Direct Recruitment of Polycomb Repressive Complex 1 to Chromatin by Core Binding Transcription Factors

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<th>Yu, Ming, Tali Mazor, Hui Huang, Hsuan-Ting Huang, Katie L. Kathrein, Andrew J. Woo, Candace R. Chouinard, et al. “Direct Recruitment of Polycomb Repressive Complex 1 to Chromatin by Core Binding Transcription Factors.” Molecular Cell 45, no. 3 (February 2012): 330–343. © 2012 Elsevier Inc.</th>
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<td>As Published</td>
<td><a href="http://dx.doi.org/10.1016/j.molcel.2011.11.032">http://dx.doi.org/10.1016/j.molcel.2011.11.032</a></td>
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<td>Publisher</td>
<td>Elsevier</td>
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<td>Version</td>
<td>Final published version</td>
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<td>Accessed</td>
<td>Sun Jan 13 15:31:28 EST 2019</td>
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SUMMARY

Polycomb repressive complexes (PRCs) play key roles in developmental epigenetic regulation. Yet the mechanisms that target PRCs to specific loci in mammalian cells remain incompletely understood. In this study we show that Bmi1, a core component of Polycomb Repressive Complex 1 (PRC1), binds directly to the Runx1/CFBβ transcription factor complex. Genome-wide studies in megakaryocytic cells demonstrate significant chromatin overlap between the PRC1 core component Ring1b and Runx1/CFBβ and functional regulation of a considerable fraction of commonly bound genes. Bmi1/Ring1b and Runx1/CFBβ deficiencies generate partial phenocopies of one another in vivo. We also show that Ring1b occupies key Runx1 binding sites in primary murine thymocytes and that this occurs via PRC2-independent mechanisms. Genetic depletion of Runx1 results in reduced Ring1b binding at these sites in vivo. These findings provide evidence for site-specific PRC1 chromatin recruitment by core binding transcription factors in mammalian cells.

INTRODUCTION

Polycomb group (PcG) proteins were first identified in homeotic transformation screens in Drosophila melanogaster through their silencing of homeobox (Hox) genes (for review see Simon and Kingston, 2009). They are now known to developmentally regulate a large number of genes and play key roles in mammalian stem cell self-renewal, cellular differentiation, and neoplasia. Two phylogenetically conserved PcG complexes have been identified: Polycomb Repressive Complex 1 and 2 (PRC1 and PRC2, respectively). PRC1 is composed of the core proteins Bmi1 (also called Pcgf4) and Ring1b and a variable number of associated components such as Ring1a, CBX proteins, PH1, PH2, and other Pcgf proteins in mammals. It silences genes through histone 2A monoubiquitination (H2Aub) and/or nucleosome compaction. Bmi1 and Ring1b-deficient animals have hematopoietic, neurologic, and skeletal defects and develop stem cell exhaustion due to impaired stem cell self-renewal (Cales et al., 2008; Park et al., 2003; van der Lugt et al., 1994). PRC2 contains the core components EZH2, Suz12, and EED and is also implicated in stem cell maintenance and lymphocyte homeostasis (Margaron and Reinberg, 2011). It catalyzes the methylation of histone 3 at lysine 27 (H3K27me).

Because PRCs do not contain inherent DNA-specific binding activity, additional factors must mediate their site-specific chromatin recruitment. In Drosophila, DNA polycomb response elements (PREs) and targeting factors have been defined. However, site-specific targeting mechanisms in mammalian cells remain less well understood.

Core binding transcription factors are heterodimeric complexes composed of a common CFBβ subunit bound to one of three tissue-specific DNA-binding CBFα subunits (now called Runx1, Runx2, and Runx3). Like PRCs, core binding transcription factors play roles in stem cell self-renewal, tissue differentiation, and cancer (for review see Appleford and Woollard, 2009). Runx1 is the predominant hematopoietic-expressed CBFα family member, whereas Runx2 and Runx3 play roles in bone and neural development. Targeted disruption of Runx1 in mice...
leads to complete failure of definitive hematopoiesis during embryogenesis due to defective emergence of the first definitive hematopoietic stem cells (HSCs) from the aorto-gonadal-mesonephros (AGM) region (Chen et al., 2008; Kissá and Herbomel, 2010; North et al., 1999; Wang et al., 1996a). In adult mice, inducible Runx1 deficiency results in blocked megakaryocyte (Mk) maturation, impaired lymphopoiesis, myeloid cell hyperproliferation, and progressive HSC exhaustion (Growney et al., 2005; Ichikawa et al., 2004; Jacob et al., 2010; Sun and Downing, 2004). Similar defects are seen with CBFβ deficiency (Talebian et al., 2007; Wang et al., 1996b).

Runx1 and CBFβ are the most common targets of genetic alteration in human leukemia, occurring in ~20%–25% of all cases (Speck and Gilliland, 2002). Runx1 is also mutated in a subset of myelodysplastic syndrome (MDS) cases and is associated with poor prognosis (Bejar et al., 2011). Germline Runx1 haploinsufficiency causes familial thrombocytopenia, platelet dysfunction, and increased MDS/leukemia risk (Song et al., 1999).

In order to further understand Runx1 transcriptional mechanisms, we recently purified Runx1-containing multiprotein complexes from megakaryocytic cells (Huang et al., 2009). Here, we report the direct physical and functional association between Runx1/CBFβ and PRC1. Moreover, we provide evidence that Runx1 recruits PRC1 directly to chromatin in a PRC2-independent manner. These findings support a mechanism of site-specific PRC1 chromatin recruitment in mammalian cells and conversely implicate a role for PRC1 in core binding factor-mediated gene regulation.

