IL-33 signaling contributes to the pathogenesis of myeloproliferative neoplasms

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Myeloproliferative neoplasms (MPNs) are characterized by the clonal expansion of one or more myeloid cell lineage. In most cases, proliferation of the malignant clone is ascribed to defined genetic alterations. MPNs are also associated with aberrant expression and activity of multiple cytokines; however, the mechanisms by which these cytokines contribute to disease pathogenesis are poorly understood. Here, we reveal a non-redundant role for steady-state IL-33 in supporting dysregulated myelopoiesis in a murine model of MPN. Genetic ablation of the IL-33 signaling pathway was sufficient and necessary to restore normal hematopoiesis and abrogate MPN-like disease in animals lacking the inositol phosphatase SHIP. Stromal cell–derived IL-33 stimulated the secretion of cytokines and growth factors by myeloid and non-hematopoietic cells of the BM, resulting in myeloproliferation in SHIP-deficient animals. Additionally, in the transgenic JAK2V617F model, the onset of MPN was delayed in animals lacking IL-33 in radio-resistant cells. In human BM, we detected increased numbers of IL-33–expressing cells, specifically in biopsies from MPN patients. Exogenous IL-33 promoted cytokine production and colony formation by primary CD34+ MPN stem/progenitor cells from patients. Moreover, IL-33 improved the survival of JAK2V617F–positive cell lines. Together, these data indicate a central role for IL-33 signaling in the pathogenesis of MPNs.

Introduction

Myeloproliferative neoplasms (MPNs) comprise a heterogeneous group of malignant clonal hematopoietic diseases including, among others, BCR-ABL1-negative polycythemia vera (PV), essential thrombocytopenia (ET), and primary myelofibrosis (PMF), as well as BCR-ABL1–positive chronic myelogenous leukemia (CML). While the BCR-ABL1 fusion protein results in a constitutively activated tyrosine kinase activity in CML, BCR-ABL1-negative MPNs often harbor mutations in the Janus kinase (JAK)/signal transducer and activator of transcription (STAT) pathway. Both types of genetic alterations lead to abnormal proliferation of myeloid cells in the absence of overt signs of morphological dysplasia (1).

Although the role of cytokines and growth factors in normal hematopoiesis is widely recognized, their precise contribution to MPN pathogenesis is still unclear. In vitro, cells from MPN patients are characterized by an intrinsic independence and/or hypersensitivity to growth-factor stimulation and cytokine stimulation (2, 3). In CML cells, the BCR-ABL1 protein stimulates constant autocrine production of IL-3, IL-6, G-CSF, and TNF (3–5). The long-term outcome of CML patients has substantially improved with the use of the tyrosine kinase inhibitor imatinib, yet its efficacy may be hampered by the action of cytokines (6). The JAK2V617F mutation is often found in BCR-ABL1-negative MPNs and similarly results in constitutively activated kinase activity, mimicking persistent signaling via multiple cytokine pathways. While JAK inhibitors have been successful in treating JAK2-mutated MPNs, elimination of the mutant clone and resistance may pose an important problem, and patients with WT JAK2 MPNs are not amenable to this therapy (7). The abnormal expression and activity of a number of proinflammatory cytokines are associated with BCR-ABL1–negative MPNs (8), possibly initiating clonal evolution (9) or promoting progression to myelofibrosis (10) and resistance against JAK2 inhibitors (11). Thus, cytokines and growth factors support the aberrant hematopoiesis associated with MPNs and provide mechanisms for drug resistance.

While several studies suggest that concomitant inflammation supports MPN pathogenesis and development, it remains elusive whether inflammation precedes and may thus initiate the myeloproliferation. Indeed, previous inflammatory conditions have been linked to myeloid malignancies (12). Moreover, recent epidemiologic studies have reported an association between MPNs and either certain autoimmune diseases (13) or antecedent chronic inflammatory conditions of infectious origin (14). Microbe-sensing receptors — and TLRs in particular — may initiate such inflamma-

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tion, and monocytes from MPN patients may display an increased responsiveness to TLR ligands, leading to excessive cytokine production (15). Therefore, and although strong causative evidence is currently lacking, microbial infections driving sustained inflammation may potentially trigger MPNs.

IL-33 is a recently identified member of the IL-1 family of cytokines that binds to a heterodimeric receptor complex consisting of ST2 (IL-1RL1) and IL-1 receptor accessory protein. IL-33 signaling is thus further transduced via recruitment of the adapters MyD88 and IL-1 receptor-associated kinase 4 (IRAK4), which are shared with TLRs. IL-33 is predominantly expressed by endothelial and epithelial cells (16, 17), and it has primarily been implicated in the induction of type-2 immune responses by binding to ST2, which is expressed on a variety of cells such as Th2 CD4+ T cells, mast cells, and basophils (16). While IL-33 has recently emerged as a cytokine with pleiotropic functions in diverse types of inflammatory processes — including inflammatory bowel disease (18) and virus-induced inflammation (19, 20) — its function in tumorigenesis is poorly characterized.

