Sepsis is the systemic inflammatory response to severe microbial infection. It is well recognized that patients with sepsis are often immune suppressed, as illustrated by failure to eradicate their primary infections, a predisposition to develop secondary nosocomial infections, and an attenuated delayed-type hypersensitivity response (1, 2). Animals with polymicrobial sepsis also exhibit widespread dysfunction in both antigen-presenting cells and T lymphocytes. Reduced CD4^+ T cell numbers caused by apoptosis-induced depletion (3, 4) and a suppression of T cell proliferative responses (5) have been shown to contribute to sepsis-associated morbidity. Moreover, interest has focused on the shift from a Th1 to a Th2 cell profile as contributing to sepsis-associated immune dysfunction (6, 7).

The role that suppressor cell populations play in polymicrobial sepsis is unknown. The present study examined the role of immature myeloid cells in sepsis, as well as their contribution to the sepsis-induced defects in acquired immunity. Immature myeloid cells with suppressor functions have been previously observed in the spleens and tumors of mice with transplantable tumors (8, 9) and in models of chronic inflammation (10). In tumor-bearing mice, these cells contribute to tumor-associated antigen-specific T cell dysfunction and tolerance (8, 11–15).

MyD88-dependent expansion of an immature GR-1^+CD11b^+ population induces T cell suppression and Th2 polarization in sepsis

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Polymicrobial sepsis alters the adaptive immune response and induces T cell suppression and Th2 immune polarization. We identify a GR-1^+CD11b^+ population whose numbers dramatically increase and remain elevated in the spleen, lymph nodes, and bone marrow during polymicrobial sepsis. Phenotypically, these cells are heterogeneous, immature, predominantly myeloid progenitors that express interleukin 10 and several other cytokines and chemokines. Splenic GR-1^+ cells effectively suppress antigen-specific CD8^+ T cell interferon (IFN)γ production but only modestly suppress antigen-specific and nonspecific CD4^+ T cell proliferation. GR-1^+ cell depletion in vivo prevents both the sepsis-induced augmentation of Th2 cell–dependent and depression of Th1 cell–dependent antibody production. Signaling through MyD88, but not Toll-like receptor 4, TIR domain–containing adaptor–inducing IFN-β, or the IFN-α/β receptor, is required for complete GR-1^+CD11b^+ expansion. GR-1^+CD11b^+ cells contribute to sepsis-induced T cell suppression and preferential Th2 polarization.
Splenic GR-1⁺CD11b⁺ cells may also play an instrumental role in the priming of B cell antibody production (16).

There has been only modest exploration of these cell populations in sepsis or other acute inflammatory processes. In this paper, we observed that an ongoing septic process induces a dramatic expansion of the GR-1⁺CD11b⁺ population in the bone marrow, spleen, and lymph nodes. Expansion of these cells was associated with splenic enlargement and lymphoid follicle disruption. The GR-1⁺CD11b⁺ cells contained immature progenitors and expressed IL-10, TNF-α, and other cytokines and chemokines. Furthermore, using a depleting antibody, we demonstrated that expansion of GR-1⁺ cells in vivo contributed to the induced Th2 polarization of antibody responses after sepsis. These cells were also capable of causing CD8⁺ T cell tolerance, as demonstrated by the suppression of antigen-specific IFN-γ production by CD8⁺ T lymphocytes in nonseptic immunized mice. Finally, we observed that signaling through MyD88, but not Toll-like receptor (TLR4), TIR-domain-containing adaptor-inducing IFN-β (TRIF), or the IFN-α/β receptor, was required for the early and complete expansion of this cell population, highlighting the importance of inflammation and TLR signaling other than that induced by microbial endotoxin in the regulation of immature myeloid cells in sepsis.

RESULTS

GR-1⁺CD11b⁺ cells accumulate in the spleen after sepsis
To examine the long-term effects of polymicrobial sepsis on the expansion of the GR-1⁺CD11b⁺ populations, the experiments were conducted in a mouse model of polymicrobial sepsis (generalized peritonitis) induced by ligation of the cecum and a double enterotomy created with a 27-gauge needle. Mortality in this model was ~10–20% and predominantly occurred during the first 96 h; thereafter, surviving mice developed abscesses surrounding the devitalized cecum. As shown in Fig. S1 (available at http://www.jem.org/cgi/content/full/jem.20062602/DC1), the presence of sepsis was confirmed for animals exhibiting a significant early leukopenia, followed by a profound granulocytosis (Fig. S2). Plasma cytokine concentrations over the first 10 d were consistent with an early exaggerated systemic inflammatory response and with sustained elevations in the plasma IL-6, KC/CXCL1, and macrophage inflammatory protein (MIP) 1β concentrations (Fig. S3).