RESULTS

Runx1 and CBFβ Interact with PRC1 in Megakaryocytic and T Lymphocytic Cells

We previously purified Runx1-containing multiprotein complexes from 12-O-tetradecanoylphorbol-13-acetate (TPA)-induced murine L8057 megakaryoblastic cells using metabolic biotin tagging and streptavidin (SA) affinity chromatography and identified associated proteins by liquid chromatography-tandem mass spectrometry (LC-MS/MS) (Huang et al., 2009).

In addition to known interacting proteins such as CBFβ, GATA-1, GATA-2, TAL1/SCL, Sin3A, PRMT1, PML, Smad2, CDK6, and the SWI/SNF complex, we identified physical and functional interactions between Runx1 and the Ets transcription factor FLI1 (Huang et al., 2009).

From these same preparations we obtained multiple components of PRC1 and TrxG chromatin-remodeling complexes (Figure 1A; Figure S1 and Table S1 available online). Physical association between FLAG-tagged and biotinylated Runx1 (FLAG-RUNX1) and the PRC1 core components Ring1b and Bmi1 was confirmed by western blot from independent SA pull-down experiments (Figure 1B). The abundant Mk nuclear protein YAP was not detected, indicating specificity of the assay. No significant difference in interactions was noted using uninduced or TPA-induced L8057 cells (Figure S2).

Physical association between CBFβ/Runx1 and Ring1b/Bmi1 was further validated by coimmunoprecipitation (coIP) assays of endogenous proteins in both directions (Figures 1C–1E). Physical interaction between CBFβ and Ring1b/Bmi1 was also observed in human Jurkat T cells (Figure 1F).

Glutathione S-transferase (GST) pull-down assays using purified recombinant proteins show that Runx1 and Bmi1 interact directly and that the runt domain of Runx1 is sufficient for Bmi1 binding (Figure 1G). Additional mapping studies indicate that a region involving amino acids 1–57 of Bmi1, which largely contains the Ring domain, contributes significantly to Runx1 binding, although sequences from amino acids 57–167 also participate (Figure 1H).

Runx1/CBFβ and Ring1b Occupy a Large Number of Common Chromatin Sites in L8057 Cells

To assess the association of Runx1/CBFβ and PRC1 at the genomic level, chromatin immunoprecipitation (ChIP) followed by massively parallel sequencing (ChiP-Seq) was performed for Runx1, CBFβ, and Ring1b in TPA-induced L8057 cells. High-quality Bmi1 antibodies are not available for ChiP-Seq. Two biological repeats were performed for each, and the data were compared to control IgG. After aligning sequences to the genome and removing redundant reads and those that mapped to multiple locations, we obtained 44,532,375 filtered reads for Runx1, 48,623,085 for CBFβ, and 56,381,939 for Ring1b (Table S2). This corresponds to a total of 7,073 Runx1, 10,186 CBFβ, and 7,063 Ring1b peaks (p < 1E-10 and false discovery rate [FDR] <5%) using the peak-calling algorithm MACS (Zhang et al., 2008); and 5,595 Runx1, 6,685 CBFβ, and 4,239 Ring1b genes bound between ~1 kb upstream of the transcription start site (TSS) to +1 kb downstream of the transcription end site (TES) (see Figure S3A for gene calls using a ~10 kb through +10 kb window). As expected, there was considerable overlap between Runx1 and CBFβ occupancy peaks (Figure 2A). Of the Runx1 peaks, 79% were bound by CBFβ, and 55% of the CBFβ peaks were bound by Runx1. There was also significant overlap of Runx1/CBFβ and Ring1b peaks. Of the Runx1 peaks, 57% were bound by Ring1b, and 57% of the Ring1b peaks were bound by Runx1. Of the CBFβ peaks, 48% were bound by Ring1b, and 70% of the Ring1b peaks were bound by CBFβ. A total of 3,688 peaks and 3,097 genes were common to all three factors.

To analyze whether Ring1b was binding at the same sites as Runx1 and CBFβ, we used the Genome Positioning System (GPS) algorithm (Guo et al., 2010), which overcomes the low resolution of ChiP-Seq experiments arising from random DNA fragmentation. Using this method, we found that 61% of Ring1b binding sites have a binding site for CBFβ or Runx1 within 100 bp (Figure 2B).

Examples of gene loci bound by all three factors are shown in Figure 2C (see Figure S3B for additional loci). The high degree of common occupancy between Ring1b and Runx1 was confirmed using a second Ring1b antibody (Figure S4A). Quantitative ChiP (qChiP) assays from independent samples validated commonly occupied peaks for 27 of 28 sites tested (Figure 2D). Each of two sites assayed in purified murine fetal liver-derived Mks also shows occupancy by both CBFβ and Ring1b (Figure 2E).

ChiP-Seq experiments carried out in uninduced L8057 cells also showed a high degree of overlap among Runx1, CBFβ, and Ring1b bound sites, although the total number of peaks (3,310 Runx1, 6,158 CBFβ, and 6,628 Ring1b) and bound genes.
Figure 1. Physical Association between Runx1/CBFβ and Ring1b/Bmi1

(A) Partial list of proteins identified by mass spectrometry following tandem anti-FLAG:SA or single SA affinity chromatography from crude nuclear extracts of FLAG-BioRunx1 plus biotin ligase birA (experimental) or birA alone (control) containing L8057 cells treated with TPA for 72 hr (Huang et al., 2009). The number of peptides obtained for each protein from each of five independent experiments is shown. See Figure S1 and Table S1 for additional details.

