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Membrane-associated Hsp72 from tumor-derived exosomes mediates STAT3-dependent immunosuppressive function of mouse and human myeloid-derived suppressor cells

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Myeloid-derived suppressor cells (MDSCs) have been identified in humans and mice as a population of immature myeloid cells with the ability to suppress T cell activation. They accumulate in tumor-bearing mice and humans and have been shown to contribute to cancer development. Here, we have isolated tumor-derived exosomes (TDEs) from mouse cell lines and shown that an interaction between TDE-associated Hsp72 and MDSCs determines the suppressive activity of the MDSCs via activation of Stat3. In addition, tumor-derived soluble factors triggered MDSC expansion via activation of Erk. TDE-associated Hsp72 triggered Stat3 activation in MDSCs in a TLR2/MyD88-dependent manner through autocrine production of IL-6. Importantly, decreasing exosome production using dimethyl amiloride enhanced the in vivo antitumor efficacy of the chemotherapeutic drug cyclophosphamide in 3 different mouse tumor models. We also demonstrated that this mechanism is relevant in cancer patients, as TDEs from a human tumor cell line activated human MDSCs and triggered their suppressive function in an Hsp72/TLR2-dependent manner. Further, MDSCs from cancer patients treated with amiloride, a drug used to treat high blood pressure that also inhibits exosome formation, exhibited reduced suppressor functions. Collectively, our findings show in both mice and humans that Hsp72 expressed at the surface of TDEs restrains tumor immune surveillance by promoting MDSC suppressive functions.

Authorship note: Fanny Chalmin, Sylvain Ladoire, and Grégoire Mignot contributed equally to this work.

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Introduction

Myeloid-derived suppressor cells (MDSCs) have been identified in humans and mice as a population of immature myeloid cells with the ability to suppress T cell activation (1). In mice, MDSCs are uniformly characterized by the expression of the cell-surface antigens Ly-6C/G and CD11b (2), while in humans, MDSCs are typically CD11b+CD33+HLA-DR+ (3–6). In tumor-bearing mice, these cells have been shown to markedly expand systemically when mice are inoculated with transplantable tumor cells or when tumors spontaneously develop in transgenic mice with tissue-restricted oncogene expression (7). In addition, an increased MDSC frequency was detected in the blood of patients with different types of cancers (4, 8–10). In mice and humans, MDSCs from tumor bearers induce antigen-specific MHC class I–restricted tolerance of CD8+ T cells (11) and are one of the major suppressors of antitumor immunity. Given that MDSCs from naive mice were generally found to lack immunosuppressive properties, it has been proposed that MDSCs require activation signals from tumor cells to support their suppressive function on T cells (12).

Recent evidence suggests that the transcriptional factor Stat3 is constitutively activated in many mouse and human cancer cells. Activated Stat3 is not only involved in tumor cell survival but has also been proposed to be the main regulator of MDSC expansion (13–15). Indeed, tumor cells that constitutively express tyrosine 705–phosphorylated Stat3 (tyrosine 705–pStat3) were shown to release tumor-derived factors that induce MDSC accumulation (13, 16–19). However, these observations were challenged by the report of Kortylewski et al., in which the specific deletion of Stat3 in hematopoietic cells enhanced the presence of MDSCs in the tumor bed (20). Therefore, the exact role for Stat3 within MDSCs remains elusive.

Tumor-induced activation and expansion of MDSCs can be mediated by the release of soluble factors but also by microvesicles known as exosomes (21, 22). These microvesicles are endo-
when using MDSCs purified from naive mice (Supplemental Figure 3). We also studied NF-κB activation and found that TDEs induced a short but strong p65 activation while TDSFs induced a prolonged but modest p65 activation (Supplemental Figure 4).

Altogether, we demonstrated that TCS triggers 2 distinct molecular pathways in MDSCs. TDSFs trigger the activation of Erk, which results in the expansion of MDSCs, while TDEs trigger the activation of Stat3 without promoting MDSC expansion.

**TDE-induced Stat3 activation determines MDSC suppressive functions.** Since our results suggested that Stat3 was not involved in MDSC expansion, we sought to determine whether Stat3 was involved in MDSC immunosuppressive functions. First, we showed that only MDSCs from tumor-bearing mice harbored pStat3 (Figure 2A), with a higher level in monocytes (Supplemental Figure 5). MDSCs from tumor-bearing mice also exerted a significant immunosuppressive effect, while MDSCs from naive mice did not express Stat3 and did not have significant immunosuppressive functions (Figure 2B).

In addition, Stat3 inhibition using selective inhibitors or siRNA blunted MDSC immunosuppressive effect in vitro (Figure 2C). Also, in vivo adoptive transfer of MDSCs from tumor-bearing mice could annihilate the effect of a tumor vaccine on the occurrence of lung metastases in a pStat3-dependent manner (Figure 2D). Importantly, the MDSC adoptive transfer had no effect on lung metastasis growth in unvaccinated mice or nude mice, thus confirming that this effect is dependent on T cells.

Finally, only MDSCs incubated in the presence of TDEs — but not those incubated in the presence of TDSFs — exerted suppressive functions on antigen-stimulated OT-1 T lymphocytes in vitro (Figure 2E) or were able to blunt IFN-γ production of tumor-specific CD8 and CD4 lymphocytes in the spleen of tumor-bearing mice in vivo (Figure 2F).

Altogether, these data demonstrate that TDEs through their capacity to activate Stat3 could mediate T cell–dependent immunosuppressive functions of MDSCs.