Interestingly, surviving septic mice developed a dramatic splenomegaly, with the spleen mass increasing by 300% by 10 d after initiation of polymicrobial sepsis (Fig. S4 A, available at http://www.jem.org/cgi/content/full/jem.20062602/DC1). The dramatic increase in spleen mass suggested an expansion of one or more cell populations within the spleen. Periodic histological analysis of the spleens of mice over 10 d of sepsis (Fig. S4 B) demonstrated that the apparent splenomegaly was associated with extramedullary hematopoiesis and marked expansion of immature myelomonocytic cells, including forms with ringed nuclei in the periarteriolar sheaths and subcapsular space, including focal involution of lymphoid follicles. Analysis of lymphoid and nonlymphoid cell populations did not reveal an increase in cells expressing CD3, B220, or CD11c. However, a dramatic accumulation of cells expressing GR-1 and CD11b occurred. As shown in Fig. 1 (A and B), splenocytes harvested from septic mice at various intervals after cecal ligation and puncture, or sham procedures, exhibited a striking increase in the percentages and absolute numbers of GR-1⁺CD11b⁺ cells. The dramatic increases in the percentages and absolute numbers of GR-1⁺CD11b⁺ cells did not occur until at least 3 d after the induction of sepsis, and the percentages continued to increase to a plateau (～7–10 d). The numbers and proportion of these cells remained elevated even out to 12 wk in surviving mice. By 10 d, the absolute numbers of these GR-1⁺CD11b⁺ cells in the spleen had increased 50-fold.

GR-1⁺CD11b⁺ cells are phenotypically heterogeneous cells
GR-1⁺CD11b⁺ cells represent a heterogeneous population of cells encompassing mature and immature myeloid forms.
To further characterize these GR-1⁺CD11b⁺ cells, splenocytes were also stained for CD31, a marker of immature myeloid development that is lost with more terminal cell differentiation (17), and Ter119, a marker of erythroid lineage, as well as F4/80, a marker for myeloid lineage development. As shown in Fig. 1 C, ~40% of the GR-1⁺CD11b⁺ cells were also CD31⁺, and the numbers of GR-1⁺CD11b⁺CD31⁺ cells were increased nearly 70-fold during sepsis. Similar results were obtained examining the GR-1⁺CD11b⁺F4/80⁺ triple-positive cells in the spleen and bone marrow (unpublished data), suggesting that the GR-1⁺ cells contained a subpopulation of developing myeloid cells. In contrast, only 6% of the GR-1⁺CD11b⁺ cells were Ter119⁺, suggesting that only a small proportion of these cells may still possess the ability to differentiate into cells of erythroid lineage (Fig. S5, available at http://www.jem.org/cgi/content/full/jem.20062602/DC1). Interestingly, however, <3% of these GR-1⁺CD11b⁺ cells were also MHC class II⁺ (Fig. S6).

As shown in Fig. 2 D, the enriched GR-1⁺ cell population from the spleens of septic mice contained large numbers of phenotypically heterogeneous cells. Many of these cells had characteristic circular or ringed-shaped nuclei. Gauging on their nuclear size, complexity, and cytoplasmic granularity as described previously in the literature, most of these cells were determined to be immature myeloid forms (18). These cells were identified on the cell-sorted cytospin preparations.

To examine whether the GR-1⁺CD11b⁺ population were an immature proliferating precursor population sensitive to myeloid growth factors, the GR-1⁺-enriched splenocytes from septic mice were cultured ex vivo on 24-well plates with GM-CSF. In the absence of GM-CSF, these cells rapidly died. In contrast, 7 d of culture with GM-CSF led to ~17% of these cells differentiating into conventional CD11chighMHC class II⁺dendritic cells and ~22% differentiating into F4/80high macrophages (Fig. 2, A–C), and all of these cells demonstrated increased MHC class II expression over freshly isolated GR-1⁺CD11b⁺ cells. In addition, cultivating these GR-1⁺ cells from septic mice in soft methylcellulose with either GM-CSF or G-CSF, but not erythropoietin, for 7 d led to an increase in the number of colonies formed (Fig. 2 E). Interestingly, the GR-1⁺ cells from sham-treated mice did not contain any significant number of progenitors capable of forming colonies in response to these growth factors. The failure of GR-1⁺ cells from septic mice to generate a significant number of colonies in response to erythropoietin and the low Ter119⁺ staining suggest that during sepsis, these...
expanded numbers of GR-1⁺CD11b⁺ cells represent a mixed population of immature, proliferating, progenitors committed predominantly to a myeloid, and not an erythroid, pathway.

**Immature myeloid cells accumulate in secondary lymphoid organs after sepsis**

We also looked for these GR-1⁺CD11b⁺ cells in other secondary lymphoid and reticuloendothelial organs. For these cross-sectional analyses, we selected intervals after cecal ligation and puncture or a sham procedure when the changes in the spleen were maximal. No significant increases in GR-1⁺CD11b⁺ cells were seen in either the liver or lung (unpublished data). In peripheral lymph nodes, however, marked increases in the percentages and numbers of these GR-1⁺CD11b⁺ cells were evident at 10–14 d after sepsis and were still increased at 12 wk (Fig. 3, B and C). Numbers remained significantly elevated in mesenteric lymph nodes in direct proximity to the cecal ligation and puncture at 12 wk, whereas numbers declined somewhat, but still remained significantly elevated, in more distal inguinal and axillary lymph nodes at 12 wk. In the bone marrow (Fig. 3 A), the numbers of these GR-1⁺CD11b⁺ cells doubled within 3 d and accounted for nearly 90% of the cells by 7 d after sepsis.