(B) Western blot for Ring1b, Bmi1, and YAP following SA-IP of FLAG-BioRunx1 complexes from TPA-induced L8057 cells. Ten percent input is shown.

(C–E) CoIP assays of endogenous proteins from TPA-induced L8057 cells. The immunoprecipitation (IP) antibody is shown on top, and the western blot antibody is shown on the right. Ten percent input is shown. IgG, species-matched control antibody.

(F) Western blot for Ring1b, Bmi1, and YAP following SA-IP of FLAG-BioRunx1 complexes from TPA-induced L8057 cells. Ten percent input is shown. IgG, species-matched control antibody.

(G) GST pull-down assay of recombinant Runx1, Bmi1, and CBFβ. In vitro transcribed and translated [35S]methionine-labeled Bmi1 or CBFβ was incubated with uncoupled beads or beads coupled with GST, GST-Runx1, or GST-runt domain fusion proteins as indicated. The beads were washed, and eluted material was separated by SDS-PAGE. An autoradiogram is shown. Ten percent of the input protein is shown.

(H) Mapping of Bmi1 interaction domain. Left view is a schematic diagram of constructs. Right view shows α-FLAG IP followed by α-V5 western blot of constructs coexpressed in COS7 cells. One percent of input is shown.
Figure 2. Common Chromatin Site Occupancy by Runx1/CFBβ and Ring1b

(A) Venn diagrams showing overlap of Runx1, CFBβ, and Ring1b occupancy peaks (left) and genes (right) in TPA-induced L8057 cells based on MACS (Zhang et al., 2008). Overlapping peaks are defined as those for which the summits of the peaks are <500 bp from each other. Bound genes are defined as having occupancy peaks between −1 kb of the TSS to +1 kb of the TES.

(B) Venn diagram showing overlap of Runx1, CFBβ, and Ring1b occupancy sites within 100 bp of one another based on GPS (Guo et al., 2010).

(C) Representative Runx1, CFBβ, Ring1b, and control IgG ChIP-Seq profiles of loci occupied by Runx1, CFBβ, and Ring1b. Other genes present in these regions are not shown.

(D) qChIP assays for Runx1, CFBβ, and Ring1b occupancy at the indicated loci in TPA-induced L8057 cells. PI, control antibody. The data are expressed as fold enrichment relative to a negative control region (~2.5 kb 5’ of the Gapdhs gene TSS), and represent the mean of three independent experiments ±SD.

(E) qChIP assays for CFBβ and Ring1b occupancy at Sav1 and Lats1 gene promoters in primary fetal liver-derived murine Mks. The data are displayed as in (D).
performed in TPA-induced L8057 cells, and gene expression
in order to correlate chromatin occupancy with functional gene
Genes in Mks
downregulated.
vector. A total of 595 genes were upregulated, and 279 were
three independent experiments, a total of 874 genes changed
produced marked reduction of CBF
transduction (p < 0.02), biological regulation (p < 0.02), and regu-
gulated genes were enriched for intracellular signaling (Benja-
the 2,782 genes bound by all three factors (Runx1, CBF
bound and upregulated, those bound only in the distal promoter, introns, or exons were
262 were upregulated (p < 4.0E-54), and 79 were downregulated
(2,526 Runx1, 4,385 CBFβ, and 4,130 Ring1b) was lower than
that observed for the induced cells (Figure S4B). A total of
0.7N [n = 4] compared to the empty vector control (4.5N ± 1.3N
As expected, transcription factor binding motif analysis under
Runx1 or CBFβ protein levels (Figure 3A).
Run1b and CBFβ occupancy peaks showed enrichment for the Runx consensus binding sequence (g.w.ACCACAra) (p =
1 kb of the TSS to +1 kb of the TES and
497 genes changed expression
HMFIN, and had reduced ploidy compared to Bmi1+/C0
findings are consistent with functional overlap of Runx1/CBFβ and Ring1b/Bmi1 in Mk maturation.
Deficiency of Ring1b and Bmi1 Impairs Mk Maturation
Runx1 or CBFβ deficiency impairs Mk maturation as evidenced by reduced ploidy and poor platelet production (Growney et al., 2005; Ichikawa et al., 2004; Talebian et al., 2007). To examine the functional role of Ring1b in Mk maturation, we measured the ability of L8057 Ring1b shRNA knockdown cells to undergo TPA-induced endomitosis. As shown in Figure 4A, Ring1b knockdown resulted in reduced ploidy (mean 2.8N ± 0.7N [n = 4] compared to the empty vector control (4.5N ± 1.3N [n = 5]), and was similar to that observed with CBFβ knockdown (mean ploidy 2.5N ± 0.5N [n = 3]).

Bmi1−/− neonatal mice are thrombocytopenic (and lympho-
phenic) but have normal hemoglobin and granulocyte levels
Park et al., 2003). To probe for a potential Mk defect in these animals, we examined bone marrow histology and cultured Mks from 5- to 6-week-old Bmi1−/− mice. This showed that Bmi1−/− Mks were smaller in size, contained more hypolobulated nuclei, and had reduced ploidy compared to Bmi1+/− littermates (Figure 4B). This is similar to the phenotype of Runx1-deficient Mks (Growney et al., 2005; Ichikawa et al., 2004). These findings are consistent with functional overlap of Runx1/CBFβ and Ring1b/Bmi1 in Mk maturation.