Here, we used a mutant allele of the inositol polyphosphate-5-phosphatase D (Inpp5d, which encodes SHIP, an SRC homology 2 domain–containing inositol-5-phosphatase) called styx to investigate the mechanisms underlying spontaneous development of MPN-like disease. Since microbial cues can be sufficient to drive inflammatory disease in genetically susceptible strains (21, 22), we assessed the suppressive effect of a genetic blockade of selected inflammatory pathways in the pathogenesis of MPN-like disease in Inpp5dstyx/styx mice (herein referred to as styx mice). We identified a critical role for MyD88 and IRAK4 in determining the phenotype. Our data indicate that microbial-derived signals are dispensable, whereas the IL-33/ST2 pathway is non-redundant for initiating involvement of the IL-33/ST2 pathway in MPN pathogenesis.

Results
Development of MPN-like disease is directed by MyD88 but independent of microbiota-derived signals. As a model of MPN, we used a Inpp5dstyx allele that was identified in an N-ethyl-N-nitrosourea (ENU) genetic screen. The styx point mutation results in a thymine-to-adenine transversion in the donor splice site of intron 5 of the Inpp5d gene, causing an aberrant transcript lacking exon 5, which in turn leads to loss of SHIP protein expression (Supplemental Figure 1, A–D; supplemental material available online with this article; doi:10.1172/JCI77347DS1). SHIP is a negative regulator of the PI3K cascade, which encodes SHIP, an SRC homology 2 domain–containing inositol-5-phosphatase D (Inpp5d, UNC93B13d/13d double mutants with impaired endosomal TLR signaling died earlier compared with styx mice, likely from an increased susceptibility to opportunistic infections (Supplemental Figure 2A).

We further hypothesized that MPN development may be provoked by synergistic signaling via multiple TLRs converging toward MyD88 and IRAK4. However, styx mice rederived into a germ-free environment, and consequently exposed to a greatly reduced quantity of TLR ligands, developed MPN-like disease at the same rate and severity as mice kept under specific pathogen-free (SPF) conditions (Supplemental Figure 2).

TLR signaling triggers host cell responses with production of effector cytokines such as TNF. Introduction of a mutation disrupting TNF binding to its receptor significantly extended lifespan but failed to completely rescue styx mice. This reveals a partial contribution of TNF to disease development and associated immunopathology in our model (Figure 1A).

In brief, progression of MPN-like disease in styx mutants is controlled by signaling through MyD88 and IRAK4, but not TLRs. Moreover, the commensal microbiota is not required to induce the observed phenotype.

A non-redundant contribution of the IL-33/ST2 pathway to MPNs. MyD88 and IRAK4 not only transduce signaling from TLRs, but they are also located downstream of the receptors for the cytokines IL-1, IL-18, and IL-33. Abrogation of signaling through the IL-1 or IL-18 pathways did not limit SHIP-controlled myeloproliferation (Figure 1C).

However, styx mice with bi-allelic deficiency in the MyD88-dependent IL-33 receptor ST2 were found to be protected from disease development (Figure 1C), demonstrating that signaling from ST2 was necessary to induce MPN-like disease in styx mutants. Dysregulated BM hematopoiesis is a key feature of MPNs in humans and is also the primary etiology for the myeloproliferative disease accompanying SHIP deficiency (23). We thus assessed hematopoietic stem cell (HSC) and myeloid progenitor cell populations in homozygous styx, styx St2−/−, WT, and St2−/− mice by flow cytometry, according to Wilson et al. (Supplemental Figure 3, A and B; ref. 26). Percentages of HSCs (Figure 2, A and B) and myeloid progenitors (Figure 2, C and D) were significantly increased in the BM of styx mice, compared with WT...
mice. However, genetic blockade of IL-33/ST2 signaling prevented the aberrant hematopoiesis associated with SHIP deficiency, since percentages of BM HSC and myeloid progenitor cell populations were comparable in styx St2−/− mice and WT or St2−/− controls (Figure 2, A–D).

In the periphery, effective hematopoiesis with granulocytosis and monocytosis were observed in styx but not styx St2−/− mice, as measured by complete blood count (CBC) analysis (Figure 2E). We next functionally analyzed styx, styx St2−/−, WT, and St2−/− BM lineage-negative (lin−) cells for their capacity to form myeloid colonies. SHIP-deficient HSCs are known for their increased capacity to form myeloid colonies due to their enhanced sensitivity to cytokines (23, 24). Accordingly, styx lin− cells exhibited markedly increased colony formation compared with St2−/− and WT controls. However, colony numbers were similarly augmented for styx St2−/− cells (Figure 2F). This implies that although disruption of IL-33/ST2 signaling normalizes hematopoietic subsets in styx mice, styx St2−/− cells retain an intrinsic hyperproliferative ability.

Taken together, these results reveal that steady-state engagement of the IL-33/ST2 pathway acts as a non-redundant trigger for the accumulation of BM HSCs and myeloid progenitors, and for the concomitant MPN-like phenotype observed upon SHIP loss of function.