Histological confirmation of these cells in the spleens of mice with severe sepsis is shown in Fig. 4 (A–C). Over the course of 10 d, there was progressive expansion of the red pulp by extramedullary hematopoiesis and marked expansion of the periarteriolar sheaths (Fig. 4 B) and subcapsular space (Fig. 4 C) by immature mononuclear cells and myelomonocytic cells with ringed nuclei. These cells were also found in small clusters within the interfollicular areas. The immature myeloid cells with ringed nuclei in all of these locations were uniformly CD11b⁺ in the spleens of mice that underwent cecal ligation and puncture (Fig. 4 D, F, and G). In contrast, CD11b showed only scattered reactivity in the sham-treated mice, mainly highlighting mature granulocytes within the interfollicular areas (Fig. 4 E). The increasing numbers and overall percentage of immature myelomonocytic cells with ringed nuclei correlated with the time progression after sepsis and was associated with cuffing in the perivascular/periarteriolar sheaths and subcapsular spaces. Finally, there was focal involution of the lymphoid follicles that paralleled the expansion of the red pulp. No immature myelomonocytic cells with ringed nuclei were identified within the follicular areas.

**Immature myeloid cells are capable of inflammatory mediator production**

Because immature myeloid cells obtained from tumor-bearing hosts are known to be immunomodulatory (8, 9), we next examined whether cells obtained from septic mice could produce inflammatory mediators, including IL-10, TNF-α, regulated on activation, normal T cell expressed and secreted (RANTES; CC chemokine ligand 5), and MIP-1β (CC chemokine ligand 4). When stimulated ex vivo with bacterial LPS, the GR-1⁺ cells from septic mice produced significantly greater amounts (more than fivefold) of IL-10 than similar GR-1⁺ cells from sham-treated animals (Fig. 5). They also produced increased quantities of TNF-α, RANTES, and MIP-1β but did not produce the Th2 cytokines IL-4 or IL-13. Unstimulated or LPS-stimulated GR-1⁺ splenocytes did not produce measurable quantities of GM-CSF, IL-12p40, IL-12p70, IL-2, IL-3, IL-5, IL-9, IL-17, vascular endothelial growth factor, or IFN-γ (unpublished data). In addition, GR-1⁺ splenocytes obtained from septic mice also produced TNF-α (218 ± 67 vs. 4 ± 1 pg/ml) and IL-10...
Immature myeloid cells affect adaptive immune responses in sepsis

To examine whether these cells could affect adaptive immune function, sham-treated and septic mice were immunized with 4-hydroxy-3-nitrophenyl acetyl–KLH (NP-KLH) using the adjuvant alum when GR-1<sup>+</sup> cells reached a maximal proportion in the spleen (10 d after cecal ligation and puncture), and the NP-specific serum immunoglobulin response was determined 10 d later. The serum immunoglobulin response to NP-KLH with alum is a T cell–dependent, B cell response, and the immunoglobulin isotypes can be used to assess polarization of the T cell response (19). Polymicrobial sepsis was not associated with any significant changes in total IgM or IgG responses (Fig. 6, A and B); however, when the total IgG response was dissected into its isotypic components, the serum IgG<sub>2a</sub> response was significantly decreased (165 ± 43 pg/ml) in response to stimulation with 5 μg/ml flagellin (TLR5 agonist), albeit in lesser quantities than with LPS stimulation.

Figure 4. Hematoxylin and eosin–stained spleens from septic mice 10 d after CLP. (A) Low power view, with the perivascular region identified (inset). (B) High power view of the perivascular region showing cuffing and infiltration, with myeloid cells showing characteristic ring features (black arrows). Note the mitotically active cell (white arrow). (C) High power view of the subcapsular region also showing infiltration, with myeloid cells exhibiting characteristic ring features (arrows). (D) CD11b<sup>+</sup> staining of the spleen from a septic animal 10 d after CLP. (E) CD11b<sup>+</sup> staining of the spleen from a sham-treated animal 10 d after CLP. Bars, 100 μm. CLP, cecal ligation and puncture.

Figure 5. Effect of ex vivo LPS stimulation on cytokine expression in GR-1<sup>+</sup> splenocytes obtained from septic mice. When GR-1<sup>+</sup> splenocytes were harvested from 7-d sham-treated or septic mice and stimulated with 10 μg/ml of bacterial LPS, IL-1α, IL-1β, IL-6, IL-10, TNF-α, RANTES, MIP-1β, and KC/CXCL1 production was significantly increased in all groups stimulated with LPS. Importantly, GR-1<sup>+</sup> splenocytes from septic mice secreted more IL-10, TNF-α, RANTES, and MIP-1β production after LPS administration than GR-1<sup>+</sup> splenocytes from sham-treated animals. Values represent the mean ± SEM of between four and six samples. *, P < 0.05 by the Student’s t test.
while the IgG1 response increased in the septic mice, consistent with a shift from a Th1 to a Th2 response (Fig. 6, C and D). When the septic mice were treated with a GR-1–depleting antibody, producing >80% reduction in total GR-1+CD11b+ splenocytes (Fig. S7, available at http://www.jem.org/cgi/content/full/jem.20062602/DC1), the sepsis-induced increase in IgG1 and the decrease in IgG2a responses were abolished, demonstrating the involvement of the GR-1+ cells in this polarization. As expected by the T cell–dependent nature of this antibody response, depletion of CD4+ cells significantly attenuated the IgM responses and completely prevented the IgG class switching in the septic animals (Fig. S8, A–D).

