RhoA GTPase controls cytokinesis and programmed necrosis of hematopoietic progenitors

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Hematopoietic progenitor cells (HPCs) are central to hematopoiesis as they provide large numbers of lineage-defined blood cells necessary to sustain blood homeostasis. They are one of the most actively cycling somatic cells, and their precise control is critical for hematopoietic homeostasis. The small GTPase RhoA is an intracellular molecular switch that integrates cytokine, chemokine, and adhesion signals to coordinate multiple context-dependent cellular processes. By using a RhoA conditional knockout mouse model, we show that RhoA deficiency causes a multilineage hematopoietic failure that is associated with defective multipotent HPCs. Interestingly, RhoA+/− hematopoietic stem cells retained long-term engraftment potential but failed to produce multipotent HPCs and lineage-defined blood cells. This multilineage hematopoietic failure was rescued by reconstituting wild-type RhoA into the RhoA−/− Lin−Sca-1−c-Kit+ compartment. Mechanistically, RhoA regulates actomyosin signaling, cytokinesis, and programmed necrosis of the HPCs, and loss of RhoA results in a cytokinesis failure of HPCs manifested by an accumulation of multinucleated cells caused by failed abscission of the cleavage furrow after telophase. Concomitantly, the HPCs show a drastically increased death associated with increased TNF–RIP-mediated necrosis. These results show that RhoA is a critical and specific regulator of multipotent HPCs during cytokinesis and thus essential for multilineage hematopoiesis.

Mammalian hematopoiesis is a hierarchical and highly dynamic process (Ghaffari, 2008). This rapid and regulated program is sustained by a rare population of relatively quiescent hematopoietic stem cells (HSCs) that continuously generate hematopoietic progenitor cells (HPCs). HPCs are the workhorses in hematopoiesis and are critical for homeostasis of the blood system, as they are primarily responsible for the expansion of HSC progenies and generating differentiated blood cells. HPCs are therefore endowed with a very high proliferation potential. Consequently, a precise yet flexible regulatory program of HPC division is crucial to the maintenance of blood cell homeostasis under normal and stress conditions, the malfunction of which can cause a variety of hematologic diseases including BM failure, anemia, leukemia, and lymphoma (Boggs and Boggs, 1976; Bonnet and Dick, 1997; Castor et al., 2005). Thus, elucidating the mechanisms governing HPC proliferation and differentiation is of great significance.

The homeostasis of hematopoietic stem and progenitor cells (HSPCs) relies on, among other mechanisms, tightly controlled cell cycle and survival machineries. Molecules involved in regulating the cell cycle, such as p16Ink4a, p21Cip1/Waf1, p27Kip1, PTEN, and Egr1, and those regulating cell survival and apoptosis, such as p53, Bcl2, Bcl-x, and Mcl1, are essential for the maintenance of HSPCs (Cheng et al., 2000a,b; Arai et al., 2004; Kozar et al., 2004; Janzen et al., 2006;
In the HSPC compartment, RhoA activity is associated with the function of hematopoiesis and cytokinesis. Defining regulatory mechanisms of cytokinesis of primitive hematopoietic cells, and understanding mechanistic relationships between cell cycle abnormalities and cell death control, may result in more detailed knowledge of the regulatory machineries for critical steps in hematopoiesis.

RhoA, Ras homologue gene family, member A (RhoA) is among the first members of the Rho GTPase family identified and is best known as a critical regulator of cytoskeleton dynamics. It cycles between the GTP-bound active and GDP-bound inactive forms in response to diverse cellular stimuli under tight regulation (Van Aelst and D’Souza-Schorey, 1997). Upon activation (i.e., RhoA-GTP), RhoA transduces signals to downstream effectors to elicit cell functions including cell adhesion, survival, cell cycle progression, and transcription; studies have reported a critical involvement of RhoA in regulating cytokinesis (Jaffe and Hall, 2005). Active RhoA and its downstream signaling components such as F-actin, myosin, and annulin are concentrated at the cleavage furrow during cytokinesis. Disruption of this process results in cytokinesis failure and multinucleated cells (Piekny et al., 2005). However, our current knowledge about RhoA function is mostly derived from dominant-negative or constitutively active mutant overexpression studies performed in cultured cell lines, which are limited by specificity and dosage issues in their physiological implications. Models in which RhoA is genetically deleted are better systems to define the role of RhoA in tissue/cell type–specific physiological conditions. To this end, several recent conditional gene–targeting studies in mouse models have begun to reveal the unique and important functions of RhoA in various mammalian organs (Geh et al., 2011; Jackson et al., 2011; Melendez et al., 2011; Xiang et al., 2011; Pleines et al., 2012; Zhang et al., 2012). It appears that RhoA signaling function is cell type and pathway dependent, and many previously suggested cellular roles of RhoA may not be applicable to complex biological processes in vivo.

In this study, we investigate the role of RhoA in regulating HSPCs and hematopoiesis using an inducible RhoA conditional KO (cKO) model (Mx-cre, RhoAfl/fl). We demonstrate that RhoA is essential for multilineage hematopoiesis and deletion of RhoA results in acute pancytopenia and BM failure. In the HSPC compartment, RhoA deficiency does not affect stem cell engraftment but significantly impairs the function of multipotent progenitor cells. RhoA-null HPCs exhibit a cytokinesis block and undergo programmed necrosis but not apoptosis. Our results suggest for the first time that programmed necrosis associated with a cytokinesis arrest is an underlying mechanism of maintaining HPC homeostasis.