Stromal IL-33 engages ST2 signaling on both the radio-resistant and the radio-sensitive compartments to induce MPN-like disease. To determine the source of IL-33 and the compartment(s) expressing ST2 in our model system, we next generated various sets of BM chimeric mice. Lethally irradiated styx mice reconstituted with styx BM did not develop MPN-like disease (Figure 3A and Supplemental Table 1), thereby indicating a non-hematopoietic origin of IL-33 for uncontrolled myelopoiesis. Since the BM is the primary site of hematopoiesis in adult mice, we investigated whether BM stromal cells produce IL-33. IHC analysis showed that IL-33 protein in BM was expressed at similar levels in styx, styx St2−/−, WT, and St2−/− mice. Furthermore, IL-33 expression was restricted to few cells — mostly of which had characteristic histological features of endothelial cells (ECs) — lining the BM sinusoids (Supplemental Figure 3). Thus, although IL-33 is not constitutively expressed in ECs along the vascular tree (17), our data demonstrate that it is expressed in some BM sinusoidal ECs.

ST2 is expressed on BM stromal and hematopoietic cells, but not on myeloid progenitors. To assess how IL-33 produced by radioresistant cells induces MPNs in styx mutants, we analyzed the expression pattern of the ST2 receptor on BM cells of styx, styx St2−/−, WT, and St2−/− mice. While surface ST2 was not detectable on BM HSCs and myeloid progenitors (Supplemental Figure 4), we identified a heterogeneous lin− population of myeloid origin cells that expressed ST2 that was CD11b−, Ly6C+ and Ly6G+ (Figure 4, A and B). Further phenotypic analysis revealed that the majority of these cells most likely represented early myeloid cells and were CD11b−, FcεRI−, and c-KIT+, while the minority were basophils, defined as CD11b−, FcεRI+, c-KIT+, and CD49b+ (Supplemental Figure 5A). These two ST2+ populations accounted for 5%–6% and 0.7% of total hematopoietic cells in the BM, respectively (data not shown). Importantly, ST2+ BM cells in styx versus
WT mice did not differ in their relative distribution or their ST2 expression levels (data not shown).

Since our BM chimera experiments indicated that the radio-resistant compartment was also able to promote MPN-like disease in an ST2-dependent manner, we correspondingly assessed ST2 expression on BM stromal cells. We found that ECs (defined as CD45–, lin–, CD31–, and CD51+) and mesenchymal stromal cells (MSCs; specified as CD45–, lin–, CD31–, CD51–, and CD140a+; ref. 27) in the BM expressed ST2, although ST2 expression was marginal on MSCs (Figure 4C and Supplemental Figure 5B).

Together, our data suggest that the BM microenvironment contains the minimal requirements to promote myeloproliferative disease on a SHIP-deficient background via activation of IL-33/ST2 signaling. Furthermore, the expression pattern of ST2 indicates that IL-33/ST2 signaling likely has an indirect effect on styx HSCs and myeloid progenitors.

IL-33 acts indirectly on HSCs and myeloid progenitors. In order to determine a potential indirect mode of action of IL-33/ST2 signaling in HSCs and myeloid progenitor cells, we used magnetic cell separation to purify lin– cells from styx or WT BM and assessed their capacity to form colonies in the presence or absence of IL-33 (Figure 4D). IL-33 alone did not affect colony formation of lin– BM cells. However, stimulation with IL-6 and/or GM-CSF, factors known to promote myeloproliferation and contribute to the dysregulated hematopoiesis characteristic of SHIP-deficient mice (23, 24, 28), increased the number of colonies from styx and WT lin– BM cells. Moreover, addition of IL-33 to IL-6 and GM-CSF did not further modulate the colony-forming ability of lin– cells (Figure 4D). These results show that IL-33 does not promote colony formation of mouse HSCs and myeloid progenitor cells directly, and it does not synergize with other known myeloproliferative factors. Also, and in agreement with our ST2 expression analysis, SHIP-deficiency is not associated with an increased sensitivity of HSCs and myeloid progenitors to IL-33, as observed for IL-6 and GM-CSF (Figure 4D).

We next performed a coculture assay to dissect how IL-33/ST2 signaling indirectly supports development of MPN-like disease in styx BM. We assessed the contribution of stromal cells, as well as the role of the hematopoietic cell population we previously identified as constitutively expressing ST2. To this end, we measured colony formation by ST2– lin– cells following coculture with IL-33–stimulated primary stromal cells (MACS-purified CD45– BM cells) or after supplementation with conditioned medium from IL-33–stimulated, ST2+ BM hematopoietic cells. Under these experimental settings, we observed an increase in colony formation of styx St2–/– or St2–/– lin– BM cells solely in the combined presence of exogenous IL-33 and ST2-expressing stromal or hematopoietic responders (Figure 4E).

Hence, we concluded that IL-33 can indirectly support development of MPN-like disease in styx mutants via the activation of the radio-resistant compartment, as also indicated by our BM chimera experiments.
experiments (Figure 3). Our results also suggest that the ST2-expressing hematopoietic population in the BM is able to sustain myeloproliferation, likely via the secretion of soluble factors. In addition, the contribution of ST2+ hematopoietic cells to development of myeloproliferation in styx mice appears to be superior to the one provided by ST2+ stromal cells, in line with our findings from the BM chimeras.

