Molecular Pathways: Targeting Tumor-Infiltrating Myeloid-Derived Suppressor Cells for Cancer Therapy

Diletta Di Mitri, Alberto Toso, and Andrea Alimonti

Abstract

Tumor-infiltrating myeloid-derived suppressor cells (MDSC) are a heterogeneous and immunosuppressive cell subset that blocks the proliferation and the activity of both T and natural killer (NK) cells and promotes tumor vasculogenesis and progression. Recent evidences demonstrate that the recruitment of MDSCs in tumors also blocks senescence induced by chemotherapy promoting chemoresistance. Hence, the need of novel therapeutic approaches that can efficiently target MDSC recruitment and function in cancer. Among them, novel combinatorial treatments of chemotherapy and immunotherapy or treatments that induce depletion of MDSCs in peripheral sites should be taken in consideration.

Background

An increasing amount of evidences from mouse and human unveiled the significance of the tumor immune microenvironment in tumor growth and progression. Consequently, activating the immune system has emerged as a promising way to treat cancer and numerous new immune-based treatments are currently under investigation for the treatment of cancer. Recent successful phase III clinical trials of therapeutic cancer vaccines include the FDA-approved Sipuleucel-T prostate cancer vaccine, melanoma peptide vaccines, and personalized lymphoma vaccines. Furthermore, two immune checkpoint inhibitors (anti-PD1 and anti-CTLA4) have reignited enthusiasm for the development of immunotherapy drugs for cancer, having demonstrated high response rates and prolonged overall survival in cancer patients. However, tumor-induced immunosuppression limits the potency of several standard and novel therapeutic interventions. Tumor-infiltrating myeloid-derived suppressor cells (MDSC) are the most common mediator of immunosuppression in tumors. MDSCs are an immune cell population coexpressing Gr-1 and CD11b myeloid lineage differentiation markers in mouse and either or both of the common myeloid markers CD33 or CD11b in cancer patients. MDSC cells represent a heterogeneous population that comprises both cells of granulocytic (G-MDSC) and monocytic (M-MDSC) origin. Monocytic MDSCs are characterized by a HLA-DR−/CD11b+/CD33+/CD14+ phenotype in humans (CD11b+/Ly6G−/Ly6C+ in mice), whereas human granulocytic MDSCs are defined by a HLA-DR−/CD11b−/CD33+/CD15+ phenotype (CD11b−/Ly6G−/Ly6C− in mice). Note, MDSCs with the phenotype of CD33+/HLA-DR−/CD14+/CD15−/CD45+ that are lineage negative (CD15−, CD14+) have also been well described in cancer patients. Importantly, both the monocytic and the granulocytic subsets display an equal immunosuppressive activity in tumors. Different studies have demonstrated that tumor formation promotes the migration of MDSCs from the bone marrow to the tumors. Mechanistically, this is associated with tumor secretion of cytokines and chemokines that induce myeloid cell trafficking, proliferation, and infiltration to the tumor bed. Indeed, the resection of solid tumors has been shown to decrease MDSC frequency in the peripheral blood and to reverse T-cell suppression, indicating that tumors directly affect this inflammatory cell population. In the bone marrow, MDSCs can be generated in response to cancer-derived factors such as granulocyte colony-stimulating factor (G-CSF), interleukin-6, granulocyte monocytic colony-stimulating factor (GM-CSF), IL-1β, prostaglandin E2 (PGE2), tumor necrosis factor α (TNFα), and vascular endothelial growth factor (VEGF) and are then recruited to the tumor site by mean of chemokines belonging to the CCL and CXCL families. Once recruited to tumors, MDSCs exert a significant effect on tumor progression, as they mediate immunosuppression of antitumor effector cells. Through the release of arginine, reactive oxygen species, and nitric oxide and secretion of immunosuppressive cytokines, MDSCs suppress tumor immunosurveillance mediated by T and natural killer (NK) cells. Indeed, antibody-mediated depletion of MDSCs was shown to restore T-cell frequency and function in vivo. In addition, MDSCs have been shown to drive the expansion of CD4+ CD25+ Foxp3+ regulatory T cells (Treg) localized in the tumor site and to inhibit antigen presentation from tumor-infiltrating dendritic cells, thus indirectly enhancing immunotolerance toward the tumor. Interestingly, MDSCs may also influence other key events in tumorigenesis, such as angiogenesis and metastasis formation. When MDSCs isolated from murine tumors are cojected with mouse cancer cells into mice, the growth rate and blood vessel density of tumors are significantly higher than in controls.
In vitro expansion of MDSCs collected from tumor cells resulted in STAT3 activation and cell proliferation. MDSCs isolated from tumor-bearing mice showed increased levels of JAK2 and STAT3 activation when exposed to conditioned media collected from tumors, indicating that MDSCs promote evasion of senescence induced by chemotherapy, thereby conferring treatment resistance. Intriguingly, senescence evasion by MDSCs is promoted through the secretion of IL1R1, which is capable of blocking IL1 signaling, needed for the execution of senescence in Pten null prostate and K-Ras/C16ve mice (15).