RESULTS

RhoA is essential for multilineage hematopoiesis

RhoA mRNA is expressed in the HSC and the progenitor (multipotent progenitor, Lin-Sca-1+c-Kit+ [LK]) compartments of the BM cells (not depicted). Biochemically, RhoA GTPase cycles between a GDP-bound inactive form and a GTP-bound active form. To examine the physiological relevance of RhoA activity, we used a Rhotekin pull-down assay to monitor relative RhoA-GTP level in response to stimuli known to activate HSPCs, including stem cell factor (SCF), stromal cell–derived factor 1α (SDF-1α), and fibronectin (Yoder and Williams, 1995; Broudry, 1997; Hattori et al., 2003). We observed that these factors all led to a substantial increase of GTP-bound active RhoA in lineage-negative (Lin–) cells (Fig. 1 A), suggesting that RhoA signaling is active and likely involved in regulating primitive hematopoietic cells in response to these hematopoietic regulatory factors.

To examine the relevance of RhoA signaling in stress-induced hematopoiesis, we examined RhoA activity in response to fluorouracil (5-FU) treatment, which was a strong myelosuppressive agent and could induce massive HSPC proliferation (Randall and Weissman, 1997; Venezia et al., 2004). 5-FU treatment caused a significant increase of RhoA activity in BM low-density monocytes without altering RhoA protein expression (Fig. 1 B). To further examine the activity of RhoA signaling within the hematopoietic progenitors, we measured the phosphorylation of regulatory myosin light chain (MLC), which is regulated by RhoA downstream effectors Rho-associate kinase (ROCK) and citron kinase (Kimura et al., 1996; Maekawa et al., 1999; Yamashiro et al., 2003). Increased phosphorylation of MLC was observed during the transition from the more primitive Lin–Sca-1+c-Kit+ (LSK) to the less primitive LK populations (Fig. 1 C). In addition, in the HSC-enriched Lin–CD150+CD48– (SLAM) population (Kiel et al., 2005), RhoA signaling in response to 5-FU treatment, monitored by the phosphorylation of MLC, closely correlated with the proliferative status of HSC (Fig. 1 D; Randall and Weissman, 1997; Venezia et al., 2004). Together these results suggest that RhoA activity is associated with the function hematopoietic progenitors.

To determine the function of RhoA in HSPCs, we crossed the interferon-inducible Mx-cre mice (Kühn et al., 1995) with RhoAfl/fl mice (Melendez et al., 2011) and induced deletion of RhoA using synthetic double-strand RNA poly I:C. Lin– cells isolated from Mx-cre+/RhoAfl/fl mice (RhoA-cKO) exhibited efficient RhoA deletion 3 d after two poly I:C injections (Fig. 1, E and F), and RhoA deletion did not cause a compensatory overexpression of the closely related Rho GTPase RhoB or RhoC (Fig. 1 F and not depicted). Interestingly, deletion of...
response to RhoA deletion and died 1 wk after poly I:C induction. By 5 d after poly I:C injections, RhoA deficiency resulted in a rapid and significant decrease of neutrophils (0.54 ± 0.09 k/µl in RhoA-cKO mice vs. 3.64 ± 0.18 k/µl in control) and a significant reduction of monocytes and platelets in the peripheral blood (PB; Fig. 1, G and H). In the erythroid lineage, RhoA deficiency did not alter the count of circulating lymphocytes in this experimental setup (Fig. 1 G), as these lineages usually posed a longer life span.

Although the Mx-cre–mediated gene targeting models have been broadly used in hematopoietic studies, gene KO is not limited to the blood system (Kühn et al., 1995). To specifically delete RhoA from the hematopoietic lineages, we induced RhoA deletion after transplantation of BM cells from Mx-cre; RhoAfl/fl mice into congenic CD45.1+ recipients. The recipients presented with multilineage cytopenia in response to RhoA deletion and died 1 wk after poly I:C induction. By 5 d after poly I:C injections, RhoA deficiency resulted in a rapid and significant decrease of neutrophils (0.54 ± 0.09 k/µl in RhoA-cKO mice vs. 3.64 ± 0.18 k/µl in control) and a significant reduction of monocytes and platelets in the peripheral blood (PB; Fig. 1, G and H). In the erythroid lineage, RhoA deficiency resulted in a small but significant reduction of red blood cells (Fig. 1 H). RhoA deficiency did not alter the count of circulating lymphocytes in this experimental setup (Fig. 1 G), as these lineages usually posed a longer life span.
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RhoA is required for hematopoietic homeostasis in competitive transplantation

In RhoA-cKO mice, severe HPC loss correlates with an acute reduction of differentiated hematopoietic cells. The loss of progenitor cells may be causal for the loss of mature cells. However, it is also possible that the loss of mature cells may lead to a feedback exhaustion of progenitors. In addition, although phenotypic HSCs are preserved in the RhoA-cKO mice, we could not determine the long-term functionality of the HSCs using the previous model as a result of the rapid death of RhoA-cKO mice after poly I:C inductions. A competitive transplantation experiment could address these concerns because of the presence of WT competitor cells, thus avoiding compensational activation/exhaustion of progenitors and sustaining the survival of the recipients to allow long-term functional analysis of donor HSCs, including secondary transplants. Consistent with the data from the noncompetitive transplantation experiment, upon deletion of RhoA we observed a rapid and persistent reduction of donor-derived (RhoA<sup>+/−</sup>, CD45.2<sup>+</sup>) blood cells in the peripheral circulation in the competitive transplant model. This reduction was observed in all major blood lineages (myeloid, T, and B cell lineages; Fig. 3), demonstrating that the hematopoietic-autonomous absence of RhoA impairs multilineage hematopoiesis.