**IL-33 induces cytokine and growth-factor secretion by BM cells.** Increased levels of several growth and survival factors in the peripheral blood have been proposed to contribute to the dysregulated hematopoiesis observed in SHIP-deficient mice (29). Accordingly, analysis of the sera of 40-day-old styx mice that were healthy in appearance showed that the levels of cytokines critical in supporting myelopoiesis — including G-CSF, IL-6, and to a lesser extent GM-CSF, M-CSF, IL-3, and IL-5 — were already elevated in several mutants at this age (Supplemental Figure 6, A–F). Conversely, the same cytokines were present at low concentrations in age-matched styx St2–/–, WT, or St2–/– mice. Although we previously identified TNF as a partial mediator of MPN-like disease, it was not elevated in the serum of young styx mice (Figure 1A and Supplemental Figure 6G). However, serum IL-33 levels were significantly augmented in the mutants (Supplemental Figure 6H).

SHIP has been suggested to regulate the production of soluble factors produced by the BM niche (29). To assess the ability of the BM microenvironment to secrete cytokines and growth factors in response to IL-33 and thus promote myelopoiesis, we isolated BM cells from styx and WT mice, and we MACS-purified them into CD45− non-hematopoietic and CD45+ hematopoietic cell fractions. Ex vivo stimulation with IL-33 increased the levels of G-CSF, GM-CSF, IL-3, and IL-6 in the supernatants of both CD45− and CD45+ cell fractions (Figure 5). IL-5 was only secreted by CD45+ hematopoietic cells. Engagement of IL-33/ST2 signaling was required, as specific cytokine secretion was abrogated in the absence of ST2 (Figure 5). Therefore, we deduced that the BM microenvironment is able to produce growth factors in response to secreted IL-33 to provoke uncontrolled myeloproliferation in **styx** mice.

SHIP-deficient myeloid cells display a higher responsiveness to cytokines, such as GM-CSF and IL-3, that leads to a reduced susceptibility to apoptotic stimuli (23, 24). Consequently, we next evaluated whether IL-33/ST2 signaling may affect the viability of **styx** BM cells. We found that ex vivo CD11b+ BM **styx St2–/–** cells cultured for short term (6 hours) without cytokine supplementation showed survival rates similar to control cells but reduced compared with ST2-proficient **styx** cells (Supplemental Figure 7A). Correspondingly, in vitro stimulation with IL-33 promoted the survival of **styx** but not **styx St2–/–** CD11b+ BM cells (Supplemental Figure 7B).

In summary, these data support the notion that IL-33 is an important trigger for the production of effector cytokines by the stromal and hematopoietic compartments. These cytokines, in turn, promote enhanced survival and proliferation of myeloid cells, eventually resulting in MPN-like disease in **styx** mutants.

**Strontal IL-33 supports the development of JAK2V617F-dependent MPNs in vivo.** To assess the contribution of IL-33/ST2 signaling to dysregulated myelopoiesis in a different model of MPN, we adoptively transferred BM cells transgenic for the JAK2V617F mutation (30) into Il33−/− recipient mice. In these chimeras, we found a lower percentage of JAK2V617F+ GMPs in the BM and a reduced frequency of both CD45− and CD45+ cell fractions (Figure 5). IL-5 was only secreted by CD45+ hematopoietic cells. Engagement of IL-33/ST2 signaling was required, as specific cytokine secretion was abrogated in the absence of ST2 (Figure 5). Therefore, we deduced that the BM microenvironment is able to produce growth factors in response to secreted IL-33 to provoke uncontrolled myeloproliferation in **styx** mice.
Figure 4. ST2 expression and function in the BM. (A) ST2 expression on hematopoietic BM cells is restricted to committed myeloid cells (CD11b<sup>int</sup>, Ly6<sup>G</sup>, and Ly6<sup>C</sup>). Representative histogram of one styx and one WT mouse is shown. (B) Cytospin of FACS-purified BM CD11b<sup>int</sup>, Ly6<sup>G</sup>, Ly6<sup>C</sup>, ST2<sup>+</sup> cells showing phenotypical heterogeneity (scale bars: 20 μm). (C) ST2 expression on BM endothelial cells (defined as CD45<sup>-</sup>, lin<sup>-</sup>, CD51<sup>-</sup>, and CD31<sup>+</sup>). (D) Lin<sup>-</sup> BM cells from styx and WT mice were cultured in methylcellulose with the indicated cytokines. Colony numbers were assessed after 7 days. (E) BM primary stromal cells were grown in vitro (46). MACS-purified CD45<sup>-</sup> cells from these cultures were stimulated with IL-33 for 24 hours, before addition of lin<sup>-</sup> cells for coculture. Alternatively, lin<sup>-</sup> cells were supplemented with conditioned medium from FACS-purified CD11b<sup>int</sup>, Ly6<sup>G</sup>, and Ly6<sup>C</sup> cells previously stimulated with IL-33 for 24 hours. Then, styx ST2<sup>−/−</sup> or ST2<sup>+/+</sup> lin<sup>-</sup> cells incubated for 48 hours under these respective conditions were cultured in methylcellulose for 7 days, and colony formation was assessed. Conditions for culture (± IL-33) and genotypes of stromal or hematopoietic stimulation responders (+: styx ST2<sup>+/+</sup>; -: styx ST2<sup>−/−</sup>) are indicated. Data are mean ± SEM and are representative of (A) n = 8 mice per group; (B) n = 2 mice per group; (C) pooled cells from 4 WT mice, repeated twice; (D) pooled data of 2 experiments, n = 6 mice per group; and (E) 1 experiment where each data point represents 2 pooled mice (n = 6 mice per group). Stromal and hematopoietic responders were pooled from 5 donors. (D and E) One-way ANOVA with Bonferroni post hoc test was used. *P < 0.05; **P < 0.01; ***P < 0.001; and ****P < 0.0001.
of blood neutrophils (defined as CD11b+ and Ly6G+) compared with control mice expressing IL-33 in the stroma (Figure 6, A and B). IL-33-deficiency in the radio-resistant compartment also correlated with delayed expansion of several hematopoietic lineages from donor JAK2V617F+ BM cells (Figure 6C). Taken together, these data suggest that stromal cell–derived IL-33 supports the development of JAK2V617F-dependent MPNs in vivo.

