly183 were also observed (29). The lack of more frequent or more functionally disabling germline *PAX5* mutations might be due to its functions in brain development and spermatogenesis.

The TFs ETV6 and RUNX1 are involved in early hematopoiesis of other blood cell lineages (e.g., megakaryocytic and erythroid development; ref. 35), but recent findings suggest broader roles in early hematopoiesis, impacting the development of multiple lineages including the B-cell lineage. Rare germline autosomal dominant loss-of-function mutations were recently identified in *ETV6*, which cause thrombocytopenia and red cell macrocytosis but also predispose to B-ALL (27, 28, 30, 36). The majority of familial mutations cluster within the ETS domain, but a mutation in the linker region (P214L) has been identified recurrently (37). These variants act in a dominant-negative fashion due to homo- and hetero-oligomerization of mutant ETV6 with other ETS family members and transcriptional repressors. They impair transcriptional activity and nuclear localization. In close to 1% of 4,405 unselected sporadic ALL cases, likely damaging germline risk variants were identified in *ETV6* (27). It has recently been suggested that ETV6 may directly regulate *PAX5* expression through the recruitment of SIN3A and HDAC3 to the *PAX5* locus (37). Thus, mutant ETV6 may contribute to a block in B-cell differentiation, lineage infidelity, and leukemogenesis.

Germline mutations in the RUNX1 transcription factor are known to cause familial platelet disorder with associated myeloid malignancy (FPDMM). Affected family members usually present with moderate thrombocytopenia. Some cases developed mainly myeloid but also lymphoid malignancies. Although both dominant-negative and haplo-insufficient mutations are associated with platelet disorders, dominant-negative RUNX1 mutations affect hematopoiesis in a broader fashion and may increase the risk of leukemia (37).

In general, coding variants in B-cell TFs can lead to dramatic changes in transcriptional activities (mostly deleterious) and

confer a very significant increase in ALL risk. For example, comparing the frequency of *ETV6* variants in ALL cases with that in general population, we estimate that pathogenic variants in this gene carry an approximately 23-fold increase in relative risk (27). There is an extreme paucity of data on genome-wide assessment of rare ALL risk variants, and it is highly probable that many other ALL risk genes are yet to be discovered in the TF gene family. Besides rare variants linked to leukemia predisposition, common variants associated with disease susceptibility have also been uncovered (24). Genome-wide association studies (GWAS) of ALL susceptibility have identified at least 11 risk loci for this cancer, many of which reside within or in close proximity to TF genes (e.g., *ARID5B, IKZF1, CEBPE, GATA3*), including B-cell TFs as well (24). These common polymorphisms are almost always intronic, although they overlap with putative regulatory DNA elements and potentially influence gene transcription *in cis* (24). The effects of these common ALL risk variants are modest, with an up to 2-fold increase in RR. Even cumulatively, these variants explain only a very small fraction of absolute risk of ALL (38). Intriguingly, most genes identified from ALL GWAS are rarely affected by somatic alterations (with the exception of *IKZF1*). Interestingly, several of these TF genes are known to regulate myeloid or T lineage development (*CEBPE* and *GATA3*), raising the question of whether ALL risk variants promote expression of these TFs in the wrong lineages and consequently disrupt proper differentiation.

Somatic Variations

In B-ALL, somatic alterations involving TF genes can be largely divided into two types: chromosomal rearrangements resulting in fusion TFs or focal copy-number alterations and sequence mutations that directly affect TF activity. Interestingly, TFs involved in fusions are frequently not affected by concomitant copy-number alterations or mutations, suggesting that the gene fusion itself gives rise to novel functions important for leukemogenesis (3).