RhoA is essential for HPC activity but is dispensable for the maintenance of HSCs

To study the functionality of RhoA-null HSCs and progenitors, we examined the frequency of donor-derived (CD45.2<sup>+</sup>) LSK and LK cells in the competitive transplantation model. We found that RhoA-deficient LK cells were not capable of competing with competitor cells. 5 mo after secondary transplantation, the percentage of donor derived (CD45.2<sup>+</sup>) LK cells dropped to 15% of the original (Fig. 4, A and B). In contrast, deletion of RhoA did not significantly affect the more...
primitive LSK population. The frequency of RhoA-null LSK cells was not significantly different from the control group, and more importantly, they were capable of engrafting into secondary recipients (Fig. 4, A and C). Efficient deletion of RhoA in the donor-derived (CD45.2+) LSK population was confirmed by PCR (Fig. 4 E). Furthermore, loss of RhoA did not alter the frequency of CD45.2+ cells in the HSC-enriched LSKCD150+ population (93.3 ± 18.0% in the RhoA-cKO group compared with 99.4 ± 4.0% in control mice; Kiel et al., 2005), indicating that RhoA might be dispensable for long-term HSC maintenance (Fig. 4, A and D).

To formally demonstrate the functionality of RhoA-null phenotypic HSCs, we performed a rescue experiment to see whether expressing RhoA in RhoA−/− LSK cells was able to restore multilineage hematopoiesis. We isolated LSK cells from poly I:C–injected competitive transplanted recipients and transduced them with lentivirus expressing human RhoA cDNA or control virus. These viruses also expressed eGFP as a reporter for transduction. The cells were transplanted into lethally irradiated CD45.1+ recipients without purifying for the eGFP+ cells. Contributions of corrected RhoA−/− cells to hematopoiesis were determined by percentage of CD45.2+ cells within the eGFP+ populations. Transduction with RhoA-expressing lentivirus, not the control virus, was able to completely rescue the multilineage differentiation defects of the RhoA−/− LSK donor cells. The percentages of CD45.2+Gr-1+ myeloid cells, B220+ B cells, and CD3e+ T cells within RhoA lentivirus–transduced RhoA−/− group were comparable with that of the RhoA+/− group that were transduced with either RhoA or control virus, whereas little or no CD45.2+ myeloid, B, or T cells were observed in the control virus–transduced RhoA−/− group (Fig. 4 F), indicating that the RhoA−/− LSK cell population still contained HSC activity. Because hematopoiesis was sustained by WT competitor cells in the competitive transplant model, these phenotypes reflected the HSC-intrinsic effects of RhoA deficiency. The results show that RhoA is absolutely required in HPCs but, surprisingly, is dispensable for maintaining HSCs.

RhoA deficiency reduces actomyosin signaling and SDF-1α–driven chemotaxis

As shown in Figs. 1 and 2, by 5 d after poly I:C injections, RhoA-deficient hosts suffered a severe pan–cytopenia and BM failure, making this later time point unsuitable for mechanistic interpretation of RhoA signaling. To investigate the mechanism associated with the loss of HPCs upon RhoA gene deletion, we performed a time course study to identify the earliest time point at which RhoA was efficiently removed from Lin− BM cells. A reduction of RhoA protein was observed 2 d after poly I:C injections, but a complete KO of RhoA was not achieved until 3 d after injections (not depicted). Therefore, we chose to use mice 3 d after poly I:C injections for the following experiments.

RhoA is involved in regulating cellular adhesion and migration, which are relevant to HSPC niche residency and maintenance (Yoder and Williams, 1995). Multiple molecular players in these pathways are regulated by RhoA. RhoA is a critical regulator of actomyosin activity, primarily through its downstream effectors ROCK (Kimura et al., 1996; Maekawa et al., 1999) and citron kinase (Yamashiro et al., 2003). Consistent with previous studies in other tissues (Chauhan et al., 2011; Jackson et al., 2011), RhoA deficiency led to a dramatic reduction of phosphorylated MLC in the isolated Lin− cells (Fig. 5 A), suggesting a deficiency in actomyosin machinery in the HPC population. In addition to p-MLC regulation, RhoA is also known to be a critical factor in regulating actin microfilament polymerization/stability through regulating mammalian diaphanous (mDia) and ROCK (Jaffe and Hall, 2005). Surprisingly, coflin activity, which destabilizes actin filament, was unchanged after RhoA deletion (Fig. 5 B). Actin polymerization was increased, rather than reduced, in RhoA-deficient cells (Fig. 5, C and D). RhoA deficiency also led to an ∼50% reduction of SDF-1α–driven chemotaxis (Fig. 5 E), consistent with the reduced p-MLC activity (Fig. 5 A). Unexpectedly, RhoA loss increased, rather than decreased, the adhesion of Lin− cells to a fibronectin-coated surface (Fig. 5 F). It is unlikely that changes in the pathways regulating adhesion...
whether RhoA deficiency alters cell proliferation in our genetic deletion model, we performed a BrdU incorporation assay to determine the distribution of RhoA−/− cells in the distinct stages of the cell division cycle (G0/G1 and S, G2/M phase). In the noncompetitive transplantation model, a significant increase of BrdU+ cells in both LSK and NK populations was observed 3 d after poly I:C induction (Fig. 6 A). However, the increased proliferation in this model is likely a secondary effect caused by the acute hematopoietic stress seen upon RhoA deletion. We observed no change in BrdU incorporation when cells from the competitive transplantation recipients were analyzed, which served as a homeostatic hematopoiesis model (Fig. 6 B). These results indicate that RhoA is not essential for regulating the G1/S transition of steady-state hematopoietic progenitors.