**TDEs trigger pStat3 expression in MDSCs through production of IL-6.** We then sought to determine the mechanisms triggering Stat3 activation. In TCS, we could not detect any presence of classical Stat3-activating factors such as SCF, PGE2, IL-10, and IL-6 (Supplemental Figure 6A). We could not detect significant levels of PGE2 in either TCSs or TDEs (Supplemental Figure 6B). We observed that incubation of purified MDSCs from the spleen of naive mice with TDEs — but not with TDSFs — induced the production of IL-6, a known Stat3 activator (26) (Figure 3A). Interestingly, besides IL-6, none of the already described Stat3-activating cytokines was detected (Supplemental Figure 7). To assess the role of IL-6 on Stat3 activation, we demonstrated that culture of MDSCs from naive mice with either recombinant IL-6 (rIL-6) or TDEs induced Stat3 phosphorylation (Figure 3B). The addition of blocking anti–IL-6 Ab to TDEs in MDSC culture completely blocked Stat3 phosphorylation, thus suggesting that IL-6 acts in an autocrine manner. To assess the in vivo relevance of this observation, we treated naive mice with 1 i.v. injection of either PBS, rIL-6, or TDEs. We observed that rIL-6 or TDEs induced similar levels of pStat3 in splenic MDSCs compared with the PBS control. In tumor-bearing mice, splenic MDSCs also harbored pStat3 and a single injection of IL-6 siRNA abolished this phosphorylation, thus demonstrating IL-6 dependence of pStat3 induction in MDSCs (Figure 3C). In order to decrease the level of TDE release in tumor-bearing mice and its effect on IL-6–induced Stat3 activation, we used dimethyl amiloride (27), an inhibitor of the H’/Na’ and Na’/Ca2+...
Figure 1

TDEs determine STAT3 activation, while TDSFs determine MDSC expansion. Bone marrow from naive mice was cultured 3 days in complete medium (CM) alone or with TCSs, TDEs, or TDSFs. (A) The percentage of Gr1⁺CD11b⁺ precursor cells ± SD was determined by flow cytometry. (B) The percentage of Ki67⁺ cells ± SD in Gr1⁺CD11b⁺ cells was determined by flow cytometry. (C) pStat3 MFI in Gr1⁺CD11b⁺ cells was determined by flow cytometry. Data represent MFI ± SD (n = 3); inset shows representative FACS histogram. (D) Purified splenic MDSCs from naive mice were treated with increasing dosages of TDEs. pStat3 expression was determined by FACS analysis. Data represent MFI ± SD (n = 3). (E) Activation of Stat3 and Erk in MDSC clones stimulated by TDEs or TDSFs was determined by Western blotting. (F) GM-CSF production by tumor cells was determined by ELISA. (G) Activation of Erk by TDSFs plus anti–GM-CSF blocking Ab was assessed by Western blotting. *P < 0.05.
intracellular CD4 and IFN-\(\gamma\) expression after restimulating in vitro with CD3 mAb.

These MDSCs were either from TB or naive mice and stimulated with previously treated alone or with tumor cell whole supernatant or TDEs, cultured alone or with bone marrow–derived MDSCs of naive mice previously treated alone or with tumor cell whole supernatant or TDE or TDSF fractions. CFSE dilution was determined by flow cytometry (\(n = 3\) mice per group). (F) TB mice were injected or not with MDSCs. These MDSCs were either from TB or naive mice and stimulated with PBS, TDEs, or TDSFs. 2 days later, spleen cells were harvested and restimulated in vitro with CD3mAb\(^*\) dead tumor cells, then stained for intracellular CD4 and IFN-\(\gamma\) (upper panel) or CD8 IFN-\(\gamma\) (lower panel). *P < 0.05. Error bars represent mean ± SD.

Altogether, these results indicate that TDEs trigger an IL-6–dependent acquisition of pStat3 on MDSC. DMA or omeprazole, by reducing exosome production, could abrogate in vivo Stat3 phosphorylation in MDSCs and their suppressor activity.

IL-6–induced pStat3 expression in MDSCs is TLR2-MyD88 dependent. Extracellular microbial components are recognized by TLRs that stimulate inflammation, but some mammalian cellular components can also stimulate TLRs (30), raising the possibility that these receptors have a role in response to danger signals released from tumor cells (31). TLRs are also the main inducers of IL-6 in myeloid cells (32). We thus explored the putative involvement of TLR family members in sensing TDEs. Splenic MDSCs from naive WT mice and mice deficient in TLR2, TLR4, or their adaptor proteins, MyD88 and TIR domain–containing adaptor-inducing interferon \(\beta\) (Trif), were examined for IL-6 production after stimulation with TDEs. TDE-induced IL-6 was fully dependent on TLR2 and MyD88 but not on TLR4 or Trif (Figure 4A). Similarly, Stat3 phosphorylation induced by TDEs was also fully dependent on TLR2 and MyD88 (Figure 4B). These observations were not biased by a different intrinsic capacity of transgenic mice to produce IL-6 or to activate Stat3 (Supplemental Figure 8). During EL4 tumor growth, Gr-1+CD11b+ cells accumulated at comparable levels in the spleen of WT and TLR signaling–deficient mice (Figure 4C). In contrast, pStat3 expression was fully dependent on TLR2 and MyD88 (Figure 4C). Moreover, MDSCs from tumor-bearing TLR2-deficient mice exhibited a drastically lower capacity to inhibit antigen-specific OT-1 proliferation than MDSCs from WT tumor-bearing mice (Figure 4D). Interestingly, EL4 growth was slightly but significantly decreased in TLR2-deficient mice (Figure 4E).