More than half of the gene fusion events in B-ALL involve one or more TF genes (3, 39). Some of those are among the first recognized genomic features of this cancer (e.g., *ETV6–RUNX1* or *TCF3–PBX1*) and impact risk stratification, patient treatment, and outcome. In these two chimeric TF proteins, the DBD of ETV6 and TCF3 is replaced by that of RUNX1 and PBX1 (40, 41), respectively, thus causing global transcriptional deregulation. Although TCF3 and PBX1 are both directly involved in lymphoid development (42), ETV6 and RUNX1 are more involved in early hematopoiesis of other blood cell lineages, and the pathogenesis remains incompletely understood. *ETV6* deletion is frequently observed in cases with ETV6-RUNX1, but *ETV6* deletion alone rarely occurs in ALL, again suggesting that loss of endogenous TF activity is not the main pathogenic mechanism of these fusion genes. Recent genomic profiling studies have identified a plethora of novel fusion genes involving other hematopoietic TFs, for example, ZNF384 (39, 43), MEF2D (44), and PAX5. Whereas *ZNF384* (30) and *MEF2D* (45) are not affected by copy-number alterations or mutations, *PAX5* deletion is very common in B-ALL (~30% of cases; ref. 46) and can be concomitant with *PAX5* fusions (3). Both result in loss of PAX5 TF activity. A number of other hematopoietic TF genes are often targeted by copy-number alterations and/or mutations [e.g., *EBF1* (46), *IKZF1* (47), *BTG1* (46)]. Gene fusions represent initiating events during early leukemogenesis, while small genomic aberrations often occur as late secondary events to potentiate and promote leukemogenic effects. There have been extensive studies on how TF gene fusions or mutations alter hematopoiesis, and the prevailing theory is that these genomic defects directly disrupt B-lymphoid cell development and create differentiation blockade (11, 48). The expansion of the immature progenitor cell pool increases the chances of acquiring oncogenic mutations and subsequent leukemic transformation. However, many TFs have complex functions (above and beyond transcription regulation during hematopoiesis), and it would be an oversimplification to assume that leukemia mutations in TF only affect B-cell differentiation.

Integrating germline and somatic genomic features of ALL offers a unique opportunity to identify interactions between leukemia and host genomes. For example, *ARID5B* risk variants are highly enriched in ALL with a hyperdiploid karyotype (24), whereas germline *ETV6* variants and *ETV6–RUNX1* fusion genes are mutually exclusive in ALL (27). Deregulation of TF genes probably drives preleukemic cells down a specific oncogenic pathway defined by characteristic somatic events. This type of integrated analysis is likely to shed new light on the roles of TF genes in ALL pathogenesis and lymphoid cell biology in general.

TFs Determine Molecular Subtypes and Prognostic Risk Groups of Childhood B-ALL

The genomic landscape of childhood B-ALL has been studied extensively (3, 49). Today, >90% of childhood ALL cases can be classified into specific genetic subgroups linked to distinct prognostic characteristics and treatment responses that have been extensively reviewed elsewhere (49). In general, B-ALLs are characterized by a very low mutational burden. However, in more than a third of pediatric patients with ALL (35%–50%), genetic alterations of B-cell TFs constitute the primary oncogenic event and determine the biological and clinical characteristics of the disease (49). Interchromosomal translocations generate fusion genes encoding chimeric TFs. Depending on the specific fusion gene present, prognostic risk groups can be determined, including low-risk (t12;21 coding for *ETV6–RUNX1*), intermediate-risk (t1;19 coding for *TCF3–PBX1*), and high-risk groups [*KMT2A* (*MLL*) translocations (11q23) and t17;19 coding for *TCF3–HLF*; ref. 49]. Some of the translocations can be acquired already *in utero* (50). Among them, *MLL* translocations are commonly strongly oncogenic and lead to poor prognostic infant ALL, usually without associated secondary mutations (51). However, *ETV6–RUNX1* and *TCF3–PBX1* mainly block B-cell differentiation and lead to expansion of pre–B-cell clones. These TF fusion genes are not sufficient to generate overt leukemia but depend on cooperating oncogenic secondary lesions to cause leukemia (50). These cooperating secondary aberrations frequently also affect B-cell TFs and are remarkably restricted to and recurrent for specific primary lesions (52). For instance, *ETV6–RUNX1* is most frequently combined with loss of the second allele of *ETV6, PAX5* deletion or downregulation, and mutations or loss of expression of the transcription cofactors

