Doxorubicin Eliminates Myeloid-Derived Suppressor Cells and Enhances the Efficacy of Adoptive T-Cell Transfer in Breast Cancer

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Abstract
Myeloid-derived suppressor cells (MDSC) expand in tumor-bearing hosts and play a central role in cancer immune evasion by inhibiting adaptive and innate immunity. They therefore represent a major obstacle for successful cancer immunotherapy. Different strategies have thus been explored to deplete and/or inactivate MDSC in vivo. Using a murine mammary cancer model, we demonstrated that doxorubicin selectively eliminates MDSC in the spleen, blood, and tumor beds. Furthermore, residual MDSC from doxorubicin-treated mice exhibited impaired suppressive function. Importantly, the frequency of CD4+ and CD8+ T lymphocytes and consequently the effector lymphocytes or natural killer (NK) to suppressive MDSC ratios were significantly increased following doxorubicin treatment of tumor-bearing mice. In addition, the proportion of NK and cytotoxic T cell (CTL) expressing perforin and granzyme B and of CTL producing IFN-γ was augmented by doxorubicin administration. Of therapeutic relevance, this drug efficiently combined with Th1 or Th17 lymphocytes to suppress tumor development and metastatic disease. MDSC isolated from patients with different types of cancer were also sensitive to doxorubicin-mediated cytotoxicity in vitro. These results thus indicate that doxorubicin may be used not only as a direct cytotoxic drug against tumor cells, but also as a potent immunomodulatory agent that selectively impairs MDSC-induced immunosuppression, thereby fostering the efficacy of T-cell–based immunotherapy.

Introduction
Myeloid-derived suppressor cells (MDSC) have been described as a heterogeneous population of immature myeloid cells that, in different pathological conditions, are impaired in their ability to terminally differentiate into mature myeloid lineages such as macrophages, dendritic cells, or granulocytes (1, 2). MDSC are functionally defined by their capability to inhibit both innate and adaptive immunity. They are potent suppressors of T-cell proliferation and activation in humans and mice (1–4). Phenotypically, mouse MDSC express the markers Gr-1 and CD11b. Two main populations have been described in mice based on the relative expression of 2 epitopes of Gr-1 (Ly6G and/or Ly6C):

- Granulocytic MDSC are CD11b+Ly6G+Ly6Clow, whereas monocytic MDSC are CD11b+Ly6G−Ly6Chigh (5, 6). In human, MDSC are generally identified as CD14−CD33+CD11b+HLA-DRneg/low cells (6). The immunosuppressive function of MDSC depends on multiple mechanisms, including the production of nitric oxide, peroxynitrites, reactive oxygen species (ROS), and the expression of inducible nitric oxide synthase (iNOS), indoleamine 2,3-dioxygenase (IDO), and/or arginase-1 (5, 7, 8).

A substantial expansion of MDSC in the blood, lymph nodes, bone marrow, and spleen has been detected in multiple mouse cancer models (5, 9). Similarly, accumulation of MDSC has been reported in the blood, lymph nodes, and tumors of patients with various types of cancers, including breast, which correlates with tumor burden and disease stage (10). Tumor-induced MDSC expansion significantly contributes to the mechanisms of cancer-induced immune suppression, and therefore significantly impedes the efficacy of immunotherapeutic approaches (1, 11, 12). Not surprisingly, multiple reports in humans and animal models have indicated that MDSC elimination or inhibition promotes anti-tumor immunity and enhances the response to immunotherapy (11). Different approaches have thus been explored to target these cells, which include the use of specific antibodies (13), all-trans retinoic acid (ATRA; refs. 14–16), or chemotherapeutic molecules such as gemcitabine (17, 18), 5-fluorouracil (5-FU; ref. 19), or docetaxel (20).

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Doxorubicin is an antineoplastic drug broadly used in the treatment of hematological malignancies, soft tissue sarcomas, and several types of carcinomas including breast cancer (21). Extensive evidence has been provided that besides its direct tumoricidal activity, doxorubicin also promotes antitumor immunity (22–26). This drug has indeed been shown to induce an "immunogenic type" of tumor cell death leading to the stimulation of dendritic cell antigen-presenting function (23). Doxorubicin administration has also been reported to enhance the proliferation of tumor-specific CD8⁺ T cells (27), and to increase the permeability of tumor cells to granzyme B produced by cytotoxic T lymphocytes (CTL; ref. 28). However, whether this drug may impact tumor-induced immunosuppression, specifically by negatively targeting MDSC, remains unclear. In this study, we investigated the effects of doxorubicin on MDSC in the murine breast cancer model 4T1 and explored the possibility of combining this chemotherapeutic drug with immunotherapy. We demonstrated for the first time that doxorubicin eliminated MDSC by triggering apoptosis of these cells. ROS may contribute to doxorubicin-mediated elimination of MDSC. In addition, residual MDSC from doxorubicin-treated mice were impaired in their suppressive function. Of importance, doxorubicin administration led to improved T- and natural killer cell function. The proportion of T- and natural killer (NK) cells expressing perforin and granzyme B was indeed significantly augmented following treatment of tumor-bearing mice with doxorubicin. In addition, doxorubicin increased the proliferation status of T lymphocytes and MDSC. Substantiating these observations, doxorubicin exhibited selective cytotoxic effects on MDSC isolated from patients with cancer. Furthermore, the combination of doxorubicin with T helper (Th) 1 or with recently identified Th₁7 lymphocytes impaired tumor development and metastatic spreading. These findings therefore highlight a novel property of doxorubicin as a potent selective MDSC-targeting agent, which may be used to enhance the efficacy of immunotherapeutic regimens.