Morpholino Knockdown of Bmi1 or Ring1b Impairs HSC Development in Zebrafish Embryos
Deficiency of either Runx1 or Bmi1/Ring1b leads to HSC exhaustion in adult animals. Runx1/CBFβ deficiency also causes defects in definitive HSC ontogeny during embryogenesis. However, a detailed examination of Bmi1/Ring1b’s role in embryonic HSC ontogeny has not been reported to our knowledge. In order to examine this, we knocked down their expression using morpholinos (MOs) in zebrafish embryos. The first definitive HSCs develop in the equivalent AGM region of the developing zebrafish embryo at about 36 hr postfertilization (hpf), and are marked by expression of c-Myb and/or Runx1 (Burns et al., 2002). As previously reported (Burns et al., 2005), Runx1 MO knockdown ablated phenotypic (c-Myb+) definitive HSC formation (Figure 5A, left panel). MO knockdown of Bmi1 and the duplicated zebrafish gene Bmi1b, or Ring1b also resulted in loss of c-Myb+/Runx1+ cells, although not to as full of an extent as Runx1 knockdown (Figure 5A, right panel).

As a complementary approach, knockdown experiments were performed in CD41-eGFP transgenic fish, which express eGFP in HSC/early progenitor cells (HSPCs) and thrombocytes (Lin et al., 2005). Like Runx1, knockdown of Bmi1/Bmi1b and Ring1b

Ring1b and CBFβ Regulate a Subset of Commonly Bound Genes in Mks
In order to correlate chromatin occupancy with functional gene regulation, CBFβ and Ring1b lentiviral shRNA knockdown was performed in TPA-induced L8057 cells, and gene expression changes were measured by cDNA microarray analysis. A previously characterized CBFβ shRNA construct (Galli et al., 2009) produced marked reduction of CBFβ protein levels (Figure 3A). Runx1 and Ring1b levels were not significantly affected. From three independent experiments, a total of 874 genes changed expression ≥1.5-fold with p < 0.05, compared to the empty vector. A total of 595 genes were upregulated, and 279 were downregulated. CBFβ was the most downregulated gene, whereas Ring1b and Bmi1 were not significantly altered. Among the 2,782 genes bound by all three factors (Runx1, CBFβ, and Ring1b) (p < 1E-10, FDR <5%, binding −1 kb from TSS to +1 kb from TES) and represented by probes on the array that passed quality control, 280 genes changed expression. A total of 217 were upregulated (p < 3.4E-46), and 63 were downregulated (p < 2.9E-5). Because distant binding events strongly influence gene expression (Maclsaac et al., 2010), we repeated these calculations including genes bound from −10 kb to TSS to +1 kb from TES. Among the 3,530 genes bound by all three factors (p < 1E-10, FDR <5%), 341 genes changed expression. A total of 262 were upregulated (p < 4.0E-54), and 79 were downregulated (p < 2.7E-6). Genes that were bound in multiple regions and those bound only in the distal promoter, introns, or exons were associated with upregulation (Table S4). Bound and upregu-
lated genes were enriched for intracellular signaling (Benja-
mini p < 0.009), regulation of biological process (p < 0.02), signal transduction (p < 0.02), biological regulation (p < 0.02), and regulation of cellular process (p < 0.03) (Dennis et al., 2003).

Although knockdown for Ring1b was not as efficient as that for CBFβ, the more potent shRNA construct (shRNA #1) produced significant Ring1b protein reduction (Figure 3B). Runx1 and CBFβ protein levels were not significantly altered. A total of 497 genes changed expression ≥1.5-fold with p < 0.05. A total of 152 genes were upregulated, and 345 were downregulated. Among the 3,530 genes bound by all three factors and represented by probes on the array, 65 were upregulated (p < 1.5E-13), and 99 were downregulated (p < 8.3E-8).

Clustering analysis of genes occupied by Runx1, CBFβ, and/or Ring1b within −1 kb of the TSS to +1 kb of the TES and a heat map of corresponding gene expression changes following CBFβ or Ring1b shRNA knockdown are shown in Figure 3C (see Figure S5 for comparable analysis based on binding −10 kb of TSS to +1 kb of TES). A total of 51 genes that were bound by all three factors changed expression with both CBFβ and Ring1b shRNA knockdown using the high stringency criteria described above (Table S5). Of the genes, 88% changed expression in the same direction (28 genes upregulated, 17 downregulated) (Figure 3D). Quantitative RT-PCR (qRT-PCR) validation studies from independent experiments confirmed the gene expression changes in representatives of each of these classes (Figure 3E). We conclude that CBFβ/Runx1 and Ring1b functionally regulate a set of commonly bound genes.
resulted in a significant reduction of eGFP+ cells in the AGM region, as well as in the caudal hematopoietic tissue (CHT), which is seeded by AGM HSCs (Figure 5B). Similar to Runx1 deficiency (Wang et al., 1996a), Bmi1/Bmi1b or Ring1b knockdown did not significantly affect primitive erythropoiesis (Figure 5C), or alter overall morphology of the embryos (Figure S6).