Figure 4. RhoA deficiency depletes HPCs but not HSCs in competitive setting. (A) CD45.2+ donor BM cells of the RhoAFl/flMx-cre+ or Mx-cre− genotype were cotransplanted into lethally irradiated CD45.1+ recipients together with equal number of CD45.1+ WT competitor cells. Three poly I:C injections were administrated 8 wk after the transplantation, and BM cells from the primary recipients were transplanted into secondary recipients 4 mo after the poly I:C injections. Data were analyzed 5 mo after secondary transplantation. Representative flow cytometry plots of CD45.2 expression within the LK, LSK, and LSKCD150− population in the competitive transplant recipients are shown. (B–D) Relative chimerism of donor-derived LK (B), LSK (C), and LSKCD150− (D) in BM of recipients. (E) DNA from sorted CD45.2+ LSK cells was used as PCR template to determine the deletion efficiency of RhoA. Data were analyzed 5 mo after secondary transplantation. Brightest band of ladder: 600 bp. (F) LSK cells from poly I:C–injected competitive transplantation recipients were transduced with RhoA-expressing or control virus and transplanted into secondary recipients. PB samples were examined 16 wk after transplantation. Percentage of donor-derived (CD45.2+) cells in gated GFP+ mature lineages of PB was determined by flow cytometry. Numbers of mice analyzed: six (A–D) and four (F) mice per group. The results from a representative experiment of three (A–D) or two (F) independent experiments are shown. Error bars indicate SEM. ***, P < 0.001.

RhoA regulates cytokinesis of HPCs through the ROCK and mDia pathways

A previous study has shown that suppression of RhoA via a dominant-negative mutant approach results in increased HSPC proliferation and engraftment (Ghiaur et al., 2006). However, recent studies in Rho GTPases have revealed that overexpression of dominant-negative mutants may produce nonspecific biological responses as a result of the inherent nonspecific biochemical function of the mutants that are capable of sequestering multiple endogenous Rho, Rac, and/or Cdc42-activating guanine nucleotide exchange factors (Wang and Zheng, 2007; Heasman and Ridley, 2008). To examine whether RhoA deficiency and migration are the primary driving force in loss of HPCs and HPC differentiation in response to RhoA deficiency.
Interestingly, a significant accumulation of G2/M HPCs upon RhoA deletion was observed (Fig. 6 A). Recent genetic studies have emphasized the critical function of RhoA during mitosis in different biological contexts (Jackson et al., 2011; Melendez et al., 2011). To examine whether mitosis is defective in the RhoA-deficient HPCs, we purified LK cells and morphologically analyzed their nuclear contents. Similar to what has been reported in keratinocytes and mouse embryonic fibroblasts (Jackson et al., 2011; Melendez et al., 2011), RhoA deficiency resulted in an ~10-fold elevation of multinucleated cells (Fig. 6 C). The nuclei were well separated but not condensed, suggesting that cytokinesis, rather than karyokinesis, was impaired. Indeed, a closer examination of 4N LK cells found a major accumulation of anaphase-like cells, which usually coincided with cytokinesis (Shuster and Burgess, 1999), whereas the frequency of metaphase cells was not significantly altered (Fig. 6 D), also suggesting a deficiency in later mitotic phases. Activation and localization of Aurora kinases, key mitotic-related kinases inactivating RhoA until anaphase (Andrews et al., 2003), were not affected by RhoA deficiency in all cell phases examined (Fig. 6 E), suggesting that the cytokinesis failure in response to RhoA deficiency is not caused by impaired Aurora kinase activity. These results indicate that RhoA is critical for regulating cytokinesis of hematopoietic progenitors through pathways other than Aurora kinase.

To dissect the downstream pathways involved in regulating cytokinesis of HPCs, we transduced control or RhoA-cKO LK cells with virus overexpressing either WT RhoA or effector binding-deficient mutant forms of RhoA, including E40L (ROCK binding deficient; Sahai et al., 1998), R68A (mDia binding deficient; Rose et al., 2005), and Y42C (protein kinase N [PKN] binding deficient; Sahai et al., 1998; Fig. 6 F). As predicted, expression of WT RhoA was able to rescue the accumulation of multinucleated cells (Fig. 6, G and H). Expression of Y42C-RhoA was also able to rescue the cytokinesis failure phenotype (Fig. 6, G and H), indicating RhoA–PKN interaction is not essential for cytokinesis. In contrast, expression of E40L and R68A RhoA was not sufficient to fully rescue the cytokinesis defects in RhoA-deficient cells (Fig. 6, G and H), indicating that both RhoA–ROCK and RhoA–mDia pathways are important for cytokinesis of HPCs.