BTG1 and *TBL1XR1* (Transducin Beta Like 1 X-Linked Receptor 1). *TCF3–PBX1* and *TCF3–HLF* are associated with *PAX5* deletion/downregulation and *TCF3* mutations (53). *TCF3–HLF* is further associated with deletions of *BTG1* and *VPREB1*, although the number of studied cases is still low due to the rareness of this group (less than 1% of B-ALL cases). In general, *PAX5* and *IKZF1* deletions are common in ALL cases (15%) and are increased in high-risk ALL (up to 28% and 70%, respectively; refs. 3, 47). Importantly, lineage-specific targeted treatment may lead to occurrence of relapse due to cell adaptation. Recently, it was shown that 65% (13 of 20) of B-ALL cases relapsed after treatment with chimeric antigen receptor (CAR)-T cells targeting CD19. This was due to leukemic cells evolving to become CD19 negative (54). Therefore, therapies not only need to be adapted to the specific B-ALL developmental lineage but also need to take into account cooperative driver mutations to be successful (55).

Impaired Cell Fate during B-ALL Development

"Classic" bifurcating tree maps for the formation of the different blood cell types from HSCs depict strict compartments and a single route for the generation of differentiated cells, including B cells. However, recent work presents blood formation as the result of a continuous lineage priming (56), suggesting that individual hematopoietic precursors have a multitude of options as opposed to the classical sequential restriction-binary switch model (57). This new model would imply that the structure of the hematopoietic system is much less rigid than previously thought, and that the system could be more versatile. Previously identified precursor cells in fact seem to correspond to an amalgam of cells with plural differentiation potential (58). This is well exemplified by B-cell development as a lineage decision-making process where the ordered expression of TFs orchestrates B-cell lineage priming (Fig. 1). However, this process is much more plastic than described in the classic model. Plasticity of B-cell development was revealed by enforced expression of C/EBPα and C/EBPβ in B-cell precursors, which led to a reprogramming into macrophages (59). Recently, this plasticity has been further demonstrated by transient expression of the transcription factor *Hoxb5* in precursor B cells, which was sufficient for stable conversion of B cells into T cells *in vivo* (60). This cell fate conversion occurs, in part, through the repression of TFs ensuring B-cell lineage priming (*Ebf1, Pax5, Bcl11a, Foxp1,* and *Foxo1*). Repression of *Pax5* and *Ebf1*, for instance, is crucial for B-cell to T-cell conversion (15). This B-cell to T-cell conversion proves that a cell can adopt an alternative fate after having committed to another cell lineage, supporting the pair-wise model of hematopoiesis proposed by Brown and Ceredig (58). This pair-wise model does not assign a single path from HSCs to each of the various terminally differentiated blood cell types. Rather, the pair-wise model of hematopoiesis suggests a rainbow of pair-wise developmental options, gradually biased from the HSCs toward producing a specific blood cell type (Fig. 1).