Increased levels of IL-33 protein in the BM of MPN patients. To address the general relevance of the findings from our mouse models of MPN, we assessed the presence of IL-33 in the BM of MPN patients. IL-33 was also expressed in human BM biopsies and was localized in the nucleus of cells that were mainly but not solely endothelial, based on their histomorphological presentation and expression of CD34 (Figure 7, A and B). Automated quantification of cells displaying nuclear IL-33 expression indicated that MPN patients newly diagnosed with ET, PMF, and PV, but not CML, display a higher percentage of IL-33+ BM cells compared with controls (Figure 7C). This increase seemed specific to BCR-ABL1–negative MPN patients, as it was not detected in other types of chronic or acute leukemia affecting the myeloid or lymphoid lineages (Supplemental Figure 8A). Hence, these data suggest that the IL-33/ST2 pathway may also play a role in the pathogenesis of human MPNs.

MPN cell lines and CD34+ stem/progenitor cells from MPN patients directly respond to IL-33. The IHC findings from patient BM biopsies raised the question as to whether IL-33 also exerts a proproliferative effect on human MPN cells. In particular, the increase in IL-33 protein expression in BCR-ABL1–negative MPNs prompted us to examine the effect of IL-33 on human JAK2V617F+ cells. In vitro experiments showed that IL-33 promoted the upregulation of CSF2 (GMCSF) and IL6 transcripts in several JAK2V617F+ cell lines (Figure 8A). These cell lines constitutively expressed ST2 on the surface (Supplemental Figure 8B). IL-33 did not stimulate the growth of MPN cell lines; however, it improved their survival (Figure 8B). Human BCR-ABL1+ CML cell lines expressed ST2 at various intensities, and they also upregulated the transcription of growth factors when stimulated with IL-33 (Supplemental Figure 8, C and D). However, IL-33 did not influence the proliferation or the survival of CML cell lines (Supplemental Figure 8E). These results suggest that JAK2V617F+ cells are more sensitive to the effects of IL-33/ST2 signaling compared with BCR-ABL1+ CML cells.

Primary human CD34+ hematopoietic stem/progenitor cells (HSPCs) express ST2 receptor and secrete cytokines and chemokines when stimulated with IL-33 (31). We detected increased ST2 expression on CD34+ stem/progenitor cells from BCR-ABL1–negative MPN patients (Figure 8, C and D). In agreement with our data from cell lines, GMCSF expression was significantly upregulated in circulating CD34+ stem/progenitor cells from CML patients and CD34+ HSPCs from controls following IL-33–mediated stimulation (Supplemental Figure 8F). Furthermore, IL-33 promoted colony formation of CD34+ MPN stem/progenitor cells but not of CD34+ control HSPCs (Figure 8E).

Collectively, these observations extend our in vivo data in SHIP-deficient mice and substantiate their relevance to human MPNs. Our findings also point toward differences as to how the IL-33/ST2 pathway may exert an effect on MPN progenitors — either via the intermediate of differentiated cells that are ST2+ in the mouse model or directly on ST2-expressing CD34+ stem/progenitor cells in MPN patients (Figure 9).
lung and intestine — organs that contain relatively high numbers of IL-33–expressing cells (Supplemental Figure 9; ref. 17). This immunopathology likely leads to rising concentrations of IL-33 in the serum, as detected in **styx** mutants. The evidence that altered hematopoiesis develops spontaneously in our model is still reconcilable with our initial hypothesis proposing that external stimuli may promote MPN development. IL-33 released during infection with pathogens (19, 20) may indeed further precipitate uncontrolled myeloproliferation. Also, opportunistic infections may be the cause of the accelerated disease observed in **styx** mice deficient in **Tlr4**, **Unc93b1**, or **Il18** (Figure 1, A and B, Supplemental Figure 2A, and Figure 1C). Accordingly, the irradiation-induced increase in proinflammatory cytokines such as IL-6 and G-CSF, but also IL-33 (35, 36), likely accounts for the accelerated disease kinetics observed in chimeric mice reconstituted with **styx** BM compared with nonmanipulated **styx** mutants (Figures 1 and 3). Irradiation-induced systemic inflammation may also mask the relative contribution of radio-resistant cells to MPN-like disease in our model. This may explain why the **styx**→WT and **styx**→St2–/– sets of chimeras develop MPN-like disease with similar kinetics (Figure 3); however, our data show that BM stromal cells can engage ST2, for example to promote colony formation in vitro (Figure 4E).