Patients and Methods

Patients
A total of n = 10 patients with confirmed solid cancers (2 patients with lung, one patient with ovarian, one patient with prostate, one patient with bladder, one patient with colon, one patient with stomach, one patient with kidney, one patient with pancreatic, and one patient with breast cancer) were enrolled in the study before treatment after giving written informed consent in accordance with the Declaration of Helsinki. The study was approved by the Ethics Committee of the University Hospital of Dijon. None of the patients had received chemotherapy or any other immunosuppressive treatment during the previous 3 months.

Animals and tumor cell lines
Six- to eight-week-old Balb/c and C57BL/6 mice were purchased from the National Cancer Institute (NCI). Six- to eight-week-old gp91Phox⁻/⁻ (C57Bl6-Cybbtm1Din) were purchased from Jackson Laboratory. The mice were housed and cared for according to the University of Arizona Institutional Animal and Care Guidelines and Use Committee (IACUC). The 4T1 and EMT6 murine mammary tumor cell lines (Balb/c origin) and the EL4 thymoma cell line (C57BL/6 origin) were obtained from the American Type Culture Collection. 4T1-luc was generated using luciferase reporter plasmid (PGL4-51; InvivoGen). Briefly, the transfection was performed using Fugene6 reagent (Promega) according to the manufacturer’s protocol. Stably transfected cells were clonally selected in presence of G418 (800 µg/mL) and luciferase expression was confirmed using the luciferase reporter assay system and a luminometer (Femtomaster FB12; Berthold Detection System), according to the manufacturer’s recommendation (Promega).

Bioluminescence imaging
Tumor-bearing animals were injected (i.p.) with n-luciferin (4.29 mg/mouse; Xenogen). Mice were anesthetized using isoflurane (1.5 L/min oxygen, 4% isoflurane) and kept in an induction chamber. Images were captured with an AMI1000 imager (Spectral Instruments Imaging). Light emission was measured over an integration time of 1 minute, 10 minutes after injection of luciferin. Luciferase activity was analyzed using the AMI1000 Software (Spectral Instruments Imaging) to quantify tumor region flux (photons per second) and to assess tumor growth.

Generation of Th₁ and Th₁7
Naïve CD4⁺CD25⁻CD62L⁻ T lymphocytes were isolated from the spleen of 6- to 8-week-old Balb/c mice according to the manufacturer’s instructions (Miltenyi Biotec). Cells were subsequently cultured at a concentration of 10⁶ cells/mL in RPMI 1640 medium supplemented with 10% FBS, 100 U/mL penicillin, 100 µg/mL streptomycin sulfate, 0.5 × MEM non-essential amino acids, and 1 mmol/L sodium pyruvate. Cells were stimulated with anti-CD3– and anti-CD28–coated beads (Invitrogen). Th₁ cells were generated in the presence of interleukin (IL)-12 (10 ng/mL), IL-2 (10 ng/mL), IL-7 (20 ng/mL), and blocking anti-IL-4 antibodies (5 µg/mL; 3-day culture). For the generation of Th₁7 cells, naïve T cells were cultured with IL-6 (40 ng/mL), TGF-β (0.5 µg/mL), blocking anti-IFN-γ (5 µg/mL), and anti-IL-4 (5 µg/mL) antibodies for 3 days. Th₁7 cultures were then prolonged in fresh medium containing IL-23 (40 ng/mL) for an additional 3 days. All cytokines were purchased from R&D Systems or Peprotech.

Chemotherapy and chemoimmunotherapy
4T1 or 4T1-Luc cells were injected (1 × 10⁶ cells) orthotopically (mammary fat pad). In some experiments, 7 and 12 days posttumor injection, mice were administered with doxorubicin (2.5 or 5 mg/kg, i.v.), cyclophosphamide (50 mg/kg, i.p.), fludarabine (50 mg/kg, i.p.), melphalan (5 mg/kg, i.p.), vincristine (1 mg/kg, i.v.), etoposide (5 mg/kg, i.p.), or control PBS. Spleens, blood, and tumors were collected 14, 17, and 23 days posttumor cell injection. For evaluating the effects of doxorubicin plus T helper lymphocyte combination therapy, mice were injected with doxorubicin (5 mg/kg) on days 7 and 12 and...
with Th$_1$ or Th$_17$ cells (1 × 10$^6$ i.v.; 2 × 10$^6$ intratumorally) on days 9 and 14 posttumor cell injection. Mice were euthanized for ethical reasons when they exhibited severe morbidity signs because of overwhelming metastatic spreading (endpoint at 4–4.5 weeks) in compliance with IACUC regulations.

**MDSC isolation**

Spleens were harvested, dissociated, and red blood cells were lysed in lysis buffer (BD Biosciences). MDSC were purified using a mouse MDSC isolation kit according to the manufacturer’s instructions (Miltenyi Biotec). The purified cells were used in other experiments.