A similar scenario also occurs in leukemogenesis, where leukemia cells largely belong to just one cell lineage, though many different leukemia types arise in a single stem/progenitor cell, which can give rise to many types of cells. *ETV6–RUNX1* and *BCR–ABLp190* are two of the most frequent drivers of B-ALL (49). Thus, at the start of B-ALL, a new but extraneous (malignant) fate must be imposed on the leukemia cell of origin to develop B-ALL (Fig. 1). The specific link between the *ETV6–RUNX1* and *BCR–ABLp190* oncogenes and human B-ALL development can be explained by two different interpretations. The classical explanation postulates that the fusion genes (*ETV6–RUNX1* or *BCR–ABLp190)* are created in a committed/differentiated target B cell (61). Under this view, the phenotype of the leukemic B cell is conferred by the B-cell phenotype of the target cell. The second interpretation to explain this specific association between *ETV6–RUNX1* and *BCR–ABLp190* oncogenes and B-ALL is that these B-ALL–associated oncogenes are capable of imposing a leukemic B-cell fate onto a non-B target cell (62). Thus, the establishment of a B-cell tumor identity would require the first oncogenic hit to enforce an aberrant lineage program (62). It would be challenging, however, to verify this in human B-ALL, because the leukemias have evolved and undergone many mutations at the time of diagnosis (63). To prove that *ETV6–RUNX1* and *BCR–ABLp190* are able to impose a leukemic B-cell fate in non-B target cells, an experimental design limiting the expression of these oncogenes to non-B target cells would be needed, because under no other circumstances would it be possible to rule out a later role for *ETV6–RUNX1* or *BCR–ABLp190* once the leukemic B-cell phenotype is established. When the expression of either *ETV6–RUNX1* or *BCR–ABLp190* is restricted to hematopoietic stem/precursor cells in mice, the animals indeed develop exclusively B-ALL, which resembles the human disease (64, 65). These mouse models were designed to initiate *ETV6–RUNX1* or *BCR–ABLp190* expression in the HSC/progenitor population but to turn it down in committed B cells. The fact that only B-ALL emerges under these particular circumstances indicates that *ETV6–RUNX1* and *BCR–ABLp190* are able to impose a specific malignant B-cell fate. These findings link B-cell leukemogenesis with the aberrant B-cell lineage programming of early progenitors and show that oncogenes such as *ETV6–RUNX1* and *BCR–ABLp190* are able to define tumor cell identity during leukemogenesis. A similar scenario, where the induction of a new tumoral identity by the tumor genetic alteration occurs at the stem cell level, has also been described in other types of hematopoietic neoplasias and solid tumors (62). Thus, the oncogene-mediated restriction of the spectrum of options available to HSC to just one pathway/fate is central to the initiation of leukemia. It explains the association between specific oncogenes and the final phenotype of the hematopoietic neoplasia it triggers. Altogether, this evidence supports the idea that both normal B-cell development and B-cell leukemogenesis are cell lineage decision-making processes, with the leukemia-initiating events being "drivers" of leukemic B-cell lineage commitment.

Leukemic B-cell Priming and the Loss of B-cell Lineage–Specific Genes

B-ALL is initiated by a first (pre)leukemic insult in a cell with the biological potential, intrinsic or acquired, to cause leukemia (Fig. 2). The first hit restricts the leukemia-initiating cells to a single-cell lineage. However, a single oncogenic insult is (with few exceptions) insufficient for B-ALL

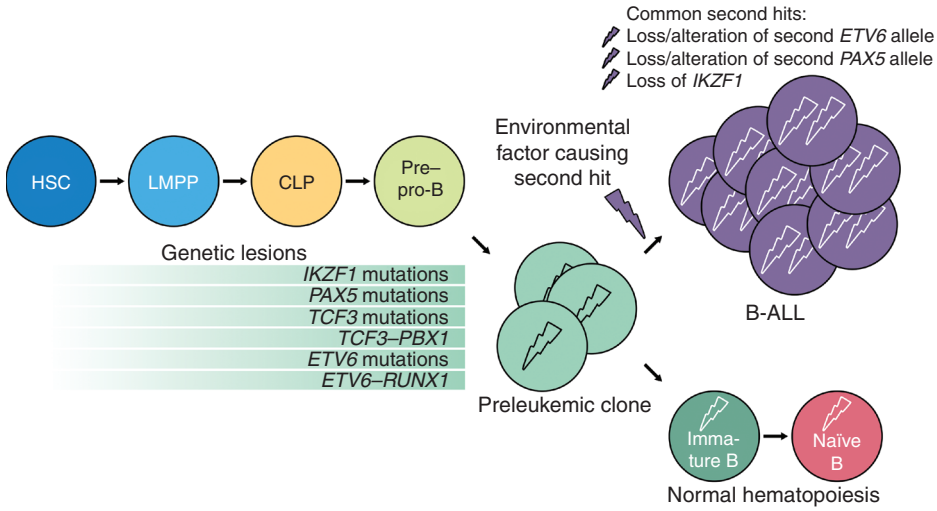

Figure 2. Scheme of leukemic hematopoiesis. Cells develop from HSCs to pre–pro-B cells and acquire genetic lesions during these stages. It is not clear at what stage each of the mutations actually occurs. Common mutations of hematopoietic TFs are shown on light green background. These mutations lead to the formation of preleukemic clones. Without a second mutagenic event, normal hematopoiesis will be sustained. In case of a secondary oncogenic event, probably triggered by an environmental factor, B-ALL arises.