Increased availability of IL-33 in the BM may similarly support disease pathogenesis in BCR-ABL1–negative MPN patients.

Critically, we observed a different ST2 expression pattern in mice compared with humans. In the BM of **styx** and WT mice, ST2 expression was restricted to non-hematopoietic stromal and committed hematopoietic cells. ST2 protein was undetectable on murine HSCs and myeloid progenitors, and addition of IL-33...
IL-33 has a dual function, both as an inhibitor of transcription when residing in the nucleus (39) or as a proinflammatory cytokine upon release (16). Our results suggest that in its extracellular function and through ST2 binding, IL-33 promotes dysregulated hematopoiesis in the styx and transgenic JAK2V617F models, as well as cytokine production in stimulated MPN cells. Interestingly, plasma levels of IL-33 are not altered in CML patients (37) and are even reduced in patients suffering from PV or ET (34). Although availability of secreted IL-33 in the niche has yet to be demonstrated, we clearly show that nuclear IL-33 is expressed to a greater extent in the BM of newly diagnosed BCR-ABL1–negative MPN patients compared with controls. Since MPN stem/progenitor cells display hypersensitivity to cytokines and growth factors, similarly to SHIP-deficient HSCs and myeloid progenitor cells (2, 23), it is conceivable that even low amounts of secreted IL-33 within the niche may suffice to initiate ST2-dependent inflammation that supports MPNs.

While the soluble form of ST2 appears to be a predictive marker for clinical stage and outcome in CML (37), no such data exist on the role for IL-33/ST2 signaling in the progression of BCR-ABL1–negative MPNs. In particular, its potential contribution to the progression to end-stage myelofibrosis is unclear. IL-33 has a known direct proangiogenic effect on ECs (40), and increased microvessel den-
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The city has been associated with fibrosis in JAK2V617F mutation-bearing MPN patients (41). Furthermore, abnormal expression and activity of a number of proinflammatory cytokines are linked to myelofibrosis (10), and our results indicate that IL-33 promotes the secretion of various cytokines in the BM microenvironment. Therefore, it may be relevant in the future to address whether therapeutic blockade of the IL-33/ST2 axis may prevent myelofibrosis or halt its progression.

In summary, our data provide evidence for a role of IL-33/ST2 signaling for dysregulated hematopoiesis in mouse models of MPN. They also indicate that IL-33 expression is specifically increased in the BM of BCR-ABL1-negative MPN patients. Our results warrant further investigation on the contribution of the IL-33/ST2 axis to disease pathogenesis in MPN patients.

Methods

Patients. PBMCs from CML or JAK2V617F-positive patients at diagnosis — or from donors who underwent peripheral blood stem and progenitor cell mobilization and collection for reasons other than hematological neoplasms — were obtained from the Department of Hematology of the University Hospitals of Bern and Zurich, Switzerland, and were enriched for CD34+ stem/progenitor cells by MACS. Samples from BM biopsies were retrieved from the archives of the Institute of Pathology, University of Bern, Switzerland; control samples were obtained from non-leukemic individuals showing minimal reactive changes. All CML patients were positive for the BCR-ABL1 transcript.

Animals. All strains used were on a C57BL/6J background. C57BL/6J mice bred at The Scripps Research Institute (TSRI) were injected with ENU, as described (42). The Inpp5d styx/styx (styx mice), Myd88poc, Irak4otiose, Tlr2languid, Tlr4lps3, TnfPanR1, and Unc93b1 3d strains are described at the Southwestern Medical Center Mutagenetix database (http://mutagenetix.utsouthwestern.edu). B6.129S7-Il1r1 tm1Imx/J, B6.129P2-Il18 tm1Aki/J, and B6.SJL-Ptprca Pep3b BoyJ mice were obtained from The Jackson Laboratory. Il33 –/– mice (43) were obtained through the RIKEN Center for Developmental Biology (Acc. No. CDB0631K; http://www.cdb.riken.jp/arg/mutant%20mice%20list.html). Il1r1–/– (St2–/–) mice have been described (44). The styx mice were rederived to germ-free status by 2-cell embryo transfer and were maintained in flexible film isolators in the Clean Mouse Facility, University of Bern, Switzerland. BM cells from transgenic JAK2V617F (Scl-Cre FF1; ref. 45) mice were provided by Radek C. Skoda (University Hospital Basel, Basel, Switzerland). For survival analyses, data were collected during the entire course of the study and pooled for graphic representation. Unless indicated in the corresponding figure, animals used in this study were 6–12 weeks old and age/sex-matched.