Altogether, these results demonstrate that in vitro and in vivo TDEs induce IL-6 production by MDSCs through activation of TLR2 and its adaptor MyD88, leading to Stat3 phosphorylation and the promotion of MDSC immunosuppressive functions.

Stat3 activation in MDSCs is dependent on Hsp72 expression at the surface of TDEs. To identify the factor present on TDEs that could induce Stat3 phosphorylation and MDSC activation, we first screened the expression of known endogenous TLR2 ligands in TDEs, TDSFs, and whole-tumor cells by immunoblotting (32–38). TDSFs did not express any TLR2 ligands. TDEs from the 3 cell lines expressed Hsp72 and Hsc73 but did not express other known endogenous TLR2 ligands (Figure 5A). To eliminate the potential role of other microparticles copurified with exosomes, we checked to determine that Hsp72 was only present in exosomal fractions, and not in other microparticles (Supplemental Figure 9). Using TDE-coated beads, we showed that Hsp72, but not Hsc73, was detected on TDE cell surface, while it was not expressed on the surface of 3T3 exosomes (Figure 5B). This was confirmed by electronic microscopy with immunogold labeling (not shown).

A physical interaction between TLR2 and Hsp72 was studied by surface plasmon resonance (Figure 5C) and involved hydrophobic interactions. In vitro, rHsp72 added to MDSC culture could trigger pStat3 expression and IL-6 production when MDSCs were obtained from WT mice but not from TLR2-deficient mice (Figure 5D and Supplemental Figure 10). Importantly, no production of TNF-\(\alpha\) could be detected. At a molecular level, exposure of MDSCs to rHsp72 induced Stat3 phosphorylation and Stat3 and p65 transcriptional activity without activation of Erk (Supplemental Figure 11). IL-6–blocking Ab blunted rHsp72-dependent Stat3 phosphorylation, thus demonstrating that rHsp72 can trigger the TLR2-dependent IL-6/pStat3 pathway in MDSCs (Figure 5D).

To eliminate the involvement of a potential contamination with endotoxins, we demonstrated that boiled Hsp72 could not induce IL-6 secretion and Stat3 phosphorylation in MDSCs; furthermore, we routinely tested for the absence of mycoplasmas (Figure 5D and data not shown). Moreover, rHsp72 effect on pStat3 induction could be abrogated by adding an anti-Hsp72 Ab, while this treatment remained inefficient when pStat3 was induced by a bacterial TLR2 ligand (PAM3CSK4) (Figure 5D).

To confirm the specific role of Hsp72 in TDEs, we stably transfected CT26 cells with Hsp72 shRNA. Two clones (called H96 and H97) with a reduced Hsp72 expression in cells and TDEs were selected (Supplemental Figure 12). Exosomes from mock-transfected CT26 cells induced Stat3 phosphorylation and IL-6 production in a TLR2-dependent manner, and this effect could be blunted by addition of a blocking anti–IL-6 Ab or an anti-Hsp72 Ab (Figure 6A and data not shown). In contrast, TDEs obtained from H96 and H97 clones had a reduced capacity to trigger pStat3 and IL-6 production in MDSCs compared with TDEs from mock CT26.

In vivo, a single i.v. injection of TDEs from mock-transfected CT26 cells but not from H96 or H97 cells induced pStat3 expression in splenic MDSCs (Figure 6B). In a tumor setting, 15 days...
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**A**

![Graph A](image)

**B**

![Graph B](image)

**C**

![Naive mice](image)

**D**

![Graph D](image)

**E**

![Graph E](image)

**F**

![Graph F](image)

**G**

![Graph G](image)
after s.c. inoculation of mock-transfected CT26 or clones H96 or H97 transfected with Hsp72 shRNA, FACS analysis demonstrated that Hsp72 shRNA CT26 tumor-bearing mice harbored a drastically lower level of pStat3 in splenic MDSCs, compared with MDSCs from mice bearing mock-transfected tumors (Figure 6C). Accordingly, adoptive transfer of MDSCs isolated from Hsp72 shRNA CT26 tumor-bearing mice have no significant immunosuppressive effect and could not abrogate the antitumor efficacy of a tumor vaccine in contrast to MDSCs from mock-transfected CT26 tumor-bearing mice (Figure 6D). To rule out a potential direct effect of IL-6 produced by MDSCs on tumor cells, we showed that the transfection of tumor cells with siRNA gp130 (the IL-6R) did not inhibit the effect of MDSC adoptive transfer (not shown).

In conclusion, the immunosuppressive effects of MDSCs from tumor-bearing mice are induced by Hsp72 expressed at the surface of TDEs that triggers TLR2 signaling in MDSCs. This event induced an IL-6–dependent Stat3 phosphorylation within MDSCs and thus their immunosuppressive activity.

**Exosome depletion by DMA restores the efficacy of cyclophosphamide by inhibiting MDSC functions.** Given that TDEs are responsible for MDSC immunosuppressive function, we tested to determine whether DMA could restore the efficacy of cancer therapies by inducing exosome depletion. We previously demonstrated that the antitumor activity of low doses of the alkylating agent cyclophosphamide was related to its capability of inducing a T cell–dependent immune response through elimination of regulatory T cells rather than to its cytotoxic effect on tumor cells (39, 40). Cyclophosphamide reduces tumor growth and prolongs the survival of tumor-bearing immunocompetent WT mice, yet is ineffective in athymic nude mice (Supplemental Figure 13). In our 3 tumor models, DMA alone had little or no effect, while the association of DMA with cyclophosphamide demonstrated a synergistic effect and drastically reduced tumor growth compared with cyclophosphamide alone (Figure 7A). A comparable synergetic effect was observed with combination of DMA and another immunotherapy, intratumoral Cpg injection (Figure 7B). Combined therapy (cyclophosphamide plus DMA) was ineffective in nude mice, underlining the critical role of T cells for the efficacy of the combined treatment (Figure 7C).