Both Bmi1 and Runx1 knockout mice have a block in T cell maturation at the CD4-CD8- double-negative (DN) to CD4+CD8+ double-positive (DP) transition stage, although Bmi1 loss predominantly impairs the DN3 (CD44-CD25+) to DN4 transition (CD44+CD25+) (Miyazaki et al., 2008), whereas Runx1 loss predominantly impairs the DN2 (CD44+CD25+) to DN3 transition (Ichikawa et al., 2004). Thus, like in Mk

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Figure 3. Regulation of a Subset of Commonly Bound CBFβ and Ring1b Direct Target Genes

(A) CBFβ lentiviral shRNA knockdown in TPA-induced L8057 cells. Western blot for CBFβ, Ring1b, Runx1, and β-actin in puromycin selected cells.

(B) Ring1b lentiviral shRNA knockdown in TPA-induced L8057 cells. Western blot for Ring1b, Runx1, CBFβ, and β-actin in puromycin selected cells.

(C) Clustering analysis showing genes occupied by either Runx1, CBFβ and/or Ring1b at -1 kb of TSS to +1 kb of TES, and heat map of corresponding gene expression changes (red, increased; green, decreased; black, no change) following CBFβ or Ring1b shRNA knockdown.

(D) Log-fold gene expression changes based on cDNA microarray analysis for genes bound by all three factors (Runx1, CBFβ, and Ring1b) (p < 1E-10, FDR <5%; occupancy -1 kb of the TSS to +1 kb from the TES) that changed expression following both CBFβ and Ring1b shRNA knockdown >1.5-fold with p < 0.05.

(E) qRT-PCR measurements of gene expression changes of representative commonly occupied genes following CBFβ or Ring1b shRNA knockdown in TPA-induced L8057 cells. Levels are normalized to Gapdhs. The mean of four independent experiments is shown ±SD.
development and HSC ontogeny, Ring1b/Bmi1 or Runx1/CBF\(\beta\) deficiencies generate partial phenocopies of one another with respect to T lymphocyte development. In total these findings argue for functional cooperation between Runx1 and PRC1 components in development.

**Runx1 Recruits Ring1b to Runx1 Binding Sites in Primary Murine Thymocytes**

To examine whether Runx1 participates in Ring1b recruitment at selected chromatin sites, we performed qChIP assays for Runx1, CBF\(\beta\), and Ring1b in primary thymocytes from Runx1\(^{fl/fl}\) or Runx1\(^{10b}\) Vav1-Cre mice, which have pan-hematopoietic deletion of Runx1 (Chen et al., 2009). In control mice (Runx1\(^{10b}\)) we observed significant enrichment for Runx1 and CBF\(\beta\) at the previously described Runx1 binding sites in the CD4 silencer (Yu et al., 2008), Th-POK regulatory regions (Th-POK RBS1 and 2) (Setoguchi et al., 2008), and TCR\(\beta\) enhancer (Setoguchi et al., 2008), as well as several sites inferred from our Mk ChIP-Seq data set (Top2b, Stat1, and Stat3 promoters) (Figure 6A). Only low levels of Runx1/CBF\(\beta\) were found at the Th-POK promoter, consistent with our previous report (Setoguchi et al., 2008). Ring1b was significantly enriched at each of the Runx1/CBF\(\beta\) occupied sites.

In the knockout mice, Runx1 and CBF\(\beta\) enrichment levels were markedly reduced at these sites, as expected (Figure 6A). Low levels of residual Runx1 are likely due to incomplete conditional

**Figure 4. Partial Phenocopies of Ring1b/Bmi1 and Runx1/CBF\(\beta\) Deficiency in Megakaryopoiesis**

(A) Representative flow cytometric plots of propidium iodide (PI) DNA ploidy analysis of TPA-induced L8057 cells transduced with the empty vector, CBF\(\beta\) shRNA, or Ring1b shRNA #1. The percentages of cells with each DNA ploidy state (2N, 4N, 16N, 32N, 64N, and 128N) and the mean ploidy (vector [n = 5], CBF\(\beta\) shRNA [n = 3], Ring1b shRNA #1 [n = 4]) are given ±SD.

(B) Phenotype of Bmi1\(^{-/-}\) Mks. Left panel shows hematoxylin and eosin-stained histologic sections of bone marrow from Bmi1\(^{-/-}\) and Bmi1\(^{+/}\) mice. Inset shows representative Mk at higher magnification (original 600x). Middle panel is a phase-contrast photomicrograph of bone marrow cells cultured from Bm1\(^{-/-}\) and Bmi1\(^{+/}\) mice in the presence of Tpo and stem cell factor. Arrowheads indicate large (maturing) Mks. Right panel shows flow cytometric plots of cultured bone marrow cells for CD41 expression and DNA content (PI). Histogram plots for different ploidy classes are shown to the right for CD41+-gated cells. Gates were set using control IgG-stained cells.
allele excision. Importantly, Ring1b is also markedly depleted at these sites. H2Aub enrichment was found at a subset of Runx1, CBFβ, and Ring1b commonly occupied sites in control mice, and was also markedly depleted upon Runx1 deletion (Figure 6B). Control experiments validated the chromatin integrity of the knockout animal samples (Figure S7).

To examine these effects in a more global manner, we performed ChIP-Seq for Runx1, CBFβ, and Ring1b in primary thymocytes from Runx1<sup>fl/fl</sup> and Runx1<sup>fl/fl</sup>, Vav1-Cre 5- to 8-week-old mice.