To further confirm the in vivo role that these cells play in suppressing an antigenic T cell response, the effect of GR-1+ cells on the CD8+ T cell IFN-γ response by splenocytes from OT-I TCR transgenic mice (C57BL/6-Tg(TCRαTCRβ)1100mjb/J) immunized with OVA-derived peptide (H-2Kb restricted, aa 257–264; SIINFEKL) was examined (Fig. 7 A). GR-1+ cells obtained from either 10-d septic or sham-treated mice were infused into C57BL/6 mice that had previously received CD8+ T cells from OT-1 TCR transgenic mice, and mice were simultaneously immunized with OVA-derived specific peptide. 10 d later, the spleens from these animals were removed, and IFN-γ responses to ex vivo stimulation with OVA-derived specific peptide were examined. IFN-γ production was markedly reduced when the animals were administered GR-1+ splenocytes from septic animals when compared with sham-treated mice, confirming that GR-1+ splenocytes from these septic mice could suppress a CD8+ T cell IFN-γ response.

To determine whether GR-1+ cells could directly suppress an antigen-specific or nonspecific CD4+ T cell proliferative response, DO11.10 OVA-TCR transgenic mice were made septic, and CD4+ splenocytes were cultured with irradiated GR-1+–containing antigen-presenting cells from the spleens of 10-d septic or sham-treated mice and were incubated with either OVA peptide, bovine serum albumin, or on CD3/CD28-coated plates. As shown in Fig. 7 B, culturing CD4+ cells with irradiated GR-1+ cells from septic mice only modestly, but still significantly, reduced both the antigen-specific (OVA) and nonspecific (CD3/CD28) proliferative responses.

**MyD88 signaling pathways are required for GR-1+CD11b+ cells to accumulate in the spleen after polymicrobial sepsis**

Polymicrobial sepsis produced by cecal ligation and puncture releases a large number of microbial products that are recognized by the innate immune system, in large part through TLR signaling pathways. To examine the cell signaling pathways required to elicit the expansion of these immunomodulatory GR-1+CD11b+ cells, wild-type C57BL/6 mice were injected with a sublethal dose (5 mg/kg body weight) of the TLR4 agonist bacterial LPS. The numbers of these GR-1+CD11b+ splenocytes were examined at daily intervals after LPS injection. As shown in Fig. 8 A, the administration of bacterial LPS produced a more rapid but transient increase in the percentages and absolute numbers of GR-1+CD11b+ splenocytes, suggesting that the likely pathway involves TLR4

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**Figure 6. Ig production after NP-KLH immunization in sham mice, septic mice, and septic mice depleted of GR-1+ cells.** 9 and 10 d after induction of sepsis by CLP, mice were depleted of GR-1+ cells by the i.p. administration of RB6-8C5 anti-GR-1 antibody, as described in Materials and methods. Mice were then immunized with NP-KLH. 7 d later, mice were bled, and serum IgM (A), total IgG (B), IgG1 (C), and IgG2a (D) responses to NP-KLH immunization were determined. Sepsis produced no difference in the IgM response while concomitantly producing an increase in the total serum IgG and IgG1, and a decrease in the serum IgG2a response consistent with Th2 polarization. The total IgG, IgG1, and IgG2a responses after sepsis were prevented by depletion of the GR-1+ cells. Horizontal lines represent the means for each group of samples. *, P < 0.01 by analysis of variance and the Student–Newman-Keuls multiple range test. CLP, cecal ligation and puncture.
signaling. The expansion of GR-1+ cells from septic mice on antigen-specific CD4+ T cell proliferation and CD8+ T cell IFN-γ responses. Mice were treated as described in Materials and methods. GR-1+ cells from septic animals markedly attenuated the IFN-γ production (determined by ELISPOT) by OT-1 splenocytes stimulated with either control peptide or OVA-derived peptide SIINFEKL ex vivo after administration and immunization in C57BL/6 mice [A]. In contrast, GR-1+ splenocytes from 10-d septic mice had only a minimal but significant suppressive effect on antigen-specific and nonspecific CD4+ T cell proliferative responses in OVA antigen-specific, D011.10 mice (B). Values represent the mean and standard error of five animals per group. The experiment was repeated twice, and the values presented are from one representative experiment. *P < 0.05 by analysis of variance and the Student-Newman-Keuls multiple range test.

**Figure 7. Effect of GR-1+ cells from septic mice on antigen-specific CD4+ T cell proliferation and CD8+ T cell IFN-γ responses.**

Discussed are the results from the experiments described in Materials and methods. GR-1+ cells from septic animals markedly attenuated the IFN-γ production (determined by ELISPOT) by OT-1 splenocytes stimulated with either control peptide or OVA-derived peptide SIINFEKL ex vivo after administration and immunization in C57BL/6 mice [A]. In contrast, GR-1+ splenocytes from 10-d septic mice had only a minimal but significant suppressive effect on antigen-specific and nonspecific CD4+ T cell proliferative responses in OVA antigen-specific, D011.10 mice (B). Values represent the mean and standard error of five animals per group. The experiment was repeated twice, and the values presented are from one representative experiment. *P < 0.05 by analysis of variance and the Student-Newman-Keuls multiple range test.