development, as shown in studies of twins with concordant childhood ALL and identical preleukemic translocations in their blood cells (66). Additional hits are necessary to convert the leukemia-initiating cell into a leukemic stem cell (LSC). Because the first hit imposes the leukemic B-cell lineage identity, what is the role of the second hit, mainly *PAX5* and *IKZF1* deletions, in this scenario? It has recently been shown that these lineage-specific genes are prominent DNA damage hotspots during leukemic transformation of B-cell precursors (67). The B-cell TF downregulation would not have an instructive role in the genesis of B-ALL, just a permissive one, preventing cells with the first oncogenic hit from being successfully terminally reprogrammed into leukemic B cells. This finding contrasts with Pax5 function in normal B cells, where deletion does not restrict precursor B cells in their lineage fate (68) and reprograms B cells into functional T lymphocytes (ref. 69; Fig. 2). In this regard, it has been proposed that the metabolic gatekeeper function of B-cell TFs may allow silent preleukemic clones to remain in a latent state (70). Thus, PAX5 and IKZF1 would limit the amount of cellular ATP to levels that are insufficient for malignant transformation of precursor B cells (65, 70). However, the development of B-ALL in mice where the expression of the first hit is restricted to HSCs indicates that the role of the B-cell TF loss during the leukemic B-cell priming might rely on a different function. The recent discovery of Ikaros acting as a guardian preventing autoimmunity by promoting BCR anergy and restraining TLR signalling is of immediate relevance to the persistence of preleukemic clones (71).

In p53-deficient cancers, the p53-mediated DNA damage response, which usually limits the reprogramming capacity of the first hit to ensure cell genomic integrity, is lost (62). B-cell TFs might have a similar role in constraining the malignant reprogramming function of the first hit. In this regard, *P53* and *PAX5* alterations seem to be mutually exclusive in human B-ALL development (63), and it has recently been shown that the reduction of Pax5 activity drastically accelerates the appearance of precursor B-ALL in mice where *BCR–ABLp190* expression is restricted to hematopoietic stem/precursor cells (65). These results align with the fact that preleukemic clones carrying *BCR–ABL*^{p190} oncogenic lesions are frequently found in neonatal cord blood (72). However, they often remain silent, because the majority of these carriers do not develop B-ALL, supporting the theory that the first hit (*BCR–ABL*^{p190} gene) creates a preleukemic clone that remains clinically silent until secondary mutational events give rise to a full blown leukemia. Overall, these findings suggest that PAX5 downregulation does not have an instructive role in the genesis of B-ALL, just a permissive one, preventing cells with the first hit (*BCR–ABL*^{p190} gene) from being successfully terminally reprogrammed into leukemic B cells. Thus, reestablishing Pax5 function might be a therapeutic strategy for the eradication of leukemic cells and for blocking disease progression. As predicted, it has been shown that restoring endogenous Pax5 expression in leukemic B cells can trigger disease remission in mice (73). It is remarkable that the presence of Pax5 mediates B-cell commitment in normal development and that its absence is required to establish B-cell identity in ALL development (Fig. 2). However, although these results suggest that Pax5 downregulation plays a role in facilitating the restriction of cell lineage options to a leukemic B-cell lineage fate (lineage infidelity), such an activity has yet to be directly demonstrated. It would not be surprising if other important B-cell TFs (e.g., E2A/TCF3) contribute to the B-ALL development through a similar mechanism.

Gene–Environment Cooperations Are Novel Determinants in B-ALL Development

The *ETV6–RUNX1* fusion gene is frequently found in neonatal cord blood, but only a few *ETV6–RUNX1* carriers