**Flow cytometry analysis**

Cell suspensions from blood, spleens, or tumors were filtered and red blood cells were lysed. For extracellular staining, cells were incubated with the indicated combinations of antibodies (CD11b, Ly6C, Ly6G (Gr-1), CD8, CD49b, CD4, CD25, F4/80, CD11c, CCR7, and CD206) or isotype controls (1 hour, 4°C). For intracellular staining, cells were fixed and permeabilized immediately after cell surface staining according to the manufacturer’s description (Affymetrix eBioscience). For IFN-γ staining, cells were incubated with a leukocyte stimulating kit (BD Biosciences) for 4 hours. For perforin or granzyme B staining, cells were incubated with anti-CD3– and anti-CD28–coated beads (Invitrogen) and IL-2 (4 ng/mL) for 24 hours. The proliferation status of the cells was assessed by staining with Ki67 according to the manufacturer’s protocol (Ki67 detection protocol; BD Biosciences). All antibodies and isotype controls were purchased from BD Biosciences or Affymetrix eBioscience. For the detection of apoptosis, spleen, and blood samples from tumor-bearing mice, untreated or treated with doxorubicin, were dissociated and processed as described earlier. Cells were then stained with Annexin V and propidium iodide (PI), according to the manufacturer’s protocol (Apoptosis detection kit; Affymetrix eBioscience). Fluorescence data were collected on a FACSeVerse or LSRFortessa (BD Biosciences). The data were analyzed using FlowJo software (Tree star Inc.).

**Suppression assays**

Spleens from naive mice were collected, dissociated, and cells were incubating on nylon wool columns (37°C, 45 minutes) after red blood cell lysis. More than 90% of the eluted cells were T lymphocytes based on T-cell receptor (TCR)$\alpha\beta$ expression. These T cells were labeled with 5 mMol/L CellTrace Violet according to the manufacturer’s instructions (Invitrogen) and were plated in 96-well plates with anti-CD3– and anti-CD28–coated activation beads (Invitrogen). Isolated MDSC from 4T1 tumor-bearing mice, treated or not with doxorubicin, were then added to the culture (MDSC-to-T-cell ratio = 1:2). After 4 days, cells were harvested, stained with anti-CD4, anti-CD8, and anti-CD25 (Affymetrix eBioscience). Cell proliferation was determined by measuring the dilution of cell trace violet by flow cytometry after gating on the CD4$^+$ or CD8$^+$ cell populations. The proliferation index was determined using the Modfit software (Verity Software House) and percent proliferation was calculated as follows: proliferation (%) = (T$^+$ – T$^0$)/(S – T$^+$) × 100, with T$^+$ is the proliferation index of the control stimulated T cells without MDSC; T is the proliferation index of control nonstimulated T cells without MDSC; and S is the proliferation index of stimulated T cells in the presence of MDSC.

**Western blot analysis**

Cells were lysed in radioimmunoprecipitation assay buffer and sonicated. Lysates were cleared by centrifugation at 14,000 rpm and protein concentration was determined with the Thermo Scientific BCA protein assay using bovine serum albumin (BSA) as standard. Equal amounts of proteins (30 μg) were separated on 10% or 16% SDS-PAGE gels, transferred onto a polyvinylidene fluoride (PVDF) membrane (Millipore) and probed with primary Abs specific for P-STAT3, STAT3, Arginase-1, IDO, cleaved caspase-3 (Cell Signaling Company), S100A9, S100A8 (R&D Systems), and actin (Sigma-Aldrich) followed by secondary antibody (Jackson ImmunoResearch). Reactive bands were visualized by exposure to film using Super Signal Chemiluminescent Substrate (Thermo Scientific).

**ROS detection**

Splenocytes from untreated or doxorubicin-treated mice were incubated for 30 minutes with the oxidation-sensitive dye dichlorodihydrofluorescein diacetate (DCFDA; 5 μmol/L; Molecular Probes/Invitrogen). Samples were then labeled with anti-Gr-1 and anti-CD11b antibodies. The level of ROS was detected using flow cytometry as described (29).

**Real-time PCR**

Cells were collected and total RNA was isolated using Trizol (Invitrogen). PCR reactions were set up in 96-well plates containing 10 μL 2× IQ Supermix (Bio-Rad), 1 μL TaqMan primer/probe set (ABI), 2 μL of the cDNA synthesis reaction [10% of room temperature (RT) reaction] and 7 μL of nuclease-free water. Reactions were run and analyzed on a Bio-Rad iCycler iQ Real-Time PCR Detection System. Primers for IFN-γ and IL-17 were obtained from Applied Biosystems (Invitrogen).

**ELISA**

IL-17 and IFN-γ concentration was detected in Th$_1$- and Th$_17$-cell culture supernatant using ELISA according to the manufacturer’s instructions (Affymetrix eBioscience).

**Immunofluorescent staining**

Tumors and spleens were harvested and frozen. Serial sections (5 μm) were performed from each tissue and mounted. Frozen slides were first fixed in 100% cold methanol for 10 minutes. After blocking for 1 hour at RT [10% normal chicken serum in Tris-buffered saline and 0.1% Tween 20 (TBS-T)/1% BSA] slides were incubated (overnight, 4°C) with anti-Gr-1 (Affymetrix eBioscience; 0.02 mg/mL in TBS-T). Slides were washed with TBS-T and incubated with a secondary chicken anti-rat antibody conjugated with Alexa Fluor 647 for 45 minutes at RT (1:200 in TBST; Invitrogen). Slides

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were washed and incubated (2 hours, RT) with a rat anti-mouse CD11b antibody conjugated with FITC (Affymetrix eBioscience; 0.02 mg/ml in TBS-T). Nuclear counterstaining was performed using Sytox orange according to the manufacturer’s instructions (Invitrogen). Slides were mounted with fluorescence mounting medium (Dako North America) and visualized using a confocal microscope (Zeiss LSM 510-META NLO).