**Figure 7.** Effect of GR-1+ cells from septic mice on antigen-specific CD4+ T cell proliferation and CD8+ T cell IFN-γ responses. Mice were treated as described in Materials and methods. GR-1+ cells from septic animals markedly attenuated the IFN-γ production (determined by ELISPOT) by OT-1 splenocytes stimulated with either control peptide or OVA-derived peptide SIINFEKL ex vivo after administration and immunization in C57BL/6 mice [A]. In contrast, GR-1+ splenocytes from 10-d septic mice had only a minimal but significant suppressive effect on antigen-specific and nonspecific CD4+ T cell proliferative responses in OVA antigen-specific, D011.10 mice (B). Values represent the mean and standard error of five animals per group. The experiment was repeated twice, and the values presented are from one representative experiment. *P < 0.05 by analysis of variance and the Student-Newman-Keuls multiple range test.

**DISCUSSION**

T cell dysfunction is a common response to polymicrobial sepsis (1), ultimately leading to increased susceptibility to ongoing and opportunistic infections and poor outcome. Recent attention has focused on the shift from a more proinflammatory Th1 to a more antiinflammatory Th2 cell immune profile as an explanation for postsepsis immune suppression; however, the underlying mechanisms that orchestrate this T cell suppression and Th2 cell polarization during sepsis are still unknown.

Although there has been some speculation that endogenous and inducible T regulatory cells may contribute to the T cell suppression and Th2 polarization in sepsis (20, 21), more recent studies have refuted some of those claims (22, 23). Several years ago, Murphey et al. observed an increased number of macrophage-like cells in the spleens of mice surviving cecal ligation and puncture (5), although they did not explore their suppressor cell function. More recently, Makarenkova et al. observed increased numbers of immature myeloid cells in the spleens of mice within 12 h of a traumatic injury and identified them as a source of arginase I activity (24).
became evident that, in association with this ongoing septic process, there was marked disintegration of the follicular regions, increased extramedullary hematopoiesis, and replacement of the splenic cellularity with large numbers of immature myeloid cells (Fig. 1). Hotchkiss and co-workers, as well as us, had previously shown that, in similar models of polymicrobial sepsis, there is a rapid apoptotic loss of CD4\(^+\) T cells and dendritic cells in the first 24 h of sepsis and that these cellular losses contribute to the adverse outcome (25–27). Although there has been considerable exploration into the role of extramedullary hematopoiesis in chronic infectious and inflammatory processes, none have explored or even described this massive expansion of an immature myeloid cell population (GR-1\(^+\)CD11b\(^+\)) in the bone marrow, spleen, and lymph nodes of mice with ongoing septic processes. We have clearly shown that by 10 d after cecal ligation and puncture, almost 40% of the spleen and 90% of the bone marrow cellularity represent immature GR-1\(^+\)CD11b\(^+\) cells. Interestingly, the administration of near lethal doses of bacterial LPS could also produce some expansion of this immature myeloid cell population. However, the increases were transient and modest compared with those seen in the septic animals, suggesting that an ongoing inflammatory process may be required for complete manifestation of the response (10).

The phenotype of these cells, the kinetics of their expansion, and their anatomical location in the spleen argue against them being functionally or phenotypically similar to those reported previously by Makarenkova et al. (24) immediately after trauma, or as mere components of extramedullary hematopoiesis. Makarenkova et al. observed a rapid influx of GR-1\(^+\)CD11b\(^+\) cells into the spleens of mice 12–24 h after traumatic injury. However, these cells, which produced large quantities of arginase I, were located in the mantle surrounding the lymphocyte-rich follicles, and very few ring cells were detected. In contrast, we saw a transient decline in GR-1\(^+\)CD11b\(^+\) splenocytes during the first 24 h of sepsis and only saw expansion of our splenocyte population after 3–5 d of sepsis. Furthermore, although both populations are clearly heterogeneous, our cells contained higher proportions of immature precursors that were concentrated in perivascular/periarteriolar and subcapsular regions of the spleen, exhibited less MHC class II expression, and made copious amounts of IL-10 when stimulated ex vivo. These cells obtained from the spleens of septic animals contained predominantly precursors committed to a myeloid and not erythroid lineage.
capacity for colony or burst formation (Fig. S5). In contrast, almost 40% of the cells differentiated into macrophages or dendritic cells when cultured with GM-CSF (Fig. 2 C), and large numbers were capable of forming colonies when incubated in soft methylcellulose with either G-CSF or GM-CSF (Fig. 2 E).

This dramatic expansion of the GR-1<sup>+</sup>CD11b<sup>+</sup> response to sepsis in the spleen is very similar to the response previously observed in mice with actively growing tumors. Similar immature myeloid cell populations have been shown to accumulate in the spleens, infiltrating into tumors in several animal tumor models (11–15), and also in the blood of some patients with cancer (28). In mice with transplantable tumors, these myeloid-derived suppressor cells, as they are now being termed (29), have also been shown to inhibit antigen-specific and nonspecific T cell functions via several different mechanisms, including arginase I, nitric oxide, reactive oxygen species, and TGF-β.