To determine whether the antitumor effect of DMA was dependent on blocking the immunosuppressive function of MDSCs, we performed adoptive transfer of MDSCs from tumor-bearing mice after cyclophosphamide injection. Interestingly, transfer of MDSCs from tumor bearers completely abrogated the antitumor effect of DMA in the CT26 model (Figure 7D). In contrast, adoptive transfer of MDSCs from naive mice had no effect on tumor growth (not shown). Finally, to determine the role of tumor-derived Hsp72 in the therapeutic effect of DMA cyclophosphamide combination, we injected naive mice with mock-transfected or Hsp72 shRNA–transfected (clone H96 or H97) CT26 cells. As expected, we observed that, in mice bearing H96 or H97 tumors, cyclophosphamide alone had the same efficacy as cyclophosphamide plus DMA, demonstrating that the efficacy of DMA was strictly dependent on tumor Hsp72 expression by TDEs (Figure 7E).

Altogether, these data demonstrate that exosome depletion using DMA enhances the antitumor efficacy of cyclophosphamide. This synergistic effect of DMA plus cyclophosphamide is dependent on T cells, MDSCs, and Hsp72.

**Human TDEs dictate Stat3 activation in MDSCs through TLR2 and Hsp72.** Human MDSCs were phenotypically determined by the expression of the common myeloid marker CD33 and MHC class II (3–6). We observed as previously reported (4, 8–10, 41) a significant increase in the frequency of MDSCs in the blood of metastatic cancer patients compared with healthy volunteers (Figure 8A). Consistent with the murine data, MDSCs from metastatic cancer patients exerted higher immunosuppressive function on T cells compared with MDSCs from healthy volunteers (Figure 8B).

In vitro, PBMCs from healthy volunteers were cultured 24 hours alone or in the presence of TDEs obtained from the H23 cell line, a lung adenocarcinoma that produced Hsp72-expressing TDEs (Supplemental Figure 14). H23 TDEs induced pStat3 expression in MDSCs, and this effect was abolished by inhibition of TLR2 and Hsp72 (Figure 8C). Treatment of PBMCs from healthy volunteers by H23 exosomes strongly inhibited T cell proliferation after nonspecific T cell triggering, and this immunosuppressive effect was significantly reduced after blockade of Hsp72 or TLR2 (Figure 8D).

DMA is not used in human therapy, but its analog amiloride, which exerts the same effect on exosome secretion (not shown), is currently used for treatment of edema or high blood pressure. In a series of 11 patients with colorectal metastatic cancer in whom amiloride was indicated for the treatment of high blood pressure, we obtained blood samples before and 3 weeks after the beginning of amiloride treatment and observed that amiloride reduced autologous serum capacity to induce phosphorylation of Stat3 in MDSCs (Figure 8E) and blunted MDSC suppressor functions (Figure 8F).

Altogether, these data demonstrated that human TDEs could activate human MDSCs and trigger their suppressive function in an Hsp72/TLR2-dependent manner. Moreover, blocking exosome formation in cancer patients with amiloride could possibly lead to the restoration of T cell functions.

**Discussion**

Our results identify a new mechanism that leads to an enhancement of tumor-associated MDSC immunosuppressive functions. First, we demonstrated that 2 distinct molecular pathways

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**Figure 3**

TDEs trigger pStat3 expression in MDSCs through autocrine production of IL-6. MDSCs from naive mice were treated with PBS or with TDSFs or TDEs. (A) IL-6 concentration in the supernatant was determined by ELISA. (B) In some wells, IL-6 or blocking anti–IL-6 mAb (aIL-6) were added. Data represent pStat3 MFI ± SD. (C) Naive mice were i.v. injected with PBS, EL4 TDEs, or rIL-6. EL4 TDE mice were i.v. injected with PBS or IL-6 siRNA. 24 hours later, spleens were harvested. MDSC percentage (denoted) and pStat3 expression were determined by FACS on gated MDSCs. (D) EL4 cells were cultured in vitro for 24 hours and treated with PBS, DMA, or omeprazole. In vivo EL4 TBE mice were injected daily with DMA for 1 week. Acetylcholine esterase activity was assayed in supernatant or serum. (E) IL-6 concentration in sera was determined by ELISA in naive mice, which received a single injection of PBS or EL4 TDEs (left), or in EL4 TBE mice, which received 1 daily injection of PBS, DMA, or omeprazole for 1 week (right). (F) EL4 TBE mice were injected with PBS alone or DMA, omeprazole, or IL-6 siRNA (si). Spleens were harvested 24 hours later, and pStat3 expression was determined by FACS. Data are shown as MFI ± SD. (G) Mice (n = 5) were vaccinated with frozen/thawed CT26 cells 1 week before i.v. injection of live CT26 admixed or not with MDSCs isolated from PBS- or DMA-treated CT26 TBE mice. Twelve days later, lung metastasis number was evaluated. Each experiment was done in triplicate. For box and whisker plots, bottoms and tops of boxes show the 25th and 75th percentiles, respectively, and middle bands show the median; whiskers show extrema. *P < 0.05.
account for MDSC expansion and activation. We then unraveled for what we believe is the first time that Stat3, rather than mediating MDSC expansion, actually promotes their immuno-suppressive functions. At the molecular level, Hsp72 on TDEs, which binds to TLR2 on MDSCs, is the ligand that is responsible for their activation and the enhancement of their suppressive ability. Additionally, we showed that amiloride was able to interfere with our proposed mechanism leading to MDSC activation, thus restoring the efficacy of immunotherapy. We showed that our proposed mechanism leading to MDSC activation was also relevant in humans.