**Signaling Pathways**

In recent years, data have emerged that link several signaling pathways with MDSC trafficking, expansion, and suppressive activity (16). Signal transducer and activator of transcription 3 (Stat3) plays a crucial role in both MDSC suppressive activity and proliferation. MDSCs isolated from tumor-bearing mice showed increased levels of JAK2 and STAT3 activation when compared with myeloid progenitors from naive mice (17). Notably, the exposure of MDSCs to conditioned media collected from tumor cells, resulted in STAT3 activation and cell expansion in vitro (18). In addition, in vivo inhibition of Stat3, by means of the multitargeted tyrosine kinase inhibitor sunitinib and the JAK2/STAT3 inhibitor curcumin, was shown to block MDSC expansion in tumor-bearing mice (19, 20).

Interestingly, new insights into the downstream of the STAT3 signaling pathway showed that STAT3 controls the modulation of the CCAAT-enhancer-binding protein beta (C/EBPβ), a transcription factor known to drive MDSC differentiation from myeloid progenitors (21). Recent findings also provided evidence that the immunoregulatory activity of tumor-induced MDSCs relies on the C/EBPβ transcription factor. Indeed, adoptive transfer of tumor antigen-specific CD8+ T lymphocytes, in mice lacking C/EBPβ, in the myeloid compartment, resulted in reduced tumor growth in both OVA-expressing EG-7 tumors and MCA203 fibrosarcomas (22). Moreover, additional members of the STAT family are implicated in the modulation of MDSC activation. On this regard, Stat1, Stat5, and Stat6 have been shown to mediate arginase and INOS1 production and to be therefore implicated in the immunosuppressive function of MDSCs. In addition, evidences indicate that NF-κB acting downstream MyD88 plays a pivotal role in MDSC activation and functionality, and MyD88−/− MDSCs showed considerably reduced ability to suppress T-cell activity and release immunoregulatory cytokines compared with the wild-type counterpart, both in vitro and in vivo (23). Also, prostaglandins and COX2 exert a regulatory role on the functionality of MDSCs (24). Indeed, in vivo administration of a COX2 inhibitor significantly reduced MDSC accumulation in a model of lung carcinoma. MDSC-mediated promotion of tumor progression was dependent on PGE2 in this model. In addition, BALB/c mice deficient for the PGE2 receptor and injected with 4T1 breast carcinoma cells had delayed tumor growth and reduced tumor-infiltration of MDSCs. Accordingly, administration of a COX2 inhibitor in 4T1 tumor-bearing mice delayed tumor progression and reduced MDSC accumulation to the tumor site (16).