actually develop B-ALL (74). Similarly, pathogenic germline variants involving key lymphoid TFs, like *PAX5* and *IKZF1*, predispose to B-ALL development (49). These acquired and germline alterations confer a low risk of developing B-ALL and represent the first oncogenic hit in the process of B-cell leukemogenesis. This first hit creates a preleukemic clone, but it needs secondary postnatal genetic alterations ("second hits") to establish an irreversibly transformed state leading to the appearance of B-ALL. However, the mechanisms of leukemogenesis in individuals carrying a genetic predisposition remain uncertain. Identifying the factors causing the irreversibly transformed state has been particularly difficult because of the inherent challenge of detecting these stages in healthy children. In this regard, preclinical models of both *ETV6–RUNX1*-associated and PAX5-associated leukemia predisposition have been instrumental in uncovering a "gene–environment cooperation" as a novel determinant in the genesis of B-ALL (64, 75). This "gene–environment cooperation" refers to the increased likelihood of B-ALL development as a result of an increased sensitivity to specific environmental exposures in the presence of a genetic predisposition (Fig. 2). The cooperating oncogenic mutations can be triggered, for example, by environmental infectious exposure. Only together do both steps (genetic predisposition plus infection exposure) lead to overt leukemia in a proportion of predisposed mice, mimicking human B-ALL incidence associated with the same genetic alterations (64, 75). However, the second cooperating oncogenic mutation seems to be unique to each genetic predisposition. Consistent with this, wild-type mice (lacking genetic predisposition) never present with B-ALL when exposed to identical environmental infectious exposure (64, 75). Although these findings show that infectious exposure plays a role in enhancing B-ALL susceptibility of preleukemic carriers, this could be due to either direct induction of cooperating oncogenic mutations or by causing epigenetic reprogramming that, in turn, influences the specific second hit that cooperates with each predisposing alteration. However, such a mechanism has yet to be demonstrated. To this end, our capacity to model these early leukemia predisposition alterations triggering B-ALL initiation *in vivo* by infection exposure has opened new opportunities to study early B-ALL development and will help to unlock the mechanisms involved in infection-driven leukemogenesis. In addition, it will facilitate the discovery of how other relevant environmental factors might promote leukemogenesis in predisposed individuals. It will be exciting to see if elucidation of the gene–environment interaction in B-ALL development will lead to strategies for the prevention of B-ALL in children at risk.

Translational Implications of the Gene–Environment Cooperation

Prevention of cancer onset is one of the biggest scientific and clinical challenges in oncology. Although genomic profiling tests for the identification of children at risk are available (74), due to the lack of adapted therapeutic strategies, the identification of preleukemic clones or B-ALL–associated germline variants in children has no clinical consequence at present. Early detection of children at risk would require novel means of differentiating "true" children at risk that require intervention and the majority of predisposed children who will never develop B-ALL. The earliest possible identification of "true" children at risk will likely facilitate the prevention of progression to clinically relevant disease. Thus, the final challenge is to understand how these genetic variants contribute to B-ALL development, to develop preventive measures to reduce the incidence of the disease. To this end, preclinical models of B-ALL–associated germline variants in children will be essential tools for testing therapeutic options (e.g., vaccinations) to prevent the occurrence of this disease (64, 65, 75).

CONCLUSION

Early B-cell development and leukemia are both cell lineage–deciding processes where developmental options become restricted. The study of normal B-cell development has guided the current understanding of the molecular basis of B-cell malignancies. The genomic and molecular characterization of B-cell malignancies has contributed to our understanding of the molecular mechanisms that underlie normal B-cell development. The role reversal of TFs, like Pax5, in normal and leukemic B-cell development is remarkable. Although the molecular nature of B-ALL has now been defined, from a therapeutic perspective, it would be important to know whether the correlation between increased B-cell TF deletions and high-risk ALL is related to their function in promoting malignant B-cell lineage identity reprogramming. Although the exact nature of the "gene–environment cooperation" remains unknown, we have now the ability to model genetic B-ALL predisposition. This unlocks new opportunities for studying how B-ALL emerges. If we can understand how the "gene–environment interaction" is regulated, then we might learn how to intervene before a preleukemic condition evolves into leukemia. This knowledge would advance medicine and would have conceptual implications for other types of cancer associated with genetic predisposition. We expect that further understanding of both normal B cell and B-ALL development will ultimately generate the answers to these remaining clinical questions and will lead to the development of new therapeutic approaches to prevent disease leukemia development in children.

Disclosure of Potential Conflicts of Interest

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