The literature clearly demonstrated that factors released by tumor cells could trigger Stat3 activation and expansion of MDSCs. Most reports suggested without clear demonstration that expansion of MDSCs may be due to Stat3 activation by tumor-derived factors. However, Kortylewski et al. (20) challenged this

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**Figure 4**

IL-6–induced pStat3 expression in MDSCs is dependent on the TLR2/MyD88 pathway. Purified MDSCs from WT or TLR2-, TLR4-, MyD88-, and Trif-deficient C57BL/6 tumor-free mice were cultured for 24 hours in complete medium supplemented or not with TDEs. IL-6 concentration in the supernatant was determined by ELISA (A), and pStat3 expression in cells was determined by FACS analysis (B). Data represent mean ± SD. (C) WT C57BL/6 mice or TLR2-, TLR4-, MyD88-, and Trif-deficient mice were s.c. injected with $1 \times 10^6$ EL4 cells. 3 weeks later, spleen cells were harvested, MDSC percentage was determined in spleen (denoted in left panels), and pStat3 expression was determined by FACS analysis on MDSC gated cells (right panel). (D) $2 \times 10^5$ OT-1 cells were labeled with CFSE, loaded with 10 μg/ml of SIINFEKL, and cultured 3 days alone or with different ratios of MDSCs from EL4 tumor-bearing WT mice or from EL4 tumor-bearing TLR2-deficient mice. Percentage of OT-1 proliferating cells was determined by flow cytometry. Each experiment was done in duplicate ($n = 3$ mice per group). (E) WT or TLR2$^{-/-}$ mice were injected s.c. with EL4 cells, and tumor growth was monitored. *$P < 0.05$. 


hypothesis by showing that, in mice with specific deletion of Stat3 in hematopoietic cells, higher numbers of Gr1⁺ CD11b⁺ cells were found in the tumor bed. In the same line, other reports suggested in models where tumor cells could produce SCF that MDSC proliferation could be due to the activation of the SCF/Kit pathway (42, 43). Finally, the group from Ostrand-Rosenberg and a recent report from Xiang et al. demonstrated that PGE2 could be involved in MDSC activation and expansion (24, 44). Here, we provided evidence in 3 models in which neither SCF nor PGE2 were involved (Supplemental Figure 6) that Stat3 is not linked to MDSC expansion but implicated in their activation (Figure 1). In contrast, GM-CSF produced by tumor cells is involved in MDSC expansion through the activation of the Erk pathway.

Exosomes are endosome-derived microvesicles that are notably secreted by the tumor cells in their environment. Interestingly, TDEs are a source of shared tumor rejection antigens and in some conditions could induce a T cell–dependent immunity in mice and human tumor models (45, 46). Therefore, injection of a high amount of TDEs could represent a source of tumor-rejection antigens relevant for immunointerventions (21). However, as TDEs retain a large part of the protein repertoire of tumor cells, they could also trigger immunosuppression. Indeed, crucial components of the immune response, such as dendritic cells, are profoundly affected by the encounter with TDEs (25). Some TDEs could also express factors such as Fas ligand that induce apoptosis of CD8 T cells and may be involved in immune evasion (47). In our study, we demonstrate for what we believe is the first time that TDEs have another immunosuppressive capacity, which is triggered by Stat3 phosphorylation in MDSCs. Tumor-derived factors had been demonstrated to trigger MDSC accumulation from hematopoietic precursors (8, 48) and Stat3 phosphorylation (16, 17), but the tumor factors involved in these effects remained to be discovered. Here, we unraveled the capacity of TDEs to induce Stat3 phosphorylation and the acquisition of suppressive function in MDSC gated cells. Data represent MFI ± SD. *P < 0.05.