**Chemotherapy and MDSCs**

An intriguing and novel aspect of MDSC biology is the impact of chemotherapy on number and activity of tumor-infiltrating myeloid cells. Importantly, some chemotherapies, such as gemcitabine, cisplatin, paclitaxel, and 5-fluorouracil (5-FU), can suppress MDSC counts, and it is postulated that this may be critical to improve the efficacy of these drugs (9, 25, 26). However, following anticancer treatment, the frequency of MDSCs does not decline to the level seen in tumor-free mice and healthy human subjects. Moreover, tumor recurrence after treatment correlates with re-expansion of MDSCs (27). In vivo, treatment with 5-FU was shown to selectively induce apoptotic cell death in MDSCs, therefore leading to a major decrease in the number of myeloid cells in the spleens and tumors of tumor-bearing mice. Accordingly, gemcitabine was able to deplete MDSCs in vivo, with no significant reduction in other cell subsets. In both cases, the selective loss of MDSCs was accompanied by an increase in the intratumoral trafficking of CD4, CD8, and NK cells, thus favoring immunosurveillance against the tumor. Despite these evidences, the effect of chemotherapeutic agents on MDSCs is still controversial. Indeed, recent findings reported that gemcitabine and 5-FU can activate the inflammasome pathway in MDSCs in vivo, therefore culminating in caspase-1 activation and production of IL1B. The inflammasome activation induced in MDSCs resulted in an increased IL17 secretion by CD4 T cells that finally dampened the anticancer efficacy of the chemotherapy (28). Therefore, a reduction in the percentage of MDSCs does not necessarily decrease their immunosuppressive function in tumors. Furthermore, other cytotoxic compounds, such as cyclophosphamide, have been correlated with an increase in MDSC numbers in breast cancer patients and melanoma-bearing mice and enhanced immunosuppression (29). Interestingly, MDSC blockage has recently been shown to revert docetaxel chemoresistance in a mouse model of prostate cancer, thus suggesting that combinatorial approaches aimed to affect MDSC trafficking or functionality should be taken in consideration. Indeed, docetaxel-induced senescence and efficacy was increased in Pten-null prostate tumors when the percentage of tumor-infiltrating CD11b+Gr-1+ myeloid cells was reduced by treating the mice with an antagonist of CXC chemokine receptor 2 (CXCR2; ref. 15). On this line, it has been observed that prostate cancer patients having tumors infiltrated by CD33+ myeloid cells, relapsed after docetaxel treatment administered in an adjuvant setting, suggesting that MDSCs may drive chemoresistance in human prostate cancer (15).

Another recent article reported that prostate cancer patients having an increased percentage of circulating myeloid cells and decreased number of lymphocytes experienced a worst survival after second-line chemotherapy (30). On this regard, several clinical studies combining chemotherapy and immunotherapy directed against MDSCs have been initiated. Most of the treatments in use at the moment target the immunosuppressive function of the MDSCs. Among them, phase II studies that imply the administration of chemotherapeutic agents in combination with phosphodiesterase 5 (PDE-5) inhibitors or Nitro-aspirin (NO-aspirin), both able to reduce arginase and INOS2 release from MDSCs, are currently ongoing in different types of cancer (7). In addition, treatment of pancreatic cancer patients receiving gemcitabine and the novel tripterpenoid CDDO-Me led to significantly increased T-cell activation, in accordance with the ability of
CDDO-Me administration to decrease MDSC production of ROS and improve T-cell function in tumor-bearing mice (7).

Clinical–Translational Advances

Interestingly, it is now clear that the tumor-promoting activity of MDSCs is mainly related to their immature phenotype. Therefore, differentiating agents are currently under investigation in the clinic. Indeed, cancer patients receiving ATRA and 25-hydroxy-vitamin D showed an increased maturation of the myeloid subsets infiltrating the tumor, associated with a potentiated immunosuppressive response (31). Alternately, agents that inhibit MDSC trafficking to the tumor bed have been used in both pre-clinical and clinical trials. Among them, antagonists of the CXCR2 receptor and for the CSF-1R are currently under investigation in different types of cancer (Fig. 1). Other compounds such as the CXCR2 antagonists have been developed extensively in pre-clinical trials. Another approach to block the recruitment and function of MDSCs in tumors is to use compounds that can reprogram the tumor secretome. On this respect, recent findings reported that a Jak2 inhibitor was capable to reprogram the tumor secretome thereby decreasing the levels of myeloid-recruiting cytokines released by the tumors. This was associated to a decreased percentage of tumor-infiltrating MDSCs and restoration of tumor immunosurveillance in a mouse model of prostate cancer (32).