**Statistical analysis**

Experiments were performed with 4 to 8 mice per group as indicated. Mice were individually processed and analyzed separately unless specified otherwise. All analyses were carried out using GraphPad Prism software (GraphPad Software). Analyses were performed by 1- or 2-way ANOVA with a Bonferroni or Dunnett posttest, or a paired t test where appropriate. Statistically significant P values were labeled as follows: ***, P < 0.001; **, P < 0.01; and *, P < 0.05.

**Results**

**Doxorubicin selectively eliminates tumor-induced MDSC in mice bearing established 4T1 mammary tumors**

The immunomodulatory effects of doxorubicin have been extensively studied (23, 26). However, the possible impact of this chemotherapeutic agent on suppressive MDSC remains elusive. To address this question, Balb/c mice were injected with 4T1 breast cancer cells and treated with doxorubicin (2.5 and 5 mg/kg; noncurative doses), 7 and 12 days post-tumor implantation (Fig. 1A). We first confirmed that 4T1 tumor growth is associated with substantial MDSC expansion and determined the basal proportion of MDSC in the absence of doxorubicin therapy at different time points following injection of tumor cells (Supplementary Fig. S1; refs. 30 and 31). Doxorubicin significantly reduced the proportion and absolute number of 4T1 tumor-induced MDSC in the spleen (Fig. 1B and C) and blood (Fig. 1D) of treated animals. It is noteworthy that although doxorubicin-mediated elimination of MDSC was prominent on day 14 and 17 posttumor cell injection, these cells were reconstituted by day 23. These results were further confirmed by confocal microscopy analysis of spleen sections (Fig. 1E). Furthermore, MDSC were also depleted within the tumor beds in mice treated with doxorubicin (Supplementary Figs. S2A–S2C). 4T1 tumor development is primarily associated with the expansion of granulocytic MDSC (30, 32). Our results indicate that doxorubicin did not significantly affect monocytic MDSC, which were low in frequency even in untreated animals, but significantly depleted granulocytic MDSC (Supplementary Fig. S2D). These results thus demonstrate that doxorubicin induced elimination of tumor-induced MDSC.

**Doxorubicin minimally affects effector immune cell populations**

To optimally promote antitumor immunity, immunomodulatory drugs should negatively target immunosuppressive cells while sparing immune effectors. We therefore sought to investigate whether doxorubicin may affect other immune cells, specifically antitumoral effector T lymphocytes and natural killer cells. Interestingly, the proportion of CD4+ and CD8+ T lymphocytes was significantly increased in the spleen and blood of doxorubicin-treated mice (Fig. 2A and B). NK frequency increased in the blood and was not altered in the spleen of the treated animals (Fig. 2C). Consistent with these results, the proliferation status of CD4+ and CD8+ T cells was augmented in doxorubicin-treated animals (Fig. 2D). This preferential targeting of MDSC resulted in a significant increase in the ratios of effector CD8+ T, CD4+ T, or NK cells to suppressive MDSC (Supplementary Fig. S3A). Importantly, the proportion of NK cells and CD8+ T lymphocytes expressing perforin and granzyme B was significantly increased in doxorubicin-treated 4T1 tumor-bearing mice (Fig. 2E and Supplementary Fig. S3B). In line with these results, doxorubicin administration resulted in augmented frequency of IFN-γ–producing CD8+ T lymphocytes (Fig. 2F). However, no change in the proportion of IFN-γ–producing CD4+ T cells was observed (Fig. 2F). It is noteworthy that doxorubicin did not change immunosuppressive Treg frequency (Supplementary Fig. S3C). Together these results indicate that doxorubicin-mediated MDSC depletion was associated with augmented effector immune cell proliferation and function.

Importantly, we further determined that doxorubicin was significantly more potent at depleting MDSC than other chemotherapeutic agents such as cyclophosphamide, fludarabine, melphalan (Supplementary Fig. S4A), vincristine, or etoposide (Supplementary Fig. S4B), which exhibited limited effects on these cells. Of note, these drugs promoted a decrease in tumor volume similar to that induced by doxorubicin. Doxorubicin was also unique at substantially increasing the effector lymphocytes (or NK) to suppressor MDSC ratios, indicating that it is endowed with a higher degree of selectivity compared with these other drugs (Supplementary Fig. S4A and S4B). Furthermore, even in combination with cyclophosphamide, doxorubicin significantly triggered MDSC elimination and increased T lymphocyte frequency (Supplementary Fig. S4C).

The observations that doxorubicin reduces MDSC frequency and absolute number and increases effector lymphocyte proportion, resulting in an increased effector T cells to suppressor MDSC ratios, were further confirmed in the EL4 (thymoma) and EMT6 (breast cancer) mouse models (Supplementary Fig. S5A and S5B). In addition, residual MDSC isolated from EL4 or EMT6 tumor-bearing mice treated with doxorubicin exhibited reduced suppressive function (data not shown).