Figure 5

Hsp72 is expressed at the surface of TDEs and bound on TLR2. (A) Endogenous TLR2 ligand expression was investigated by immunoblots in TDEs, whole-cell lysates, and TDSFs from EL4, TS/A, and CT26 tumor cells. CTRL, control. (B) TDEs from EL4, TS/A, and CT26 tumor cells and exosomes from control 3T3 cells were coated on beads and labeled with control isotype or anti-Hsp72 or anti-Hsc73 Abs. Then FACS analysis was performed to determine expression of Hsp72 and Hsp73 at the surface of exosomes. One representative FACS histogram (blue line) is represented with its isotype control (pink area). (C) Surface plasmon resonance studying the binding of Hsp72 to TLR2 protein. FSL-1 (a bacterial TLR2 ligand) was used as positive control; LPS was used as negative control. (D) Purified myeloid cells from naïve WT or TLR2-deficient C57BL/6 mice were cultured in complete medium supplemented or not as indicated. pStat3 expression was determined by FACS analysis on MDSC gated cells.
clude that the Hsp72/TLR2 pathway described here is a new pathway involved in MDSC activation. Hsp72 is a molecular chaperone present at elevated levels in various human tumors, and its expression often correlates with increased tumor cell proliferation, poor response to chemotherapy, and poor survival (49, 50). In addition to its classical intracellular localization, Hsp72 is also expressed on the plasma membrane of malignantly transformed cells or TDEs (51). Many reports also focused on the possible immunoadjuvant effect of Hsps, which enhance the maturation of dendritic cells (51) and NK cells (52), thus leading to immune-mediated protection (53). These results suggested that complexes of Hsps with peptides might represent a unique and efficient way to induce immunity, a hypothesis that was challenged by reports showing that Hsps can also downregulate an immune response in some autoimmune models such as rheumatoid arthritis in rats (54) and diabetes in mice (55). The mechanism proposed for the immunoregulatory function of Hsps involved the generation of IL-10–producing immunosuppressive T cells (56). In this regard, it is noteworthy that extracellular Hsp72 could also render APC resistant to adjuvant-induced maturation (57). In this study, we propose that Hsp72 expression in exosomes is detrimental for the antitumor response. To the best of our knowledge, this is the first study that provides a mechanistic explanation linking Hsp72 expression by tumor cells and the induction of immunosuppression in mice and humans. Hsp72 cytokine properties are well described and related to its capacity to bind to TLR4/CD14 complex (58) or TLR2 (59). Conflicting reports suggest that adjuvant Toll-dependent effects of Hsps are due to LPS or lipopeptide contamination (60). In our study, we performed physical measurement of the interaction between Hsp72 and TLR2 by surface plasmon resonance (Figure 5C). The in vivo immunosuppressive role of TDEs led us to search for drugs interfering with exosome secretion by tumor cells that might theoretically represent a strategy to restore tumor immunity and to impair tumor progression. A promising tool may be

Figure 6
pStat3 expression in MDSCs is dependent on Hsp72 on TDEs. (A) Purified myeloid cells from naive WT or TLR2-deficient mice were either untreated or treated as indicated. (B) Naive mice were i.v. injected with TDEs from shRNA mock CT26 cells or Hsp72 shRNA CT26 clones H96 or H97. 18 hours later, spleen cells were harvested and pStat3 expression was determined by FACS. (C) Naive BALB/c mice were s.c. injected with 1 × 10⁶ H96, H97, or mock CT26 cells. 2 weeks later, spleens were harvested and pStat3 expression determined by FACS. For A–C, pStat3 was determined by FACS analysis on MDSC gated cells. Data represent MFI ± SD. Experiments were performed in triplicate (n = 3 mice per group). Inset shows immunoblot of pStat3 expression in sorted MDSCs from mice bearing mock CT26 or Hsp72 shRNA CT26 clone H96. (D) Mice were vaccinated with frozen/thawed CT26 cells 1 week before i.v. injection of live CT26 cells admixed or not with MDSCs isolated from mice bearing shRNA mock-transfected or Hsp72 shRNA-transfected (clone H96) CT26 tumors. Twelve days later, lung metastasis numbers were evaluated. Experiments were performed in triplicate (n = 5 mice per group). For box and whisker plots, bottoms and tops of boxes show the 25th and 75th percentiles, respectively, and middle bands show the median; whiskers show extrema. *P < 0.05. Error bars represent mean ± SD.
represented by drugs such as DMA and its analog amiloride, which interfere with the activity of efflux pumps expressed on acidic vacuoles, such as Na+/H+ export, and associated to exosome secretion (61). DMA and amiloride reduce exosome secretion in vitro and in vivo (Figure 3D) and blunt Stat3 phosphorylation in MDSCs and their T cell–suppressive function in mouse cancer models (Figure 3, F and G) and in cancer patients (Figure 8, E and F). Moreover, in 3 mouse tumor models from 2 different mouse strains, DMA

Figure 7
Exosome depletion restores the efficacy of immunotherapy. Immunocompetent mice (A) were injected s.c. with 1 × 10⁶ CT26, TS/A, or EL4 cells. Mice were then either untreated or treated with 1 i.p. injection of 100 mg/kg cyclophosphamide (CTX), daily i.p. injection of DMA, or both. Mean tumor volume ± SD (n = 6 mice per group). (B) WT mice were injected as in A with CT26 and treated with intratumoral CpG 1668 injection (10 μg once a week) with or without DMA. (C) Nude mice were treated as in A. (D) BALB/c mice were injected s.c. with 1 × 10⁶ CT26 cells. Mice were then either untreated or treated with 1 i.p. injection of cyclophosphamide or 1 i.p. injection of cyclophosphamide plus repeated daily i.p. injections of DMA with or without an i.v. adoptive transfer of 5 × 10⁶ MDSCs from CT26 tumor-bearing mice. Data shown represent mean tumor volume ± SD (n = 5 mice per group). (E) BALB/c mice were injected s.c. with 1 × 10⁶ mock-transfected (left panel) or Hsp72 shRNA–transfected (clone H96, middle panel; clone H97, right panel) CT26 cells. Mice were then either untreated or treated with 1 i.p. injection of cyclophosphamide, i.p. injection of DMA twice a week, or both. Mean tumor volume ± SD (n = 6 mice per group). Experiments were performed in duplicate. *P < 0.05.
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enhances the antitumor efficacy of cyclophosphamide, an antican-
cer drug with cytotoxic and immunological properties (39).

In conclusion, we here describe an immunosuppressive pathway
involved in tumor-induced tolerance in mice as well as in humans.
This study supports the hypothesis that drugs interfering
with exosome secretion such as amiloride may enhance the efficacy
of current chemotherapies.