**RhoA deficiency causes programmed necrosis but not apoptosis or autophagy in the multipotent progenitor population**

Regulation of apoptosis is essential for the maintenance of HSPCs (Domen and Weissman, 1999). Recent findings have indicated that molecules regulating autophagy, in addition to apoptosis, are also important for HSPC maintenance (Mortensen et al., 2011). Although necrosis has initially been postulated as an accidental and unregulated cellular event, accumulating evidence suggests that necrosis can also be tightly regulated (Galluzzi and Kroemer, 2008), but its molecular mechanism remains elusive and its role in the maintenance of HSPCs remains unclear.
Figure 6. RhoA–ROCK and RhoA–mDia interactions are required for HPC cytokinesis. (A) Noncompetitive transplantation experiments were performed similarly as described in Fig. 1G. A BrdU chase at 0.5 mg/recipient was performed 30 min before the analysis. Cell cycle distribution of LK and LSK cells in the noncompetitive transplanted recipients was examined by BrdU incorporation assay. (top) Representative flow cytometry plot. The red rectangle indicates G0/G1 phase, green rectangle S phase, and purple rectangle G/M phase. (bottom) Quantification of cell cycle distribution. (B) Competitive transplantation experiments were performed similarly as described in Fig. 1G. A BrdU chase at 0.5 mg/recipient was performed 30 min before the analysis. Cell cycle distribution of LK and LSK cells in the competitive transplanted recipients was examined by BrdU incorporation assay. (top) Representative flow cytometry plot. The red rectangle indicates G0/G1 phase, green rectangle S phase, and purple rectangle G/M phase. (bottom) Quantification of cell cycle distribution. (C) Representative images from competitive transplantation experiments. (D) Frequency of mitotic cells in LK and LSK cells from RhoAfl/fl and RhoA-cKO mice. (E) Representative images of metaphase and telophase from RhoAfl/fl and RhoA-cKO mice. (F) Western blot analysis of HA-RhoA and HA in HEK293T cells transfected with WT, R68A, Y42C, and R40L. (G) Quantification of RhoA from RhoAfl/fl and RhoA-cKO mice. (H) Quantification of 4N cells in GFP.
The reduction of Rhoa-null HPCs could be the result of decreased survival or other defects in response to cytokinesis failure. Consistent with a specific loss of LK cells, we observed a specific increase of cell death in the LK population (Annexin V/7-AAD staining; Fig. 7, A–C). In contrast, the frequency of cell death in the more primitive LSK population was not statistically different from the control group (Fig. 7, A–C). Similarly, in the competitive transplantation model, we observed an increase in cell death specifically in the donor-derived Rhoa-null LK population, suggesting that increased death is intrinsic to the Rhoa-/- HPC population. However, the survival of Rhoa-null LSK cells was comparable with the WT control counterpart (not depicted). Thus, Rhoa is critical in regulating survival of LK cells, but not the more primitive LSK population.

The majority of dead Rhoa-null cells were observed in the 7-AAD+ instead of Annexin V+ population (Fig. 7, A–C), which was unusual and suggested that the increased cell death might not be caused by apoptosis because Annexin V+ staining is a hallmark of apoptosis, whereas 7-AAD stains dead cells independently of the death mechanism. Consistent with this possibility, we found no evidence of caspase 3 cleavage in Rhoa-null cells, by either Western blot or immunofluorescence (Fig. 7, D and E). Additionally, we did not observe a reduction of prosurvival signals such as Bcl-2, Bcl-xL, and Survivin or an increase of proapoptotic proteins such as p53 (Fig. 7 F), which was consistent with the involvement of a nonapoptotic cell death mechanism. There was also no change of the ratio between the two LC3B forms (Fig. 7 G), the hallmark of autophagy, suggesting that autophagy was not involved either. Electron microscopic examination of Rhoa-/- Lin- cells showed characteristics of necrosis, including the loss of membrane integrity and swelling of organelles (Fig. 7 H), suggesting that the increased death of Rhoa-/- HPCs is related to increased necrosis. Although necrosis has been viewed as an accidental process, recent studies implicate pathways such as the TNF–receptor–interacting protein kinase (RIP) pathway as critical for regulating programmed necrosis (Vandenabeele et al., 2010). To examine whether the TNF–RIP pathway was altered in Rhoa-null HPCs, we probed for expression of genes of this pathway. We noticed increased mRNA levels of molecules involved in the TNF–RIP pathway, including Tifa, Ripk3, Ferritin H1 (Fth1), and Glud1 in Rhoa-cKO LK cells (Fig. 7 I; Vandenabeele et al., 2010), suggesting that Rhoa deficiency is associated with an increase of TNF–RIP-mediated programmed necrosis cascade. Interestingly, we observed a strong positive correlation between necrosis and mitotic failure (Fig. 7 J), implying that these cellular defects are closely associated. Finally, in addition to rescuing multilineage hematopoiesis potential (Fig. 4 F), expressing WT Rhoa was also able to rescue the increased necrosis phenotype within Rhoa-/- LK population in the competitive transplant setting (Fig. 7 K).

**DISCUSSION**

Rho family GTPases are well recognized intracellular signaling molecules, integrating a variety of signals to regulate multiple cellular processes, including cytoskeleton arrangement, gene expression, and cell cycle progression (Jaffe and Hall, 2005). The Rho GTPases Rac1, Rac2, RhoH, and Cdc42 have been genetically demonstrated to be uniquely involved in HSPC maintenance and homing/engraftment activities (Gu et al., 2003; Cancelas et al., 2005; Yang et al., 2007a,b; Chae et al., 2008). A previous study using a dominant-negative mutant of Rhoa overexpression approach found that inhibition of Rhoa activity enhanced HSPC proliferation and engraftment activities (Ghiat et al., 2006). However, general concerns about a dominant-negative mutant overexpression approach, including a lack of specificity and dosage dependency and thus questionable physiological relevance, complicate a clear interpretation of such studies. Models in which Rhoa is genetically deleted are valid experimental systems to define the role of Rhoa in tissue/cell type–specific functions under physiological conditions.