From the Runx1<sup>fl/fl</sup> mice we obtained 1,898,522 Runx1, 2,109,935 CBFβ, and 1,543,887 Ring1b aligned and filtered reads (Table S2). This corresponds to 1,507 Runx1, 4,033 CBFβ, and 712 Ring1b peaks (p < 1E-10, FDR <5%), and 1,364 Runx1, 3,369 CBFβ, and 665 Ring1b bound genes (binding between −1 kb of TSS to +1 kb of TES). Similar to our findings in L8057 cells, there was considerable overlap of the occupancy peaks and genes of all three factors (Figure 6C). Of the Ring1b bound genes, 46% were also bound by Runx1, and 71% were bound by CBFβ. A total of 292 genes were bound by all three factors (Table S6).

From the Runx1<sup>fl/fl</sup>, Vav1-Cre mice, we obtained 1,597,571 Runx1, 2,571,167 CBFβ, and 2,197,463 Ring1b aligned and filtered reads (Table S2). None of the Runx1 or CBFβ peaks met the statistical cutoff of a p value of <1E-10 and FDR <5%. Although 23 Ring1b peaks remained in the Runx1-deficient thymocytes, only one of these corresponds to a Runx1/CBFβ commonly bound site from the control mouse. A more detailed analysis of the binding data revealed that even in the Runx1 knockout animals, some residual Runx1 binding could be detected, reflecting incomplete excision of the floxed allele. To quantify this, we counted the number of unique reads associated with peaks bound by all three proteins in the control animal and at the same loci in the knockout animal (Figure 6D). For Ring1b, 7% of the regions had no reads at all in the knockout (compared to 8% for Runx1 and 2% for CBFβ). At the remaining sites, the median ratio of reads at these locations in the control to knockout was 4.1 for Runx1, 5.2 for CBFβ, and 1.3 for Ring1b. The reduced read numbers in the Runx1-deficient thymocytes occur despite the fact that the libraries for Ring1b and CBFβ were sequenced more deeply in these mice. (The expected ratios based on the number of uniquely mapped reads would be 1.2 for Runx1, 0.8 for CBFβ, and 0.7 for Ring1b.) Examples
Figure 6. Runx1 Dependency of Ring1b Chromatin Occupancy at Commonly Bound Sites in Primary Murine Thymocytes

(A) qChIP assays for Runx1, CBFβ, and Ring1b in primary thymocytes from either Runx1<sup>fl/fl</sup> or Runx1<sup>fl/fl, Vav1-Cre</sup> 6-week-old mice. Fold of enrichment is shown relative to a negative control region (see Experimental Procedures). The mean of three independent assays is shown ±SD.

(B) qChIP assay for H2Aub at each of the individual sites tested in (A).

(C) Venn diagrams showing overlap of Runx1, CBFβ, and Ring1b peaks and bound genes from primary thymocytes of 5- to 8-week-old Runx1<sup>fl/fl</sup> mice. Peaks are filtered for p < 1E-10, FDR < 5%, and overlaps are defined as MACS summits within 500 bp of each other. Bound genes contain occupancy peaks within ~1 kb of the TSS to +1 kb of the TES.
of ChIP-Seq profiles showing the concomitant decrease in Runx1, CBFβ, and Ring1b reads upon Runx1 depletion are shown in Figure 6E. We conclude that Runx1/CBFβ participates in Ring1b recruitment at some commonly bound sites.

To examine the possibility that PRC1 may recruit or stabilize Runx1, qChIP assays were performed from primary thymocytes of 5- to 6-week-old Bmi1−/− mice. With the exception of the TOP2b promoter, we observed no significant difference of Runx1 enrichment at the sites tested (Figure 6F). These data are consistent with Runx1-mediated recruitment of PRC1, rather than PRC1-mediated recruitment or stabilization of Runx1.

**Ring1b Occupancy at Commonly Bound Runx1/CBFβ Sites Occurs Independent of PRC2**

A proposed model of PRC1 chromatin recruitment involves its direct binding to H3K27me3 residues, which are first generated by the action of PRC2 (Simon and Kingston, 2009). In order to examine whether H3K27me3 is involved in PRC1 recruitment at sites commonly occupied by Runx1/CBFβ, we measured H3K27me3 enrichment levels at each of the tested sites in wild-type primary thymocytes. Although significant H3K27me3 enrichment was observed at the Th-POK RBS1, RBS2, and promoter regions, all of the other sites had only background levels (Figure 7A).

To test this further, we examined Runx1, CBFβ, and Ring1b chromatin occupancy in thymocytes from Ezh2fl/fl, Vav1-Cre, Rosa26-flox-stopper-flox-EYFP mice (Wilson et al., 2011). Flow cytometry of thymocytes and splenocytes showed that 91.2% and 95.9% of the total cells expressed EYFP, respectively, indicating efficient activation of Cre in these tissues. Of the CD3+ populations (T cells), 96.3% and 98.4% were EYFP positive and had 12- and 29-fold decreases in Ezh2 mRNA levels compared to control mice for spleen and thymus, respectively (Figure 7B). Despite this marked Ezh2 depletion, qChIP assays from the thymocytes of these animals demonstrated no significant loss of Ring1b, Runx1, or CBFβ chromatin occupancy at the sites tested (Figure 7C). This strongly suggests that recruitment of Ring1b to these Runx1/CBFβ occupied sites occurs independent of PRC2 activity.