Figure 8. IL-33/ST2 signaling promotes MPN development. (A) Indicated JAK2V617F+ cell lines were incubated for 24 hours ± IL-33, and expression levels were measured for the transcripts of the indicated genes. Mean expression levels of technical duplicates are represented as fold induction and have been normalized to conditions without IL-33. (B) The MPN cell lines SET-2 and HEL were cultured ± IL-33, and percentage of live cells (annexin V–DAPI–) was assessed at the indicated time points. Results show means ± SEM. (C) Representative histograms showing ST2 expression on blood CD34+ stem/progenitor cells from controls and MPN patients cultured in standard CFC medium ± IL-33 for 2 weeks. Data are mean ± SEM and show fold changes in colony numbers after normalization to conditions without IL-33. Healthy (n = 5) and 10 MPN donors were used. (A) One representative of 2 independent experiments, and (B) pooled values from 3 individual experiments are shown. (C and D) Pooled data from 2 independent experiments are shown. (B) Standard Student’s t test. (C) Standard Student’s t test with Welch’s correction, and (D) Wilcoxon signed-rank test were used. *P < 0.05; **P < 0.01.
Colony formation assay. Purified, lin− murine BM cells were cultured at a starting density of 2 × 10³ to 5 × 10³ for 7 days in MethoCult-based medium (StemCell Technologies Inc.) supplemented with 15% FCS, 100 U/ml penicillin, 100 μg/ml streptomycin, 2 mM L-glutamine, 100 μM 2-mercaptoethanol, and 20% BIT (50 mg/ml BSA in IMDM, 1.44 U/ml rh-insulin, 250 ng/ml human holo transferrin). The following cytokines were always included: 50 ng/ml rm SCF, 10 ng/ml, 50 ng/ml rm Flt3-ligand, and 10 ng/ml rm IL-3. The following cytokines were added when specified: 10 ng/ml rh IL-6, 100 ng/ml rm GM-CSF, and 100 ng/ml rm IL-33 (all from ProSpec). Colonies were counted using a DMIL inverted microscope (Leica Microsystems) mounted with an Intensilight C-HGFI unit (Nikon). Alternatively, 1 × 10⁴ primary blood CD34+ stem/progenitor cells from MPN patients or healthy donors were plated in MethoCult H4435 Enriched medium (StemCell Technologies Inc.) with or without 100 ng/ml rh IL-33 (ProSpec). Colonies were counted after 14 days.

Flow cytometry. BM cells were resuspended and filtered through 70 μm cell strainers (Falcon Technologies BD) to obtain single-cell suspensions. Following rbc lysis, FcR blockade, and lineage depletion, HSCs and myeloid progenitors were stained as described previously (26), using the antibodies indicated in Supplemental Table 2. Live/dead cell discrimination was performed using DAPI (Biorad) and annexin V (BioLegend). The gating strategy used to discriminate HSC and myeloid progenitor cell populations is shown in Supplemental Figure 3, A and B.

Blood-derived, MACS-purified CD34+ human stem/progenitor cells were carefully thawed in HBSS containing 10% human serum. After centrifugation, cells were resuspended in IMDM and analyzed for colony formation or ST2 surface expression. The gating strategy used to assess ST2 expression on primary human CD34+ stem/progenitor cells is shown in Supplemental Figure 10.

Figure 9. Models for the development of MPN in the BM microenvironment. (A) Model for SHIP-deficient mice. Stromal cell–derived IL-33 is released under stress or steady-state conditions through a pathway that is yet to be determined. IL-33 engages its receptor ST2 on stromal cells or, preferentially, on a committed population of myeloid cells. Signal transduction via the ST2→MyD88→IRAK4 axis promotes the secretion of several cytokines and growth factors promoting myoproliferation — among others GM-CSF and IL-6 — that bind to their respective receptors and activate the JAK2/STAT5 pathway (49). SHIP is a negative regulator in this process, and impaired SHIP-mediated inhibition results in MPN-like disease. (B) IL-33 released by stromal cells in the human BM engages ST2 receptor on CD34+ HSPCs. Activation of cell signaling downstream of ST2 leads to the production of autocrine cytokines and growth factors that support proliferation.
Coculture experiment. Regarding preparation of BM stromal responders, BM stromal cell (BMSC) cultures were set up from epiphyses from 5 mice per group, as described previously (46). CD45-BMSCs were MACS-purified after 3 weeks of expansion, and ST2 expression was confirmed by flow cytometry (data not shown). Then, $5 \times 10^4$ purified BMSC were stimulated with 100 ng/ml rm IL-33 for 24 hours. In preparation of supernatant from BM hematopoietic responders, $5 \times 10^4$ FACs-purified CD11b$^\text{int}$ Ly6G$^-$ Ly6C$^-$ hemato-poietic BM cells pooled from 5 mice per group were stimulated with our without 100 ng/ml rm IL-33. Supernatant was collected after 24 hours and stored frozen. Next, $5 \times 10^3$ lin$-$ MACS-purified BM cells pooled from 6 mice per group were added to IL-33-stimulated BMSCs for coculture or supplemented with supernatant from IL-33-stimulated hematopoietic cells. After 48 hours of culture, $5 \times 10^3$ lin$-$ cells were seeded for colony formation assay as described above.