Given the abilities of immature myeloid cells to facilitate immune suppression in mouse cancer models, as well as to suppress antigen-specific T cell responses and to influence B cell antibody production, the expansion of these immature myeloid populations in sepsis may similarly orchestrate the Th1 to Th2 immune polarization that is known to occur in sepsis. Challenging mice with T cell–dependent antigens, such as NP-KLH, offers the opportunity to explore in vivo the shift in antibody class switching to IgG<sub>2a</sub> or IgG<sub>1</sub> production, which is dependent on cytokines, including IFN-γ and IL-4, and reflects this predilection toward a Th2 versus a Th1 CD4<sup>+</sup> T cell response (16, 19). 10 d after sepsis, immunization with NP-KLH led to an increase in the IgG<sub>1</sub> production at the expense of IgG<sub>2a</sub>, consistent with a preferential Th2 response. In contrast, partial depletion of the GR-1<sup>+</sup> cells in vivo blocked the characteristic increase in the IgG<sub>1</sub> secretion while also preventing the fall in the IgG<sub>2a</sub> responses, demonstrating a contributory role for these GR-1<sup>+</sup> cells in this shift from a Th1 to Th2 response.

Consistent with these findings was the observation that GR-1<sup>+</sup> cells from septic mice substantially attenuated the IFN-γ response by CD8<sup>+</sup> T cells to specific antigenic stimulation. These results are very similar to the suppression of cytotoxic T cells to antigen-specific stimulation by GR-1<sup>+</sup> cells obtained from tumor-bearing hosts (11). Surprising, however, were the modest reductions in antigen-specific CD4<sup>+</sup> T cell proliferation that we observed when GR-1<sup>+</sup> cells were cultured with DO11.10 CD4<sup>+</sup> OVA transgenic T cells immunized with OVA peptide. The answer may simply be that these GR-1<sup>+</sup> cells express very little MHC class II, whereas they retain relatively high levels of MHC class I expression (11). Therefore, in the DO11.10 CD4<sup>+</sup> OVA transgenic mouse model, these GR-1<sup>+</sup> cells were probably unable to present antigen via MHC class II and, therefore, could not directly affect CD4<sup>+</sup> T cell proliferative responses. In contrast, they could present antigen in the context of class I expression and suppress CD8<sup>+</sup> T cell IFN-γ responses.

Interestingly, the numbers of immature myeloid cells decreased in mice in which the abscess had spontaneously resolved 12 wk after sepsis (unpublished data). Furthermore, when these same animals with abscess resolution were immunized with NP-KLH and alum, the antibody response more closely approximated baseline isotype levels (Fig. S9, available at http://www.jem.org/cgi/content/full/jem.20062602/DC1). Similar decreases in the numbers of immature myeloid cells have been reported in tumor-bearing animals upon resection of their primary tumor (30).

The similarities in the appearance of these myeloid-derived suppressor cells in sepsis and in animals with tumors or other chronic inflammatory processes suggest that there are common signals involved in the expansion of these cell populations. Polymicrobial sepsis produced by a ligation and puncture of the cecum releases large quantities of microbial products into the peritoneum and systemic circulation. It is not at all surprising that polymicrobial sepsis produced a comparable expansion of the GR-1<sup>+</sup>CD11b<sup>+</sup> population in C3H/HeJ mice lacking a functional TLR4 receptor, suggesting that although LPS contributes to the septic response in wild-type mice, signaling through TLR4 is not required during polymicrobial sepsis, as signaling through other TLRs by pathogen-associated molecular patterns likely also contributes to the expansion of these cell populations. Considering the fact that mice with defective TLR4 signaling also exhibit mortality comparable with wild-type mice after sublethal polymicrobial sepsis (31), the findings suggest that neither mouse expansion of myeloid-derived suppressor cells nor survival after sepsis are entirely TLR4 dependent.

Two major pathways activated by TLR signaling include the induction of both inflammatory mediators through MyD88 and type I IFN production. Because both MyD88...
and TRIF pathways can lead to type I IFN production, mice deficient in the type I IFN receptor were used to ascertain the role of type I IFN in sepsis-induced myeloid cell accumulation. The increases in the GR-1+CD11b+ population were unaffected in mice lacking TRIF or IFN-α/βR signaling, indicating that TLR signaling to type I IFNs is not important in the induction of these cells. However their expansion was completely prevented for the first 7 d in septic mice lacking MyD88 signaling and was still considerably attenuated after 14 d. The studies were confirmed in MyD88−/− mice on two backgrounds (B6 and B6 × 129(F2)) to ensure that these findings were not strain dependent. This observation, in particular, suggests that the expansion of this cell population represents a fundamental component of inflammatory signaling in the host innate immune response to TLR ligation by pathogens. In response to microbial products released during cecal ligation and puncture, activation of inflammatory signaling through MyD88, presumably through ligation of multiple TLR receptors, plays a key role in the expansion of these cell populations.