**DISCUSSION**

In this study we provide evidence that core binding transcription factors contribute to site-selective physical and functional recruitment of PRC1 in mammalian cells. In *Drosophila*, PREs have been defined based on functional assays and consist of several hundred base pair sequences (Simon and Kingston, 2009). These regions contain binding sites for the transcription factor PHO (ortholog of the mammalian transcription factor YY1), which participates in PcG recruitment in some cases. Less is known about PcG recruitment in mammalian cells. Several examples of noncoding RNA-mediated recruitment have been uncovered, particularly in X chromosome inactivation (Zhao et al., 2008). Woo et al. recently defined a PRC recruitment site within the human HOXD cluster (Woo et al., 2010). We recently showed that the lineage-specific transcription factor GATA-1 physically and functionally associates with PRC2 during erythroid terminal maturation (Yu et al., 2009). The findings in the current study indicate that Runx1 and CBFβ contribute to direct PRC1 recruitment at some sites in Mks and lymphocytes. It is of interest to note that both YY1 and Runx factors share a common central TGG core element in their DNA consensus binding sites.

There is prior evidence that PRC1 can be recruited to chromatin independent of PRC2 (Pasini et al., 2007; Schoeftner et al., 2006; Vincenz and Kerppola, 2008). Our data are consistent with the existence of PRC2-independent mechanisms and suggest that direct interactions with DNA-binding proteins, such as core binding transcription factors, may be responsible in some cases. Similar to our findings, direct interaction between PRC1 and PHO has been described in *Drosophila* (Mohd-Sarip et al., 2006).

Like many transcription factors, Runx proteins both activate and repress transcription in a gene and developmental context-dependent manner. For example, Runx1 activates the *Pig.1* gene in myeloid and B cells, but represses it in T lymphocytes and Mks (Huang et al., 2008). Some Runx-associated repressive events are mediated by Groucho/TLE family proteins. However, there is also evidence that Groucho-independent mechanisms exist (Walrad et al., 2010). The findings from the current study suggest that PRC1 may be involved in some of these alternate repressive pathways.

Genetic suppressor screens in *Drosophila* indicate that SWI/SNF and TrxG chromatin remodeling factors play antagonistic roles to PcG-mediated gene silencing (Simon and Kingston, 2009). Interestingly, we identified multiple components of the SWI/SNF and TrxG (ASH2/SET complex) complexes in our Runx1-containing multiprotein complex purifications. Bakshi et al. recently reported that SWI/SNF physically interacts with Runx1 and controls hematopoietic target genes (Bakshi et al., 2010). Moreover, they showed that reduced Runx1 levels correlate with impaired SWI/SNF chromatin occupancy at several common loci. Collectively, these findings suggest that Runx proteins may differentially recruit PcG and SWI-SNF/TrxG complexes in a gene- and developmental-specific context.

Adult HSC self-renewal is impaired in both Bmi1/Ring1b and Runx1-deficient animals (Calés et al., 2008; Jacob et al., 2010; Park et al., 2003; Sun and Downing, 2004; van der Lugt et al., 1994). Our data in zebrafish embryos indicate that Ring1b and Bmi1, like Runx1/CBFβ, are also involved in definitive HSC ontogeny (Figure 5). However, the fact that Bmi1−/− mice (Park

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(D) Ratio of the number of reads obtained from ChIP-Seq for CBFβ, Ring1b, and Runx1 at commonly occupied sites in thymocytes from Runx11fl/fl versus Runx11−/−. Vav1-Cre mice in log-base-2. The red horizontal bars represent the median value, the boxes represent the 25th–75th percentile (%) range, and the whiskers extend to the most extreme data point within 1.5× of the interquartile range. The expected log ratios based on the number of reads in each experiment are ~ −0.29 for CBFβ, ~ −0.51 for Ring1b, and 0.25 for Runx1.

(E) Examples of ChIP-Seq profiles showing concomitant reduction of Runx1, CBFβ, and Ring1b occupancy at commonly occupied sites.

(F) qChIP assays for Runx1 in primary thymocytes from 5- to 6-week-old Bmi1−/− or wild-type littermate controls. The mean of three independent assays is shown ±SD.
et al., 2003; van der Lugt et al., 1994) lack the complete failure of HSC development seen in Runx1/Cbfβ mouse embryos (Wang et al., 1996a) indicates that either PRC1 is not absolutely required for Runx1 function in HSC ontogeny or that compensatory mechanisms exist. Runx1 is also an upstream regulator of Bmi1 in HSCs (Motoda et al., 2007), which could explain some of the HSC phenotypic overlap.

How dysregulation of Runx proteins predisposes to cancer is not fully understood. All of the human leukemia-associated Runx1 chromosomal translocations generate fusion proteins...
that retain the runt domain. Moreover, many malignancy-related Runx1 somatic and germline point mutations affect the runt domain. It will be of interest to determine if any of these abnormal products lead to altered PRC1 chromatin recruitment and epigenetic changes and whether this plays a role in Runx1-related malignancies.

In summary the data presented in this study provide evidence that core binding transcription factors contribute to chromatin recruitment of PRC1 at site-specific loci in megakaryocytic and lymphocytic cells. Future studies will be needed to determine if other lineage-specific transcription factors also play a direct role in recruiting PRC1 in different tissue contexts.

**EXPERIMENTAL PROCEDURES**

See Supplemental Experimental Procedures for more details.