Methods

Cell culture

The mouse colon carcinoma CT26 cells, lymphoma EL-4, embryo fibroblast
NIH/3T3 cells, and human lung adenocarcinoma H23 were obtained from
ATCC and mammary adenocarcinoma TS/A from Health Protection Agen-
cy Cultures Collections (HPACC). MSC cell lines were a gift from Vincenzo
Bronte (Istituto Oncologico, Padova, Italy). All cells were grown in RPMI
1640 medium with glutamax-I (Lonza) supplemented with 10% (v/v) FBS
(Lonza) and with Pen/Strep Amphotericin B (Lonza) in an atmosphere of
95% air and 5% CO\(_2\) at 37°C. Absence of mycoplasma contamination was
assayed every 2 weeks by PCR.

Mice

Female C57BL/6, BALB/c, and nude mice (aged 6 to 8 weeks) were obtained
from the Centre d'élevage Janvier and from Charles River Laboratories.

MDSCs

Generation of cells from bone marrow progenitors. Bone marrow cells were
obtained from the femurs and tibias of WT mice. Five million bone mar-

Figure 8

Exosomes produced by human cancer cell lines or meta-
static cancer patients dictate Stat3 activation in MDSCs and
their immunosuppressive function through TLR2 and Hsp72. (A) The frequency of MDSCs, defined as HLA-DR CD33+
cells, is shown in the PBMCs of healthy volunteers (H.V.)
(n = 11) and metastatic cancer patients (n = 18). Each plot
is an individual measure, and the horizontal bar is the mean.
(B) Immunosuppressive function of MDSCs from peripheral
blood of healthy volunteers and metastatic cancer patients
on stimulated T cell proliferation. T cell stimulation was
induced by a mixture of anti-CD2, anti-CD3, and anti-CD28
beads (n = 10). (C) PBMCs from healthy volunteers were
cultured for 24 hours in medium alone or medium containing
TDEs from H23 cells with or without blocking TLR2 Abs or
anti-Hsp72 polyclonal Abs (pAbs), pStat3 was determined
by flow cytometry on MDSC gated cells (n = 10). (D) Immu-
osuppressive function of MDSCs from blood of healthy
volunteers either untreated or treated with TDEs from H23
cells alone or with blocking TLR2 Abs or anti-Hsp72 pAbs
(n = 8). (E) PBMCs from metastatic cancer patients were
incubated overnight in serum-free medium supplemented
with autologous serum or PBS. pStat3 expression in gated
MDSC was determined by flow cytometry. pStat3 MFI ratio
between PBS and serum condition was represented. The
same patients were sampled before and after 3 weeks of
amiloride treatment (n = 11). (F) Immunosuppressive func-
tion of MDSCs prepared from peripheral blood of metastatic
cancer patients, treated with amiloride or not treated, on T
cell proliferation stimulated as in B. *P < 0.05. Error bars
represent mean ± SD.
row cells were cultured in RPMI 1640 medium supplemented with 10% FBS and 10 ng/ml GM-CSF or in the presence of 50% v/v control (from 3T3 fibroblasts) or TCS, ultracentrifugated TCS (TDSFs), or exosomes (TDEs) (50 μg/well). On day 5 of culture, cells were collected and analyzed by flow cytometry.

**Cell isolation and functional assays.** Single-cell suspensions were prepared from spleens, and red cells were removed using ammonium chloride lysis buffer. Gr-1+ cells were isolated from spleens of tumor-bearing mice or naive mice by labeling the cells with PE Cy7 Ab to Gr-1, then using magnetic PE Cy7 beads and LS MACS columns (Miltenyi Biotec) according to the manufacturer’s protocol. The Gr-1+ cells were cultured 24 hours in different conditions: supplementation with 50% of control 3T3 fibroblasts supernatant or TCSs, TDSFs, or TDEs (50 μg/well). Some cells were treated 24 hours or for indicated times with 1 μg/ml rHsp72 (Stressgen ESP555), 10 ng/ml rIL-6 (R&D Systems), 1 μg/ml Pam3CSK4 (InvivoGen), 0.25 μM JSI124 (Calbiochem), 30 μM STA21 (Biomol), 10 ng/ml LPS (Sigma-Aldrich), 50 μg/ml poly(I:C) (InvivoGen), 1 μg/ml anti-IL-6 mAb (R&D Systems), or 5 μg/ml anti-Hsp72 pAb (Stressgen), 2 μg/ml anti-Gr-CMF-Abcam).

Recombinant Hsp72 was tested for LPS contamination using Limulus amebocyte assay (Limulus amebocyte lysate QCL100; Cambrex). The level of endotoxin was less than the lowest control standard.

In functional assay, we used spleen cells from OT-1 mice. CD8+ T cells were purified with CD8 microbeads (Miltenyi Biotec) and stained 10 minutes with CFSE (1 μM in PBS) at 37°C, then washed 3 times in complete medium. CD8+ cells were cultured with specific peptide SIINFEKL (Bachem) (10 μg/ml) in the presence of MDCS (1:1, 1:4, 1:8, 1:16 ratios). Three days later, proliferation of OT-1 T cells was evaluated with CFSE dilution by flow cytometry. For Y705-pStat3 determination, PBMCs were isolated with anti-mouse CD11b beads (Miltenyi Biotec) from spleens, and red cells were removed using ammonium chloride lysis buffer. We incubated 1 × 106 freshly prepared cells resuspended in RPMI 10% FBS and 10 ng/ml anti-Hsp72 pAb (Stressgen) or 20 μg/ml anti-TLR2 pAb (Santa Cruz Biotechnology Inc.).

T cell proliferation was evaluated by CFSE dilution of CD3+ cells alone or with CD3+ (in the original ratio) activated with the Treg Suppression Inspector (Miltenyi Biotec).