In summary, the results demonstrate for the first time that the numbers of GR-1+CD11b+ cells increase dramatically in the spleen, lymph nodes, and bone marrow during polymicrobial sepsis and remain elevated for up to 12 wk. These cells are heterogeneous, metabolically active, can secrete several cytokines, and are immature, but they are predominantly committed to development along myeloid pathways. Signaling through MyD88 is required for the complete expansion of these cell populations, with an incomplete increase in the numbers of these cells in the spleen or bone marrow in the absence of MyD88 signaling. In mice, these cells contribute to the T cell suppression seen after sepsis by suppressing CD8+ T cell IFN-γ production, and to the polarization from a Th1 to a Th2 immune response induced by augmenting B cell antibody production toward IgG1 (Th2) and away from IgG2a (Th1). What remains unresolved is whether a comparable expansion of these immature myeloid populations also occurs in human sepsis and contributes to the immune suppression and polarization that occurs. Further studies will be required to determine whether these findings translate to a better understanding of the human innate and adaptive immune responses to severe sepsis.

MATERIALS AND METHODS

Mice. All experiments were approved by the Institutional Animal Care and Use Committees at the University of Florida College of Medicine, Rhode Island Hospital and Brown University, or Schering-Plough Biopharma. Specific pathogen-free C57BL/6 mice, C3H/HeJ mice (TLR4 receptor mutation) and their control mice (C3H/HeOuJ), OT-1 TCR transgenic mice (C57BL/6-Tg(TCRαRα)1100Mjb/J), DO11.10 OVA TCR transgenic mice (BALB/c-TgOVTcRαβB1100) and B6.129P2/J mice were all purchased from the Jackson Laboratory. IFN-αBR/129 mice on the 129S6/SvEv background (H-2b) and wild-type Sv129 mice were purchased from B&K Universal. All mice were maintained at the University of Florida College of Medicine. MyD88−/− mice on a B6 × 129(F2) background and TRIF−/− mice were a gift of S. Akira (Hyogo College of Medicine, Hyogo, Japan) to Schering-Plough Biopharma and were maintained at Schering-Plough Biopharma. MyD88−/− mice on a B6 background were obtained from S. Akira and were maintained at Rhode Island Hospital and Brown University.

Cecal ligation and puncture. For induction of polymicrobial sepsis, mice underwent cecal ligation and puncture or a sham procedure, as previously described (4, 32), to obtain a mortality of 10–20% by 10 d. At various intervals, bacterial counts from the blood and peritoneal wash (3 ml of phosphate-buffered saline) were determined by culturing aliquots on sheep RBC-agar plates. Total and differential white blood cell counts were also determined using an automated cell counter (Hemavet 1700 FS; Drew Scientific Inc.). Plasma cytokines were determined by Luminex technology (Beadlyte Mouse Multi-Cytokine Detection System; Upstate Cell Signaling Solutions).

Flow cytometry. Spleens, lymph nodes, and bone marrow cells were analyzed by flow cytometry, as previously described (32). Antibodies included anti–GR-1 (Ly-6-G and Ly-6-C; clone RB6-8C5) conjugated to allophycocyanin (APC), anti-CD11b (integrin αM chain; Mac-1α chain; clone M1/70) conjugated to FITC, anti–MHC class II (I-A/I-E; 2C9) conjugated to FITC, anti-F4/80/α antigen (panmacrophage marker; clone BM8) conjugated to PE, Ter119 conjugated to FITC (clone ter119), anti–CD11c (clone N418) conjugated to APC, Fe-Block (CD16/CD32 Fcγ III/II receptor; 2.4G2), and 7-amino-actinomycin D (D4800– and CD11c-specific antibodies purchased from ebioscience; all other antibodies were purchased from BD Biosciences).

Cell purification. All magnetic bead kits were obtained from Miltenyi Biotec. Erythrocyte-depleted splenocytes and lymphocytes were isolated using either anti–GR-1 (Ly-6-G and Ly-6-C; clone RB6-8C5) conjugated to APC followed by anti-APC MicroBeads for GR-1+ splenocytes. Anti-CD8a (Ly-2) MicroBeads were used alone for OT-1 CD8+ splenocyte isolation.

Ex vivo stimulation and cytokine production. Enriched GR-1+ cells were plated at 106 cells/well with RPMI 1640 supplemented with 10% fetal calf serum, 2 mM l-glutamine, 200 U/ml penicillin, and 50 μg/ml streptomycin, and stimulated with 10 μg/ml of bacterial LPS (Escherichia coli 0111: B4). The culture supernatant was analyzed for cytokines.

Ex vivo differentiation and colony formation. 106 GR-1+ splenocytes were positively enriched and cultured with RPMI 1640 medium supplemented with 10% fetal calf serum, 2 mM l-glutamine, 200 U/ml penicillin, and 50 μg/ml streptomycin. Cells were stimulated for 7 d with 10 ng/ml GM-CSF (R&D Systems). The cells were phenotyped by flow cytometric analyses.