**Doxorubicin preferentially triggers MDSC apoptotic program**

We next investigated the mechanisms underlying doxorubicin-mediated elimination of MDSC and specifically explored whether this drug may trigger the MDSC apoptotic program. Flow cytometry analysis after staining of spleen cells with anti-Gr-1, anti-CD11b antibodies, Annexin V and PI, and gating on the Gr-1+CD11b+ population indicated...
Figure 1. Doxorubicin eliminates tumor-induced MDSC. A, schematic of the experimental design followed to evaluate the effects of doxorubicin on MDSC in the 4T1 breast cancer model. Mice were injected orthotopically (mammary fat pad) with 4T1 tumor cells ($1 \times 10^6$). Doxorubicin (2.5 or 5 mg/kg) was administered intravenously on day 7 and 12 posttumor injection. Spleen and blood samples were harvested and evaluated on days 14, 17, and 23. B, proportion of MDSC (CD11b$^+$Gr-1$^+$) in the spleen of 4T1 tumor-bearing mice post-doxorubicin treatment (right) and representative flow cytometry analysis 17 days posttumor injection (left). C, absolute number of MDSC in tumor-bearing mice treated or not with doxorubicin. D, proportion of MDSC in the blood of tumor-bearing mice after doxorubicin treatment. E, confocal microscopy analysis of CD11b$^+$Gr-1$^+$ cells in the spleens from untreated or doxorubicin-treated mice 17 days posttumor injection (5 days after the last doxorubicin treatment). CD11b (green), Gr-1 (red), and sytox orange nuclear staining (Nuc, blue). Scale bar, 20 μm. *, $P \leq 0.05$; **, $P \leq 0.01$; ***, $P \leq 0.001$. $n = 4$ mice per group. Data represent one of 3 experiments performed and analyzed independently.
that doxorubicin increased the proportion of apoptotic (Annexin V⁺, PI⁻) and secondary necrotic (Annexin V⁺, PI⁺) MDSC (Fig. 3A). Consistent with these data, caspase-3 cleavage was detected in MDSC isolated from 4T1 tumor-bearing doxorubicin-treated animals (Fig. 3B). Importantly, in line with the results depicted in Fig. 2A and B, the number of dead (apoptotic and necrotic) T lymphocytes (CD4⁺ or CD8⁺) was not significantly modified by doxorubicin (Fig. 3C). These data thus demonstrate that doxorubicin preferentially induced apoptosis of MDSC with no detectable toxic effect on effector T lymphocytes.

MDSC isolated from untreated tumor-bearing mice were more sensitive to doxorubicin in vitro than the MDSC-depleted cell population or than 4T1 cells (Fig. 3D and data not shown).
shown). Treatment of these purified MDSC with N-acetylcysteine (NAC, an ROS scavenger) prevented their killing by doxorubicin, suggesting that ROS may play a role in this process (Fig. 3D). Consistent with this result, the levels of ROS were increased in the immediate hours following doxorubicin treatment of MDSC in vitro (Fig. 3E), and MDSC isolated from EL4 tumor-bearing gp91^−/^ mice (lacking the gp91phox glycosylated subunit of the NADPH oxidase flavocytochrome b558, responsible for the production of superoxide ion O2^−) were less sensitive to doxorubicin-mediated cytotoxicity in vitro (Fig. 3F). Interestingly, in vivo, the effects of doxorubicin administration on MDSC were partially impaired in EL4 tumor-bearing gp91^−/^ mice compared with wild-type mice (data not shown).

Figure 3. Doxorubicin selectively induces MDSC apoptosis. A similar experimental design as described in Fig. 1 was followed. Spleens were collected 5 days after the last doxorubicin administration. A, spleen samples were labeled for MDSC (CD11b^+^Gr-1^+^) and Annexin V and PI. Representative flow cytometry analysis (left, gated on C11b^+^Gr1^+^ cells), and proportion of apoptotic and secondary necrotic MDSC (right). B, detection of caspase-3 cleavage in MDSC isolated from mice treated or not with doxorubicin 17 days posttumor injection. C, spleen samples were labeled with anti-CD4 or anti-CD8 and Annexin V and PI. Gated CD4^+^ or CD8^+^ T lymphocytes were then analyzed for their Annexin V and PI status. Percent of apoptotic or secondary necrotic necrotic CD4^+^ (top) and CD8^+^ (bottom) T lymphocytes in doxorubicin-treated or untreated mice. Similar experimental design as in A. D, effects of doxorubicin used at the indicated concentrations on MDSC isolated from 4T1 tumor-bearing mouse spleens (or on the MDSC-depleted cell population) determined by MTT assays. Cells were cultured in quadruplicate for 30 hours with or without NAC (5 mmol/L). % cell survival = (OD560[treated cells at the indicated doxorubicin concentration]/OD560[untreated cells]) × 100. E, analysis of ROS production by MDSC isolated from tumor-bearing mice and treated in vitro with the indicated concentrations of doxorubicin and for the indicated period of time. Cells were incubated with DCFDA and analyzed by flow cytometry. The mean fluorescent intensity representing ROS levels in MDSC is shown. F, same as in D, but with MDSC isolated from EL4 tumor-bearing wild type or gp91^−/^ mice. *, P ≤ 0.05; **, P ≤ 0.01; ***, P ≤ 0.001. n = 4 mice per group. Data represent one of 3 experiments performed and analyzed independently.
Doxorubicin impedes the suppressive activity of residual MDSC isolated from tumor-bearing mice

A cardinal characteristic of MDSC is their ability to suppress the activation and proliferation of T cells. MDSC depletion by doxorubicin was not complete as ∼15% of residual MDSC could still be detected 17 days after doxorubicin administration. Therefore, it was important to determine whether the suppressive function of these remaining MDSC was affected by doxorubicin. As expected and previously reported (32), MDSC isolated from tumor-bearing mice were treated or not in vitro with doxorubicin (100 ng/mL, 24 hours) and their ability to impair the proliferation of cell trace violet-labeled naive CD4+ T cells induced by anti-CD3 and anti-CD28–coated activation beads was evaluated by flow cytometry. Data represent one of 2 experiments performed and analyzed independently. pi, proliferation index.