**Exosome isolation and labeling**
48-hour supernatants of confluent tumor cells were collected and sequentially centrifuged (4°C) at 300 g for 10 minutes and then at 1200 g for 30 minutes. Exosomes were then pelleted at 100,000 g for 12 hours and washed once in PBS. The protein concentrations of exosomes were measured by Lowry assay (Bio-Rad). For some experiments, exosomes were further separated from other microparticles by centrifugation on a 30% sucrose/D20 cushion for 2 hours; these preparations were used to ascertain the presence of Hsp72 in the exosomal fraction and not in the other microparticles. For FACS staining, we bound the exosomes to surfactant-free white aldehyde-sulfate latex beads (3 μm; Invitrogen) and concentrated 1 μg/ml anti-Hsp72 pAb (InvivoGen) alone, coated anti-CD3 and killed tumor cells; and coated plus soluble anti-CD3 (2 μg/ml), soluble anti-CD28 (2 μg/ml), 30 μM JSI124 (Calbiochem), 30 μM STA21 (Biomol), 10 ng/ml LPS (Sigma-Aldrich), 50 μg/ml poly(I:C) (InvivoGen), 1 μg/ml anti-IL-6 mAb (R&D Systems), or 5 μg/ml anti-Hsp72 pAb (Stressgen), 2 μg/ml anti-Gr-CMF-Abcam).

**Quantitation of released exosomes**
The amount of released exosomes was quantified by measuring the activity of acetycholinesterase, an enzyme that is specifically present in these vesicles. Exosome fractions (25 μl) were suspended in 100 μl of PBS and incubated with 1.25 mM acetylcholine and 0.1 mM 5,5’-dithiobis(2-nitrobenzoic acid) in a final volume of 1 ml PBS. Beads were saturated for 30 minutes in glycan (100 mM) at room temperature, then washed twice with PBS supplemented by 3% of FBS. A classic staining was realized on exosomes with control isotype or anti-Hsp72 (provided by Gabriele Multhoff, Department of Radiation Oncology, University Hospital, Technische Universität München) or anti-Hsc73 (Santa Cruz Biotechnology Inc.) Abs.

**Electronic microscopy**
Exosome preparations were stained with osmium tetroxide, then observed with a Hitachi H-7500 electronic microscope equipped with an AMT camera.

**Molecular biology**
ELISA. ELISA kits were used to detect IL-6, IL-10 (BD Biosciences), VEGF, TNF-α, PGE2 (R&D Systems), and IL-1β (Biolegend) according to the manufacturers’ protocol.

Western blotting. The following mouse mAbs were used: anti-β-actin (Sigma-Aldrich), anti-Hsc73, anti-Stat3 (Santa Cruz Biotechnology Inc.), anti-Hsp60 (Stressgen), and anti-flotillin (BD Biosciences). The following rabbit polyclonal Abs were used: anti-Hsp72, anti-Hsp90β (Stressgen), anti-veriscan, anti-HMG1B (Abcam), anti-pStat3, anti-pERK, anti-Erk (Cell Signaling Technology), and anti-BSA (Sigma-Aldrich). Rat polyclonal anti-Grp94 (Stressgen) and goat polyclonal anti-tsg101 (Santa Cruz Biotechnology Inc.) were also used. Secondary Abs HRP-conjugated polyclonal goat anti-mouse, swine anti-rabbit, and goat anti-rat immunoglobulins (Jackson ImmunooResearch) and polyclonal rabbit anti-goat immunoglobulins (Dako) were also used.

**shRNA transduction**
CT26 cells were transduced with MISSION Lentiviral Transduction Particles (Sigma-Aldrich) to silence Hsp72 or with negative control particles according to the manufacturer’s instructions. One population trans-
duced with control particles (mock) and 5 transduced with 5 different shRNAs specific for Hsp72 (H95 to H99) were obtained, and 2 subclones (H96 and H97) were then selected after checking Hsp72 downregulation by Western blotting.

**siRNA transfection**

For in vivo experiments, Silencer Select Predesigned siRNA specific for murine IL-6 (forward: 5′-CUAAGGAUUAAGAGCAUCCAGCA-3′, reverse: 5′-UGUGGCUGAAUUUCCACC-3′; and forward: 5′-GAUUGAUAUCGUCAUUATr-3′, reverse: 5′-UAACGUGUAAAUUGCA-3′) or negative control siRNA (Applied Biosystems) were prepared with transfection reagent JetPEI (Polyplus Transfection) according to the manufacturer’s instructions.

MDCs were transfected in vitro with Silencer Select Predesigned siRNA specific for murine St3 (forward: 5′-GGUGUAUUAGCCCGAGCA-3′, reverse: 5′-UUGUGUGACUUCUCCACC-3′; and forward: 5′-GAUUGGAAUCAUCGUCAUUATr-3′, reverse: 5′-UAACGUGUAAAUUGCA-3′) or negative control siRNA (Applied Biosystems) with transfection reagent INTERFERin (Polyplus Transfection) according to the manufacturer’s instructions.

**RESULTS**

**SPR analysis**

Design and fabrication of homemade chips compatible with Surface Plasmon Resonance have been performed as previously published with the help of the MIMENTO technological platform (Besançon, France) (62). Biacore experiments were performed with the Biacore 2000 apparatus at 25°C with a flow rate of between 2 and 30 μl/min.

**Statistics**

Results were analyzed with GraphPad Prism 5. Appropriated statistical tests were used according to the variance, matching pairs, and distribution. P < 0.05 was considered significant. Data are represented as mean ± SD.

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