For the colony-forming assays, 105 GR-1+ splenocytes from sham and septic mice were cultured in Methocult methylcellulose media (StemCell Technologies Inc.) containing recombinant mouse G-CSF, GM-CSF, or erythropoietin (all at 10 ng/ml; R&D Systems) for 10 d. Colonies containing >30 cells were enumerated.

Antigen-specific CD8+ T cell IFN-γ production. 3–5 × 106 purified T cells from OT-1 TCR transgenic mice were injected i.v. into naive C57BL/6 recipient mice. 2 d later, mice were injected i.v. with 5 × 106 GR-1+ cells obtained 10 d after sepsis or sham procedure. Mice were immunized s.c. with the specific peptide (100 μg of the OVA-derived peptide SIFNKFL) mixed with incomplete Freund’s adjuvant. 10 d later, lymph node and spleen cells were isolated and restimulated in vitro with the specific (SIFNKFL) or control (RAHYNIVTF) peptide and analyzed via IFN-γ ELISPOT.

ELISPOT assay. MultiScreen HA plates (Millipore) were coated with and blocked with phosphate-buffered saline with 1% bovine serum albumin before plating. Spleen and lymph node cells were plated at 2.5 × 105 cells/well with HL-1 (Cambrex) supplemented with 2 mM l-glutamine, 200 U/ml penicillin, and 50 μg/ml streptomycin. Cells were stimulated with either 10 μM OVA257–264 or bovine serum albumin for 48 h. The cells were treated with 1 μg/ml biotinylated anti–mouse–IFN-γ (XMG1.2; BD Bioscience) and a 1:1,000 dilution of streptavidin–alkaline phosphate conjugated to APC followed by anti-APC MicroBeads for GR-1+ cell isolation.
Antigen-specific and nonspecific CD4+ T cell proliferation. The MHC class II-restricted OVA T cell transgenic mouse strain DO11.10 was used to determine whether GR-1+ cells suppress antigen-specific or nonspecific CD4+ T cell proliferation. DO11.10 transgenic mice were made septic and immunized with 100 μg OVA257-264, peptide (Generscript) in alum. At day 7, erythrocyte-depleted splenocytes and lymph node cells underwent CD4+ T cell purification by positive selection (>98% purity). The negative fraction was irradiated with 3,000 rads. 2 × 105 antigen-presenting cells from sham-treated mice (containing <10^6 GR-1+ cells) or 2 × 10^5 antigen-presenting cells from septic mice (containing 7.5 × 10^6 GR-1+ cells) were mixed with 2.5 × 10^4 CD4+ T cells. Cells were restimulated with 10 μg/ml OVA257-264 peptide or 1 μg/ml anti-CD3, and 1 μg/ml anti-CD28 or 10 μg/ml of bovine serum albumin for 48 h. In the final 16 h of culture, 1 μCi [3H]thymidine (GE Healthcare) was added. Proliferation was determined by the incorporation of [3H]thymidine in the cell co-culture.

Immunization with NP-KLH and humoral immune responses. An NP-KLH immunization model was used, as described by Hurov et al. (33). When indicated in the figures, animals were depleted either of GR-1+ cells or CD4+ T cells by i.p. injection of purified rat anti-mouse GR-1+ hybridoma IgG1 (RPE65) or rat anti-mouse CD4 hybridoma IgG1 (GK1.5). At day 10 after surgery, mice were immunized s.c. with 100 μg of the T cell–dependent antigen NP-KLH (Biosearch Tech) and alum. Serum titers of NP-specific antibodies were determined by ELISA. 96-well plates (Immuno 4HBX; Dynex Tech) were coated with 1 mg of NP-bovine serum albumin (Biosearch Tech) per milliliter. NP-specific antibodies were bound to biotin-conjugated goat anti-mouse IgG isotype antibodies, anti-IgG1, anti-IgG2a, and anti-IgG3 (CatLab). Streptavidin-conjugated horseradish peroxidase was incorporated to detect the biotin-IgG with 2,2'-azino-di(3-ethylbenzthiazolinesulfonate) substrate.

Morphologic and histologic analysis. For cytopsins, 10^5 enriched GR-1+ splenocytes were stained using One Step II Wright-Giemsa Stain Solution (Criterion Sciences). Hematoxylin and eosin staining tissues were fixed in 10% neutral buffered formalin with 0.03% eosin (Sigma-Aldrich), paraffin embedded, sectioned (5-μm sections), and mounted for staining. For immunohistochemical staining, spleens were mounted in Tissue Tek optimum cutting temperature compound (Sakura Finetek) and flash frozen. 4-μm cryosections were stained with a rat anti-mouse CD11b at a 1:50 dilution (BD Biosciences), followed by a biotinylated rabbit anti-rat (Vector Laboratories) secondary antibody, and visualized using Vulcan Fast Red (Biocare Medical). Slides were counterstained with hematoxylin (Vector Laboratories), followed by bleaching with Tris-buffered saline.

Statistics. Continuous variables were first tested for normality and equality of variances. Differences among groups in flow cytometric analyses were evaluated by analysis of variance for multiple groups and the Student’s t test for two groups. Significance was designated at the 95% confidence level.

Online supplemental material. Fig. S1 relates the bacteremia and blood leukocyte responses to sepsis produced by cecal ligation and puncture. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20062602/DC1.

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