**Figure 4.** Doxorubicin impairs MDSC immunosuppressive function. A and B, MDSC isolated from untreated or doxorubicin-treated mice were incubated for 4 days with cell trace violet-labeled naive T cells (MDSC: T-cell ratio = 1:2). A, effects of MDSC from the indicated groups of mice on the proliferation of CD4+ (left) or CD8+ (right) T lymphocytes assessed by flow cytometry. B, effects of MDSC on CD25 expression by gated CD4+ (top) or CD8+ (bottom) T lymphocytes. C, MDSC isolated from tumor-bearing mice were treated or not in vitro with doxorubicin (100 ng/mL, 24 hours) and their ability to impair the proliferation of cell trace violet-labeled naive CD4+ T cells induced by anti-CD3 and anti-CD28–coated activation beads was evaluated by flow cytometry. *; *P < 0.05; **; *P < 0.01; ***; *P < 0.001. n = 4 mice per group. Data represent one of 2 experiments performed and analyzed independently. 

Doxorubicin in vitro impaired their immunosuppressive function (Fig. 4C). Various mechanisms have been implicated in MDSC suppressive function including the production of ROS or the expression of arginase-1 or IDO involved in the catabolism of arginine or tryptophan, respectively (1). Depletion of these amino acids from the microenvironment results in the inhibition of T-cell proliferation, notably through the downregulation of the ζ-chain of the TCR complex (1, 11). Similarly, ROS exhibit suppressive effects on T lymphocytes (1, 33). Five days after doxorubicin treatment of 4T1 tumor-bearing mice, the production of ROS (Fig. 5A) and the expression of arginase-1 (Fig. 5B) and IDO (Fig. 5C) by residual MDSC was impaired. Additional molecules reported for their role in MDSC development and/or immunosuppressive function such as CD73, CD39, S100A8/9, or STAT-3 were not significantly altered by doxorubicin treatment (Supplementary Fig. S7A and S7B).
Previous reports have indicated that some chemotherapeutic drugs such as docetaxel can promote MDSC differentiation into macrophages (M1; ref. 20). To evaluate this possibility, MDSC from doxorubicin-treated mice were analyzed for the expression of markers expressed by M1 (CCR7) or M2 (CD206; Mannose Receptor) macrophages. The expression of these 2 cell surface markers was not detected on MDSC following doxorubicin treatment, indicating that this drug did not promote MDSC differentiation into macrophages (Supplementary Fig. S7C). Finally, further investigation indicated that the proliferation status (Ki67 expression) of residual 4T1 tumor-induced MDSC was reduced by doxorubicin therapy (not shown).

Altogether, these results indicate that 5 days after doxorubicin administration, MDSC that have not been eliminated by the drug exhibited reduced expression of arginase-1 and IDO, decreased ROS level, and curtailed immunosuppressive activity.

Figure 5. Doxorubicin decreases ROS production and arginase-1 and IDO expression by MDSC. A similar experimental design as described in Fig. 1 was followed. Spleens were harvested 5 days after the last doxorubicin treatment (day 17). A, analysis of ROS production by MDSC in tumor-free (tumor-free) or in tumor-bearing (tumor-bearing) mice treated with the indicated concentration of doxorubicin. Cells were incubated with DCFDA. Representative flow cytometry analysis of gated CD11b+Gr-1+ cells positive for DCFDA (top). Percent of MDSC positive for DCFDA (left bottom). Mean fluorescent intensity representing ROS level in MDSC from the indicated groups (right bottom). B and C, Western blot analysis depicting expression of arginase-1 (B) or IDO (C) in MDSC isolated from doxorubicin-treated or -untreated mice. *, P ≤ 0.05; **, P ≤ 0.01; ***, P ≤ 0.001. n = 4 mice per group. Data represent 1 of 3 experiments performed and analyzed independently.
Doxorubicin acts synergistically with Th1 or Th17 cell therapy

Doxorubicin depleted tumor-induced MDSC and curtailed the suppressive function of residual MDSC, thereby averting one major mechanism of cancer-mediated immunosuppression. Moreover, the proliferation status and activation of responder effector lymphocytes and NK were restored in doxorubicin-treated mice. We therefore reasoned that this drug may create a favorable environment that may allow for successful combinatory immunotherapy. To address this hypothesis, we evaluated a chemo-immunotherapy regimen consisting of doxorubicin followed by infusion of T helper lymphocytes.