Rhoa is best appreciated as a key regulator of actomyosin, the signal effects of which are involved in adhesion, migration, mitosis, and gene expression. Rhoa regulates actin polymerization through mDia and ROCK (Narumiya et al., 1997). Additionally, Rhoa is critical for the spatial organization of actin filaments through ROCK– and citron kinase–mediated MLC phosphorylation (Yamashiro et al., 2003; Matsumura, 2005). In this study, we found that Rhoa deficiency in HPCs...
results in reduced MLC activity, yet RhoA signaling is dispensable for F-actin microfilament polymerization. We found that cytokinesis and migration, two cellular processes using myosin machinery as a driving force, are defective upon RhoA deletion. Together with data from other RhoA cKO models, our results highlight the diverse and context-dependent functions of RhoA and the uniqueness of RhoA GTPase in the primitive hematopoietic compartment. The findings suggest...
that despite the commonalities shared by different Rho GT-Pases, such as structures, regulators, and effectors, the physiological function of each Rho GTPase can be unique and context specific.

In the present study, we demonstrate that RhoA is critical for multilineage hematopoiesis, the regulation of mitosis of HPCs, and the survival of the progenitors via regulation of programmed necrosis. Recent studies are consistent with our findings of a critical, but cell type–specific role for RhoA in hematopoiesis, in which a role of RhoA in the terminal differentiation of mature hematopoietic cells has been shown. Deletion of RhoA in B cells using CD19-Cre blocks B cell differentiation without affecting proliferation (Zhang et al., 2012). Megakaryocyte-specific RhoA deletion using PF4-Cre causes macrothrombocytopenia and generates defective platelets (Pleines et al., 2012). Additionally, our unpublished data using T cell– and erythroid-specific RhoA KO models indicate that RhoA is critical for T and red blood cell differentiation and function, although via different mechanisms at different cell differentiation stages. It will be of great interest to characterize the function of RhoA in other hematopoietic lineages using the cKO genetic models.

One striking finding of our study is that RhoA is absolutely required in HPC survival and the subsequent production of mature blood cells, but it is dispensable for the long-term maintenance of HSCs. RhoA, to our knowledge, is the first molecule identified to be specifically required for the regulation of multilineage progenitor cells but not the stem cells. There are several possible mechanisms accounting for this differential requirement of RhoA. Although no increased activity/expression of closely related RhoB/RhoC was observed upon RhoA deficiency, endogenous RhoB/RhoC activities might be sufficient to maintain the stem cells but not enough to rescue the deficiency of RhoA in HPCs. Alternatively, the different behaviors of RhoA+/− HSCs and HPCs could reflect the intrinsic difference between the two cell populations. Additional signals within the HSC population might not need RhoA signaling, but the RhoA pathways are turned on upon HSC differentiation to HPCs. Should this be the case, it will be interesting to identify the signaling pathways responsible for this difference. Another possibility is that the difference between RhoA-null HSCs and HPCs may come from the distinct cell cycle division kinetics and history of the two populations. Therefore, the faster and/or more divisions a cell goes through, the higher the likelihood of its experiencing a cytokinesis failure in response to loss of RhoA. Because HPCs commonly go through faster and more cell cycles than stem cells, they could more be vulnerable to cytokinesis failure.

Previous studies on endomitotic megakaryocytes suggest that the generation of 4N megakaryocytes from 2N cells is caused by the failure of the MLC-driven late ingression rather than the initial formation of cleavage furrow, which is followed by a backward movement and refusion of the two daughter cells (Geddis et al., 2007; Lordier et al., 2008). Similar to the endomitosis of megakaryocytes, in the RhoA-null HPCs we have observed a significant accumulation of anaphase cells, rather than metaphase or telophase cells. Interestingly, nuclei of the phenotypic anaphase cells are surrounded by Lamin B–labeled nuclear envelopes (unpublished data), which should only reform during or after telophase, suggesting the accumulation of anaphase cells is not because of blockage at the anaphase–telophase transition but rather is likely caused by a regression of cleavage furrow during cytokinesis. Whether the suppression of MLC activity in response to the loss of RhoA in HPCs directly contributes to the cytokinesis failure phenotype, as described for megakaryocytes, will need to be further investigated.

Cytokinesis failure can trigger aberrant segregation of chromosomes and activate cell death pathways (Castedo et al., 2004a,b). Increased necrosis, but not apoptosis or autophagy, is observed coinciding with the cytokinesis failure after RhoA deficiency. Differing from megakaryocytes, which undergo endomitosis and presumably obtain a unique mechanism to sustain survival, HPCs are normally diploid and lack the ability to withstand the stress from polyploidy and therefore undergo cell death. Consistent with the possibility that RhoA loss may induce a genomic stress from polyploidy of the cytokinesis blockage, a transcriptome analysis revealed an increase of the expression of DNA damage/repair pathway genes in the RhoA-null population (unpublished data). Interestingly, the correlating result of such cytokinesis arrest and genomic stress from the loss of RhoA is manifested by overexpression of multiple components of the TNF–RIP-mediated program necrosis pathway and phenotypic necrosis, rather than apoptosis or autophagy. Although poly I:C used in this study to induce the deletion of RhoA is known to trigger a transient increase of TNF–RIP-mediated necrosis (Penning et al., 1998), the observed necrosis after RhoA deficiency is not caused by a side effect of poly I:C treatment. In the competitive transplantation model, an increase of necrosis in the HPC population is observed 5 mo after secondary transplantation when any poly I:C effects should have been long gone. We conclude that the TNF–RIP-mediated necrosis of HPCs may be a consequence of RhoA deficiency and cytokinesis arrest.