CBC. Blood was obtained through retro orbital bleeding of anesthetized mice and collected in Microvette (Sarstedt) tubes. CBC was assessed on a VetabcTM Animal Blood Counter (Scil Animal Care Company GmbH).

Chimeric experiments. Mice were irradiated twice with an individual dose of 650 cGy with 4 hours recovery time between. Mice were then adoptively transferred i.v. with $1 \times 10^7$ cells from whole BM of donor mice.

Scoring of Disease Activity Index (DAI). DAI was determined twice every week using a score index approved by the local authorities and based on previous reports (47, 48). Score was determined according to specific criteria. Behavior scores were as follows: apathy (2.8); hiding, not active, aggressive upon touch (1.8); hiding, calm, active upon touch (0.5); and active, attentive (0). Breathing scores were as follows: impaired, heavy breathing (2.8); and normal breathing (0). Body condition scores were as follows: emaciated (1.8); under-conditioned (0.5); and well-conditioned (0). Exercise and posture scores were as follows: paralysis (2.8); bent posture, strong bristling of hairs, motoric disorder (1.8); uncoordinated upon touch, bent posture, mild bristling of hairs (0.5); and normal (0).

Histology and IHC. Mouse and human tissues were fixed in 4% formaldehyde for 24 hours prior to dehydration and paraffin embedding. Sections were deparaffinized and stained with hematoxilin and eosin (H&E) or PAP under standard conditions. Antigen retrieval for IHC was performed with treatment in a 1 mM Tris/1 mM EDTA pH 9.0 solution for 18 minutes or in Bond Epitope Retrieval Solution 2 (Leica Biosystems) for 30 min at 95°C, for murine (IL-33) or human tissue (IL-33 and CD34), respectively. After an endogenous peroxidase block, primary goat anti-mouse IL-33, goat anti-human IL-33 (both from R&D Systems), and mouse anti-human CD34 (Dako) antibodies were used at a dilution of 1:100, 1:400, and 1:200, respectively. A secondary rabbit anti-goat antibody (Dako) or rabbit anti-rat antibody (Leica Biosystems) (1:100), followed by a tertiary horseradish peroxidase–linked (HRP-linked) anti-rabbit antibody (Dako or Leica Biosystems), was used undiluted to detect positive cells.

IHC of tissues from Il33$^{-/-}$ mice was performed to exclude unspecific staining of the murine IL-33 antibody used in this study. As another negative control for antibody specificity, we incubated the goat anti-mouse IL-33 antibody with rm IL-33 prior to the staining of tissue from Il33$^{-/-}$ mice. We also stained tissue from Il33$^{-/-}$ mice with a goat anti-rabbit isotype control antibody (Dako). Slides were quantified with Aperio Group LLC. Settings used for analysis were adjusted and controlled by a board certified pathologist in a blinded fashion.

Quantitative PCR assay. Mouse primary BM cells were MACS-purified with a murine CD45 micro-bead assay (Miltenyi Biotec) according to the manufacturer’s protocol. RNA from human cell lines or primary MACS-purified CD34$^+$ stem/progenitor cells from donors was purified using TRI-reagent (Sigma-Aldrich). RNA was transcribed into cDNA using M-MLV reverse transcriptase (Promega). FastStart SYBR Green Master (Roche Diagnostics) was used to detect the target genes GCSF, GMCSF, IL6, and GAPDH (Qiagen). All reactions were run in a StepOnePlus Real-Time PCR System (Invitrogen). Expression levels of genes were normalized to GAPDH mRNA, and IL-33-stimulated versus unstimulated groups were compared applying the $2^{-\Delta\Delta Ct}$ method.

Human MNP cell lines. The human CML cell lines JURL-MK1, KU812, LAMA-84, and NALM-1 were provided by Patrick Ziegler (University Hospital Aachen, Aachen, Germany). The human JAK2$^{V617F}$ cells lines HEL 9.2.17 (HEL), SET-2, and UKE-1 were provided by Radek C. Skoda (University Hospital Basel, Basel, Switzerland).

Cytokine measurement. MACS-purified primary cells were stimulated with 100 ng/ml rm IL-33 for 24 hours ex vivo. Cells were centrifuged for 5 minutes at 500g, and supernatant was removed. Cell culture supernatant and serum cytokines were analyzed by Multiplexing LASER Bead Technology (Eve Technologies).

Statistics. Two-tailed standard Student’s $t$ test with or without Welch’s correction and Wilcoxon signed-rank tests were used as indicated for single comparisons. For datasets where multiple comparisons were performed, one-way ANOVA was performed with Bonferroni post hoc test. For survival curves, log-rank (Mantel-Cox) test was used. For all statistical analyses, $P$ values of less than 0.05 were considered significant.

Study approval. Patients and donors gave written informed consent, and the analyses of samples were approved by the cantonal Ethics Committee from Bern (Ethics Committee Bern, Bern, Switzerland) and Zurich (Ethics Committee Zurich, Zurich, Switzerland). All animal experiments were performed in accordance with institutional and federal regulations governing animal care and use, and were approved by TSRI Institutional Animal Care and Use Committee (La Jolla, California, USA) and the Cantonal Veterinary Office of Bern (Bern, Switzerland).

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