Th17 lymphocytes represent a recently described subset of T helper cells with controversial effects on tumor development. Recent reports have demonstrated that Th17 generated from naive CD4⁺ T cells (Supplementary Fig. S8A and S8B) as depicted in Fig. 6A. The chemoimmunotherapeutic regimen significantly reduced the number of CD8⁻ T lymphocyte-dependent immune response and to impair tumor growth (34). Th1 can also promote antitumor immunity (35). In our current study, mice bearing established 4T1 tumors were treated with doxorubicin and received either Th1 or Th17 lymphocytes generated from naive CD4⁺ T cells (Supplementary Fig. S8A and S8B) as depicted in Fig. 6A. The chemoimmunotherapeutic regimen significantly reduced the number of CD8⁻ T cells (Supplementary Fig. S8A and S8B) as depicted in Fig. 6A. The chemoimmunotherapeutic regimen significantly reduced the number of 4T1 metastatic nodules in the lungs and impaired tumor growth when compared with the monotherapies (Fig. 6B and Supplementary Fig. S8C). Importantly, MDSC depletion persisted in mice treated with doxorubicin plus Th1 or Th17 cells, whereas these cells eventually re-expanded post-treatment in mice receiving doxorubicin alone (Fig. 6C and D). Consistent with these results, the frequency of CD8⁻ CD4⁺ T lymphocytes was significantly increased in doxorubicin plus Th1- or Th17-treated animals (Fig. 6D), but NK proportion remained unchanged (data not shown). These data thus indicate that doxorubicin administration resulted in the promotion of a favorable environment fostering the antitumoral efficacy of Th1 and Th17 lymphocytes.

Doxorubicin induces apoptosis of MDSC isolated from patients with cancer

To determine whether similar effects of doxorubicin can be observed on human MDSC, CD33⁺ cells were isolated from the blood of patients with different types of cancer (n = 10). CD33⁺ cells exhibited a phenotype consistent with that reported for human MDSC (Fig. 7A; ref. 36) and importantly were endowed with significant suppressive capabilities (Fig. 7B). Our results indicate that these immunosuppressive cells were sensitive to doxorubicin-induced cell death (Fig. 7C and E). Importantly, CD33⁻ depleted cells (CD33⁻) from the same patients were significantly less sensitive to doxorubicin (Fig. 7D and E), indicating that this chemotherapeutic molecule preferentially targets MDSC. CD33⁻ T cells were also minimally affected by doxorubicin (not shown). These results thus suggest that doxorubicin exhibit effects on human MDSC comparable to those observed on mouse MDSC, thus supporting the implementation of this drug in clinical chemoimmunotherapeutic approaches.

Discussion

The development of malignant tumors is commonly associated with the occurrence and persistence of an immunosuppressive environment. The expansion of MDSC, a main suppressive cell population (13), has been widely documented in many animal tumor models as well as in patients with different types of cancers and represents a major obstacle for efficient cancer immunotherapy (5, 9, 10). Several strategies have been explored to either eliminate or curtail, the immunosuppressive function of MDSC. Depletion of Gr-1⁺ MDSC using anti-Gr-1 monoclonal antibody resulted in restored T-cell antitumor activity. However, anti-Gr-1 also led to the elimination of mature granulocytes and was associated with severe immunosuppression (13). The promotion of MDSC differentiation using ATRA, a natural metabolite of vitamin A, has also been considered. ATRA administration enhanced T lymphocyte function and fostered the efficacy of cancer vaccines (14). In recent years, evidence has been provided that chemotherapeutic drugs can not only kill tumor cells, but also enhance antitumor immunity through different mechanisms (37). Chemotherapeutic agents can promote the function of antigen presenting cells, NK, and T lymphocytes (23, 26, 37) but may also negatively target immunosuppressive cells such as Treg or MDSC (17, 19, 20, 38, 39). For instance, gemcitabine has been reported to deplete MDSC in tumor-bearing mice, resulting in enhanced antitumor immunity (17–20). Additional reports have demonstrated that 5-Fluorouracil (19), or docetaxel (20), can eliminate, impede the suppressive function, or promote the differentiation of MDSC.

Doxorubicin has been a key chemotherapeutic agent used against a variety of human cancers. More recently, this drug has been widely studied for its ability to modulate anticancer immunity (23–26, 28). Reports have demonstrated that doxorubicin induces an “immunogenic type” of tumor cell death and promotes antitumor immune responses (23). In this study, we highlight a novel property of doxorubicin: its ability to avert a major mechanism of tumor-induced immunosuppression by eliminating and inactivating tumor-induced MDSC. We established that doxorubicin administration reduced the number of MDSC in the spleen, blood, and in the tumor beds of animals bearing established 4T1 mammary tumors. Importantly, doxorubicin selectively eliminated MDSC while enhancing the proliferation status, activation, cytokine production of effector T lymphocytes and/or NK cells. This primary targeting of MDSC while effector T cells (and NK) were spared translated into a substantial increase in effector lymphocytes to MDSC ratios. Compared with the other chemotherapeutic drugs that we evaluated, doxorubicin was endowed with the highest degree of selectivity. Indeed, although associated with a reduction of tumor volume comparable to that observed after doxorubicin treatment, most of these other agents had limited effects on MDSC and some of them, such as cyclophosphamide, even led to a slight increase in MDSC as they targeted T cells.
Figure 6. The combination of doxorubicin and Th1 or Th17 impairs 4T1 tumor development. Mice were injected orthotopically (mammary fat pad) with 4T1 tumor cells (1 × 10^6). Doxorubicin (5 mg/kg) was injected intravenously on day 7 and 12 posttumor cell injection. Th1 or Th17 lymphocytes were administered on day 9 and 14 posttumor cell injection, intravenously (1 × 10^6) and intratumorally (2 × 10^6). Tumor volume and number of metastatic nodules were evaluated on day 19 posttumor injection. A, schematic of the experimental design. B, number of metastatic nodules (left) and tumor volume (right). C, representative flow cytometry analysis of MDSC frequency in mice administered with the indicated therapies. D, proportion of MDSC, CD4^+^, and CD8^+^ T cells in mice receiving the indicated therapies; n = 8 mice per group. Data are representative of 3 independent experiments. *, P ≤ 0.05; ***, P ≤ 0.01; ***, P ≤ 0.001.
Figure 7. Doxorubicin selectively kills MDSC isolated from patients with cancer. CD33+ cells were isolated from cancer patient PBMCs by magnetic cell sorting. A, phenotypic analysis of the isolated cells. Representative results of n = 10 patients. B, ability of the CD33+ purified cells to impair the proliferation of cell trace violet-labeled T lymphocytes induced with anti-CD3 and anti-CD28–conjugated microbeads (at the indicated MDSC to T-cell ratios). pi, proliferation index. C and D, purified CD33+ MDSC or CD33− cells were exposed to the indicated concentrations of doxorubicin for 24 hours and stained with Annexin V and PI (% dead cells = % of PI+ + % AnnexinV+ PI− cells). A total of n = 10 patients were analyzed. E, representative dot plots obtained with CD33+ MDSC or CD33− cells isolated from a patient with cancer. (*, P ≤ 0.05; **, P ≤ 0.01; *** P ≤ 0.001).
Of therapeutic relevance, the addition of doxorubicin to cyclophosphamide resulted in a significant elimination of MDSC similar to that observed when doxorubicin was administered alone. This peculiar property of doxorubicin further highlights the interest and advantage of using this drug as a potent immunomodulatory agent in chemoimmunotherapeutic approaches.