In summary, we demonstrate that RhoA deficiency leads to acute BM failure and pan-cytopenia. RhoA signaling is required for HPC cell cycle progression but not HSC engrafment, and deletion of RhoA results in cytokinesis failure in HPCs. Interactions between RhoA and its downstream effectors ROCK and mDia appear to be critical signaling events as interruption of these interactions cause cytokinesis arrest. Cytokinesis failure in HPCs in response to the loss of RhoA is followed by programmed necrosis possibly involving TNF–RIP signaling. It is likely that RhoA-regulated HPC cytokinesis and the associated programmed necrosis are an underlying mechanism of HPC homeostasis and that HSCs and HPCs are equipped with distinct mechanisms involving RhoA to control cell division and death.

MATERIALS AND METHODS

Mice. C57BL/6 × B129 mixed background RhoAfl/fl mice were generated as previously described (Melendez et al., 2011) and crossed with Ms–cre mice. 6–8-wk-old Ms-Cre+/RhoAfl/fl and Ms–cre–/RhoAfl/fl mice were used throughout.
this study. Two to three doses of poly I:C (Amgen Inc.) were administrated intraperitoneally to both mutant and littermate control mice on alternate days (10 µg/gram body weight). Time points are expressed as days after the final injection. Mice were bred and housed in a pathogen-free facility at Cincinnati Children’s Hospital Medical Center in compliance with the Cincinnati Children’s Hospital Medical Center Animal Care and Use Committee protocols.

Transplantation assays. For congenic transplantation experiments, 3 × 10⁶ BM cells from CD45.2⁺ RhoA⁺/-/- or RhoA⁻/+ mice were mixed with an equal amount of WT BM cells and transplanted into lethally irradiated CD45.1⁺ BoyJ WT recipients via the tail vein. After 8 wk, the number of hematopoiesis, recipients were subjected to poly I:C injections, and samples were collected for analysis. Experiments were replicated twice.

For competitive transplantation experiment, 3 × 10⁶ CD45.2⁺ RhoA⁺/-/- or RhoA⁻/+ BM cells were mixed with an equal amount of CD45.1⁺ BoyJ WT recipients via the tail vein. After 8 wk, three doses of poly I:C were administrated, and PB samples were collected monthly for chimeric analysis. Four to five mice per group were used for each experiment.

For in vivo rescue experiments, lethally irradiated CD45.1⁺ primary recipients were reconstituted with 3 × 10⁶ CD45.2⁺ RhoA⁺/-/- or RhoA⁻/+ donor BM cells together with an equal amount of CD45.1⁺ WT competitor BM cells. Three poly I:C injections were administrated 6 wk after transplantation, and PB samples were collected to ensure RhoA deletion had occurred in the CD45.2⁺ RhoA⁺/-/- (in contrast to intact RhoA in the RhoA⁺/-/- cells) donor-derived cells, whereas CD45.1⁺ competitor-derived cells were not affected. These primary recipients were sacrificed, and BM LSK and LC cells were isolated via immune-magnetic separation and FACS. LSK cells were transduced with a lentivirus vector expressing human RhoA and eGFP cDNA, or the control eGFP cDNA, driven by a ubiquitously expressing modified viral promoter, MND (Challita et al., 1995). In brief, LSK cells (mixture of CD45.2⁺ donor cells and CD45.1⁺ competitor cells) were prestimulated overnight in StemSpan SFEM medium (STEMCELL Technologies) supplemented with 2% fetal calf serum, 1% penicillin/streptomycin, 50 ng/ml recombinant murine SCF (mSCF), 10 ng/ml mouse IL-3 (mIL-3), 1 mM deoxyribonucleotide triphosphate (dNTP), and 40 µg/ml low-density lipoprotein LDL (Sigma-Aldrich). LSK cells were transduced with either RhoA- or eGFP-expressing lentivirus vectors at a multiplicity of infection of 25, twice separated by 8–12 h. Sorted LSK cells were also cultured with either RhoA- or GFP-expressing lentivirus vector at a multiplicity of infection.

Isolation of HSPCs. To isolation of HSCs and progenitors, Lin⁻ cells were enriched using a Lineage Cell Depletion kit (Miltenyi Biotec) according to the product manual. Isolated cells were then stained with biotin-labeled B220, CD3e, CD4, CD8, CD11b, Gr1, and Ter119 antibodies, followed by APC-Cy7- or streptavidin, PE-Cy7-Sca-1, APC-CD117, FITC-CD34, and PE-CD135 for isolating different myeloid progenitor populations. The FACSAria II flow cytometer (BD Biosciences) was used for isolating different HSC populations or APC-Cy7- or streptavidin, PE-Cy7-Sca-1, APC-CD117, FITC-CD34, and PE-CD135 for isolating different myeloid progenitor populations. The FACSAria II (BD) was used to perform the isolation.