Another intriguing aspect of MDSC biology is their localization in the tumor-bearing mice and patients with cancer, which needs to be taken in consideration for future therapeutic interventions targeting these cells (Fig. 1). Indeed, extramedullar hemopoiesis (EMH) in reticuloendothelial and parenchymal tissues in cancer patients is well described (33–35), even if its role in MDSC accumulation is only partially known (36, 37). Notably, when tumor cells are injected in adult non-tumor-bearing mice, having few splenic progenitors, hematopoietic progenitors mobilize from bone marrow, arrest, and accumulate in lymphoid and parenchymal organs other than in the tumors (38). On this regard, studies using 4T1 tumor-bearing mice revealed a splenic myeloid cell reservoir that primarily comprises CD11b<sup>+</sup>Ly6C<sup>high</sup> cells (39). Circulating MDSCs arrest and accumulate in the splenic marginal zones and periarteriolar lymphatic sheaths, migrate to the red pulp and proliferate within the subcapsular red pulp (Fig. 1). The GR1<sup>dull</sup> subset of MDSCs may have a higher proliferation rate in bone marrow (40), although both MDSC subsets can proliferate in the spleen and in tumors (39, 41). Splenic MDSC counts also correlate with tumor G-CSF transcript and tumor growth (6). Indeed, it has been recently demonstrated that MDSCs can suppress T cells in the spleen promoting tumor immunosuppression (22). Accordingly, splenectomy in mice can change the amount of tumor-infiltrating MDSCs, promoting tumor regression in murine models of cancer (42). Therefore, MDSCs in cancer patients may affect tumorigenesis by acting in multiple sites, not only in the tumors. These data also suggest that treatments that target MDSCs should affect the recruitment of these cells in multiple sites to be effective as anticancer treatments. Radiotherapy on the spleen could be envisioned as a potential treatment to target splenic MDSCs in combination with compounds that can either impair the recruitment of MDSCs or promote their maturation. This approach is used in the clinic for the treatment of different hematologic disorders including myeloproliferative disorders in patients with splenomegaly. However, data demonstrating that such an

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**Figure 1.**

Secretion of cytokines from the tumor is associated with mobilization of both monocytic and granulocytic MDSCs from the bone marrow to the peripheral blood. In the bone marrow, MDSCs can be generated in response to cancer-secreted factors such as G-CSF, IL6, GM-CSF, IL1β, PGE2, TNFα, and VEGF. Circulating MDSCs are arrested in the spleen and accumulate in the splenic marginal zones and periarteriolar lymphatic sheaths, migrate to the red pulp, and proliferate within the subcapsular red pulp. Finally, the release of specific chemokines, belonging to the CCL and CXCL family, drives the recruitment of circulating MDSCs to the tumor and their localization in the tumor bed.
Tumor-Promoting Role of MDSCs

References

tion of MDSCs could enhance the efficacy of sipuleucel-T, a type of immunotherapy approved by FDA for the treatment of castrate-resistant prostate cancer patients. These patients are already sub-jected to leukaepheresis during the first procedure of the protocol and they could benefit from the removal of these cells (1).

Another possible entry point for cancer therapy could be to use MDSCs as vehicle to deliver different types of treatments. As discussed above, an important aspect in the biology of MDSCs is their capability to massively infiltrate almost all types of tumors, and to reach peripheral metastatic sites. Intriguingly, administra-tion of MDSCs loaded with the VSV oncolytic virus (vesicular stomatitis virus) to colon carcinoma-bearing mice significantly prolonged their survival by inducing tumor response as compared with systemic viral therapy (43). Furthermore, injection of MDSCs infected with a radioactive form of *Listeria monocytogenes* (*Listeria*) led to complete elimination of metastasis and significant reduction of tumor growth in mice bearing pancreatic tumors (44). Importantly, both bacterial and virus infection were shown to attenuate the immunosuppressive activity of MDSCs and a subset of infected myeloid cells even acquired an immunnostimulatory phenotype.

In sum, both preclinical and clinical evidences demonstrate that MDSCs play a prominent role in supporting tumorigenesis and that different mechanisms may be targeted to limit their tumor-promoting activity.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

Conception and design: D. Di Mitri, A. Toso

Development of methodology: A. Toso

Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): A. Toso

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): A. Toso

Writing, review, and/or revision of the manuscript: D. Di Mitri, A. Toso, A. Alimonti

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): A. Alimonti

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