Further investigation indicated that doxorubicin selectively triggered the apoptotic program of MDSC. No change in the apoptosis rate of T or NK cells was detected post-doxorubicin treatment compared with untreated groups. This selective effect may be partly explained by the preferential targeting of highly proliferative cells by doxorubicin. Indeed, MDSC in untreated tumor-bearing mice expressed high level of Ki67, a marker of cell proliferation (data not shown), whereas T lymphocyte proliferation was low in untreated tumor-bearing mice. The triggering of apoptosis by doxorubicin through the induction of ROS production has been described in tumor and normal cells such as cardiomyocytes (40). In vitro, the ROS scavenger NAC impaired doxorubicin-mediated elimination of MDSC, and MDSC isolated from gp91<sup>-/-</sup> mice were less sensitive to doxorubicin. The effects of doxorubicin on MDSC were partially impaired in EL4 tumor-bearing gp91<sup>-/-</sup> mice. These results strongly suggest that, early after its administration, doxorubicin may induce ROS-dependent triggering of the MDSC apoptotic program, resulting in the rapid elimination of most of these cells. Of note, MDSC that were not eliminated and that were found later (5 days) after doxorubicin treatment exhibited an overall impaired suppressive activity, which, at this time point, was associated with a reduction of ROS production.

A previous report has indicated that docetaxel reduced MDSC number by promoting their differentiation into M1 macrophages (20). We did not detect any changes in the expression of M1 or M2 macrophage markers on MDSC following doxorubicin treatment. In addition, no change in the frequency of macrophages or DC was detected in the treated mice. However, as mentioned earlier, the suppressive function of the limited number of residual MDSC that were not depleted by doxorubicin was significantly impaired.

Because doxorubicin administration induced MDSC depletion and was associated with restored T lymphocyte activity, we reasoned that it may create a favorable environment for efficient immunotherapy. Infusion of in vitro generated Th<sub>1</sub> cells has been reported to promote antitumor immunity (35). Th<sub>1</sub> lymphocytes have recently emerged as a new effector CD4<sup+</sup> T helper cell subset (41) exhibiting effector functions distinct from Th<sub>1</sub> and Th<sub>2</sub> lymphocytes (42). Th<sub>17</sub> have been identified as major contributors to the pathogenesis of multiple autoimmune conditions in animals and humans (42). However, the role of Th<sub>17</sub> cells in cancer remains controversial. Although some studies have documented the antitumoral efficacy of these cells (34, 43–45), others have reported on their immunosuppressive properties (46). These conflicting results related to the protumoral versus antitumoral properties of Th<sub>17</sub> may be explained by the high degree of plasticity of these cells (47–49). Supporting the antitumoral role of in vitro polarized Th<sub>17</sub>, Muranski and colleagues demonstrated that adoptive Th<sub>17</sub> cell therapy has the potential to eliminate established tumors. The antitumoral efficacy of Th<sub>17</sub> lymphocytes depended on their ability to produce both IFN-γ and IL-17 (43, 44). Consistent with these studies, our own results indicated that Th<sub>17</sub> generated from OT-II mice exhibit antitumoral effects against B16-OVA melanoma (unpublished data). In this study, we demonstrated that the therapeutic efficacy of adoptively transferred Th<sub>0</sub> or Th<sub>17</sub> lymphocytes was significantly enhanced by doxorubicin administration, resulting in impaired development of the highly metastatic 4T1 mammary carcinoma.

Doxorubicin is widely used in chemotherapeutic regimen primarily for its conventional direct tumoricidal activity. Here we highlight a new application for this drug as a selective MDSC-targeting agent, which can be used to overcome a major mechanism of tumor immune evasion. These results advocate for the implementation of doxorubicin in combination strategies to enhance the efficacy of immunotherapy.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

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Development of methodology: D. Alizadeh, M. Trad, B. Bonnotte, N. Larmonier
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): D. Alizadeh, M. Trad, N.T. Hanke, C.B. Larmonier, B. Bonnotte
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): D. Alizadeh, M. Trad, C.B. Larmonier, N. Janakashvili, B. Bonnotte, E. Katsanis, N. Larmonier
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References


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