Microscopy. For immunofluorescent microscopic experiments, FACS-isolated cells were cultured in Iscove’s modified Dulbecco’s medium (IMDM; Invitrogen) with 10% FBS, 50 µ/ml penicillin, 50 µg/ml streptomycin, 100 ng/ml mSCF, recombinant human thrombopoietin (rHtPPO; PeproTech), and recombinant human granulocyte colony stimulating factor (rh-G-CSF; Amgen Inc.) on CH-296 (Takara Bio Inc.)-coated coverslips overnight and then fixed with 4% paraformaldehyde (Electron Microscopy Sciences) at room temperature for 15 min. Fixed cells were permeabilized with 0.2% Triton-X-100 for 1 h. Antibodies and dyes used include anti-α-tubulin (Sigma-Aldrich), anti-Latan B (M-20; Santa Cruz Biotechnology, Inc.), anti-Cleaved Caspase 3, anti-phosphorylated Aurora A/B/C (Cell Signaling Technology), Alexa Fluor 488 goat anti-mouse IgG (H+L), goat anti-rabbit IgG (H+L), Alexa Fluor 555 donkey anti-goat IgG (H+L), and DAPI (Invitrogen). Samples were mounted using VECTASHIELD Mounting Medium (Vector Laboratories). Slides were imaged on an LSM710 LIVE Duo Confocal Microscope at 40×/1.1 LD C-Apochromat (water immersion) objective (Carl Zeiss) at room temperature using the LSM710 Point Scanner (Carl Zeiss). Images were taken and analysis using Zen 2011 software (Carl Zeiss). For H&E and Hema3 staining, cells and tissues were mounted using Permount Mounting Medium (Thermo Fisher Scientific) and imaged on a Motic BA 310 microscope (Tediella) using a CCIS EF-N Plan Achromatic 40×/0.65 and 100×/1.25 objectives at room temperature by Moticam 580 camera (Tediella). Images were taken using Motic Image Plus (Tediella) software and processed using Image software (National Institutes of Health).

For electron microscopic analysis, isolated Lin⁻ cells were fixed by 2.5% glutaraldehyde (Electron Microscopy Sciences) in PBS overnight. Cells were embedded in low melting temperature agarose, postfixed in 2% osmium tetroxide with 1.5% potassium ferrocyanide, 4% uranyl acetate solution, and then dehydrated by a series of ethanol solution and propylene oxide. Fixed cells were embedded in resin (Embed 812; Electron Microscope Sciences). Ultrathin (90 nm) sections were prepared by an ultra-microtome (Ultra Cut E; Reichert-Jung), and electron microscopic pictures were taken using an electron microscope (H7600; Hitachi High-Technologies America).
In vitro viral transduction. For retrovirus production, REW13 empty vector or REW13 vectors overexpressing WT RhoA or effector binding mutant forms of RhoA (E64LYA42C, and R68A) were transfected into HEK 293T cells using the calcium phosphate precipitation method. Viral supernatant was harvested at days three and four of transfection. LK cells were cultured in IMDM supplemented with 10% FBS, 50 U/ml penicillin, 50 µg/ml streptomycin, 100 ng/ml rmSCF, rhTPO (PeproTech), and rhG-CSF (Amgen Inc.) for 2 d before transduction. Viral particles were enriched by 20 µg/ml recombinant fibronectin CH-296 (Takara Bio Inc.). Stimulated LK cells were transduced for 24 h and further cultured freer of virus for an additional 24 h before analysis.

 Colony-forming units assay. 50,000 BM cells were seeded in cytokine-supplemented MethoCult GF M3434 medium (STEMCELL Technologies) for 7 d, and colonies were enumerated based on size and morphology.

 Adhesion and migration assays. For adhesion assay, 10^5 Lin^- cells were cultured at 37°C in CH-296–coated 96-well plates in 10% FBS supplemented IMDM for 2 h. Nonadherent cells were removed by 2× PBS wash. Adherent cells were recovered by 10-min trypsin treatment, and the number of adherent cells was counted.

 For migration assay, 10^5 Lin^- cells were cultured in the top chamber of Transwell (Corning) in IMDM with 0.5% BSA (Sigma-Aldrich). 100 ng/ml recombinant fibronectin CH-296 (Takara Bio Inc.) was added into the bottom chamber as a chemotactant cue. 4 h later, cells migrated into the bottom chamber were collected for enumeration.

 Protein activity and expression assays. For Rhotekin RBD pull-down assay, isolated Lin^- cells were starved overnight and stimulated with 10 ng/ml SCF or SDF-1α (PeproTech) was added into the bottom chamber as a chemotactant cue. 4 h later, cells migrated into the bottom chamber were collected for enumeration.

 Transcript expression. Total RNA was extracted from FACSorted HSPCs using a RNeasy Micro kit (QIAGEN) according to the manufacturer’s protocol. 20–50 µg of total protein was loaded depending on antigen level/antibody quality for Western blot analysis. Antibodies used include RhoA (67B9), RhoB, RhoC (D40E4), phosphor-MLC (Ser19), total MLC, phosphor-cofilin (Ser3), cofilin, Cleaved Caspase-3 (Asp175), Bcl-2, Bcl-xl, Survivin, p53, LC3B (Cell Signaling Technology), and Lamin B (M-20; Santa Cruz Biotechnology).

 Data analysis. Results are shown as mean ± SEM from at least three individual experiments per group. Statistical analysis between control and RhoA-cKO was assessed by an unpaired, two-tail Student’s t test except for the phase distribution of mitotic cells (Fig 6 G), which is assessed by a x^2 test, *P < 0.05; **P < 0.01; ***P < 0.001, except for Fig 3, in which *P < 0.01.

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