**Cells and Cell Culture**

The L8057-birA and L8057-FLAG-4mRunx-1 cell lines were generated and cultured as previously described (Huang et al., 2009). Cell maturation was induced by adding 50 mM (final concentration) TPA to the medium for 3 days.

**Conditional Knockout Mice**

Runx1 b/c mice were kindly provided by D. Gary Gilliland (Growney et al., 2005) and interbred with Vav1-Cre mice (Georgiades et al., 2002). EZH2 b/b, flox-stopper-flox Rosa26-EYFP, Vav1-Cre mice (Wilson et al., 2011) were kindly provided by Stuart Orkin. Bmi1 stopper-flox Rosa26-EYFP, Vav1-Cre mice (Wilson et al., 2011) were kindly provided by Maarten van Lohuizen (van der Lugt et al., 1994). All animal procedures were approved by the Children’s Hospital Institutional Animal Care and Use Committee.

**Runx1 Multiprotein Complex Purification and Proteomic Analysis**

Runx1-containing multiprotein complexes were purified and characterized as previously described (Huang et al., 2009). Copurified proteins were separated by SDS-PAGE, and the entire lane was analyzed by LC-MS/MS using an LTQ linear ion-trap mass spectrometer (Thermo Scientific). Peptide sequences were determined by matching protein or translated nucleotide databases with the acquired fragmentation pattern by the software program SEQUEST (Thermo Scientific) (Eng et al., 1994).

**CoIP Assays**

CoIP assays were performed as previously described (Yu et al., 2009). See Supplemental Experimental Procedures for more details.

**GST Pull-Down Assays**

See Supplemental Experimental Procedures.

**ChIP and ChIP-Seq**

Cells were fixed with 0.4% formaldehyde at room temperature for 10 min. For primary Mk studies, fetal liver cells were harvested from embryonic day 13.5 C57BL/6 murine embryos, cultured in the presence of 1% thrombopoietin (Tpo)-conditioned medium (Villeval et al., 1997) for 4 days, and mature Mks were enriched by discontinuous BSA density gradient as previously described (Drachman et al., 1997). For primary thymocyte studies, whole thymuses from 5- to 8-week-old mice were dissected, and single-cell suspensions were generated by gentle grinding of the tissue and passage through a 100 μm cell strainer in RPMI 1640 medium containing 10% heat-inactivated fetal calf serum. Thymocytes were crosslinked with 1% formaldehyde (final concentration) for 5 min at room temperature.

qChIP assays were performed as previously described (Yu et al., 2009). A site 2.5 kb upstream from the Gapdhs gene TSS was used as the internal control, and fold of enrichment was calculated using the 2 ΔΔCT method. The real-time PCR primers are listed in Table S7.

For ChIP-Seq, purified DNA was prepared for sequencing on a Beckman Coulter SPRI-TE following manufacturer’s instructions. The seq-prepped DNA was PCR amplified using Illumina primers for 18 cycles. Samples were sequenced on either the Illumina Genome Analyzer II or Illumina Hi-Seq 2000 following the manufacturer’s protocols. Raw ChIP-Seq data were processed using the Illumina software pipeline. Only ChIP-Seq reads that aligned to exactly one location in the reference mouse genome (UCSC, mm9) were retained. See Supplemental Experimental Procedures for data analysis details.

**RNA Interference, qRT-PCR, and cDNA Microarray Analysis**

Validated shRNA clones in the plKO.1-puro vector (TRCN00000084942 [CBFβ], TRCN00000040581 [Ring1b], and TRCN000000257390 [Ring1b]) were obtained from Sigma-Aldrich, and the empty vector was used as control. Twenty-four hours after infection, cells were washed twice with PBS and fresh medium was added. Forty-eight hours after transduction, puromycin (2 μg/ml final concentration) and TPA (50 nM final concentration) were added. The cells were cultured for another 72 hr before harvest and analyzed by qRT-PCR or cDNA microarray. The qRT-PCR primers are listed in Figure S7.

**Zebrfish Maintenance and MO Microinjection**

All animal procedures were approved by the Children’s Hospital Institutional Animal Care and Use Committee. See Supplemental Experimental Procedures.

**ACCESSION NUMBERS**

The ChIP-Seq and cDNA microarray data have been deposited in the Gene Expression Omnibus public database under accession numbers GSE33653 and GSE33659, respectively.

**SUPPLEMENTAL INFORMATION**

Supplemental Information includes seven figures, seven tables, and Supplemental Experimental Procedures and can be found with this article online at doi:10.1016/j.molcel.2011.11.032.

**ACKNOWLEDGMENTS**

M.Y. is supported by a grant from the Wendy Will Case Cancer Fund and an American Heart Association postdoctoral fellowship award. A.B.C. is supported by a grant from the NIH (R01-HLO82952). E.F. is the recipient of the Eugene Bell Career Development Chair and is supported by NIH Grants U54-CA112967 and R01-GM089903. This work used computing resources funded by the National Science Foundation under Award No. DB1-0821391, and sequencing support from the NIH (P30-ES002106). The authors would like to thank D. Gary Gilliland, Stuart Orkin, and Maarten van Lohuizen for providing knockout mouse strains and Ross Tománek and Steven Gygó at the Taplin Mass Spectrometry Facility for assistance with protein identification.

Received: February 28, 2011

Revised: September 15, 2011

Accepted: November 23, 2011

Published online: February 9, 2012

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