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Inhibition of Tumor-Induced Myeloid-Derived Suppressor Cell Function by a Nanoparticulated Adjuvant

Audry Fernández,* Circe Mesa,* Ilaria Marigo, † Luigi Dolcetti, †,‡ Marilyn Clavell,* Liliana Oliver,* Luis E. Fernández,* and Vincenzo Bronte †

The interaction between cancer vaccine adjuvants and myeloid-derived suppressor cells (MDSCs) is currently poorly understood. Very small size proteoliposomes (VSSP) is a nanoparticulated adjuvant under investigation in clinical trials in patients with renal carcinoma, breast cancer, prostate cancer, and cervical intraepithelial neoplasia grade III. We found that VSSP adjuvant induced a significant splenomegaly due to accumulation of CD11b+Gr-1+ cells. However, VSSP-derived MDSCs showed a reduced capacity to suppress both allogeneic and Ag-specific CTL response compared with that of tumor-induced MDSCs. Moreover, splenic MDSCs isolated from tumor-bearing mice treated with VSSP were phenotypically more similar to those isolated from VSSP-treated tumor-free mice and much less suppressive than tumor-induced MDSCs, both in vitro and in vivo. Furthermore, different from dendritic cell vaccination, inoculation of VSSP-based vaccine in EG.7-OVA tumor-bearing mice was sufficient to avoid tumor-induced tolerance and stimulate an immune response against OVA Ag, similar to that observed in tumor-free mice. This effect correlated with an accelerated differentiation of MDSCs into mature APCs that was promoted by VSSP. VSSP used as a cancer vaccine adjuvant might thus improve antitumor efficacy not only by stimulating a potent immune response against tumor Ags but also by reducing tumor-induced immunosuppression.

The online version of this article contains supplemental material.

Abbreviations used in this paper: CIM, Center of Molecular Immunology; DC, dendritic cell; HA, hemagglutinin; HPTLC, high-performance thin-layer chromatography; LN, lymph node; MDSC, myeloid-derived suppressor cell; Nos, NO synthase; OMP, outer membrane vesicle; poly IC, polyinosinic-polycytidylic acid; TAA, tumor-associated Ag; VSSP, very small size proteoliposomes.

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Tumor vaccination is a promising strategy for cancer treatment due to the specificity of response, low toxicity, and induction of long-term memory (1, 2). However, even though there is preclinical evidence for the efficacy of cancer vaccine candidates (3–6), reproducible objective responses in clinical trials are limited (7–10).

The reasons underlying the unsatisfactory clinical responses of cancer vaccines are likely different and not completely established. Tumor-induced immunosuppression is one of the factors contributing to lack of established tumor eradication after immunotherapy (11). Different cell populations with regulatory function are mobilized by tumors contributing to restrain the immune response (12–14). Among these, myeloid-derived suppressor cells (MDSCs) have been described that are able to suppress antitumor immunity through inhibition of CD4+ and CD8+ T cell function (15–18) and control of NK cell cytotoxicity (19, 20). MDSCs are a heterogeneous myelomonocytic population lacking the markers of more mature myeloid cells and commonly expressing both CD11b and Gr-1 markers in mice (12). Suppressive mechanisms of MDSCs require an interplay between the l-arginine metabolizing enzymes arginase (Arg) and NO synthase (Nos) and the Nox family of phagocytic oxidases (21, 22).

Very small size proteoliposomes (VSSP) is an adjuvant based on the combination of outer membrane vesicles (OMPs) from Neisseria meningitidis with GM3 ganglioside (23). This product is currently under investigation as part of the formulation of several cancer vaccine candidates at different development stages (4, 24–26). VSSP promotes dendritic cell (DC) maturation, Ag cross-presentation to CD8+ T cells, Th1 polarization, and enhances CTL response (27, 28). However, the capacity of VSSP to influence regulatory cells has not previously been addressed. In this work, we evaluated whether VSSP could modulate the function of tumor-induced MDSCs.

Materials and Methods

Cell lines

MBL-2, EL-4, and EG.7 (EL-4 cell line transfected with the gene encoding for OVA) lymphomas and MCA203 sarcoma are derived from C57BL/6 mice (H-2b). CT26 is a carcinogen-induced, undifferentiated colon carcinoma derived from BALB/c mice (H-2k). The C26GM cell line was obtained from C26 colon carcinoma (H-2b) genetically modified to release GM-CSF (29) and always grown in the presence of 0.8 mg/ml G418 antibiotic (Invitrogen, Milan, Italy).

Mice

Female 8-wk-old C57BL/6 and BALB/c mice were purchased from Harlan (San Pietro al Natisone, Italy) and from the Center for Laboratory Animal Production (Havana, Cuba). Transgenic mice expressing a TCR specific for aa 512–520 from influenza hemagglutinin (HA) presented by H-2Kb (CL4 mice) were a gift from L. Sherman (The Scripps Research Institute, La Jolla, CA). Thy1.1+ congenic mice on BALB/c background and pnel1-1 mice expressing transgenic TCRs that recognize gp10026–33 peptide in an H-2Db–restricted manner were provided by N. Restifo (National Cancer Institute, Bethesda, MD). OT-I TCR transgenic mice and CD45.1+ congenic mice on C57BL/6 background were bred to obtain CL4-Thy1.1+ double transgenic mice. All mice were maintained at the animal facilities of Istituto Oncologico Veneto (Padua, Italy) and of the Center of Molecular Immunology (CIM; Havana, Cuba). Animal care and experiments were done according to institutionally approved protocols of Istituto Oncologico Veneto and CIM.
VSSP preparation

VSSP adjuvant was prepared by hydrophobic conjugation of the GM3 ganglioside with the OMP complex from *N. meningitides* strain 385 (Finlay Institute, Havana, Cuba), as described by Estevez et al. (23). Briefly, GM3 and OMP were dissolved in 0.1 M Tris-HCl buffer (pH 8.5), containing sodium deoxycholate and SDS, and then dialyzed to remove detergents. This procedure allowed ganglioside and proteins to hydrophobically incorporate into VSSP and conferred high solubility to the nanoparticulated (24.7 ± 1 nm) conjugate. GM3 ganglioside was obtained from canine erythrocytes, and purity was monitored by high-performance thin-layer chromatography (HPTLC) (23).

Generation of bone marrow-derived DCs

Bone marrow cells were harvested from femurs and tibias and single-cell suspension cultivated in the presence of 20 ng/ml recombinant mouse GM-CSF (PeproTech, Rocky Hill, NJ) as described elsewhere (30). Eighteen hours before harvesting, DCs were matured with 1 μg/ml LPS (Sigma, Milan, Italy) and pulsed with the relevant peptide at 2 μg/ml.

**CD11b** cell induction and isolation

BALB/c or C57BL/6 mice were challenged s.c. on day 0 with 5 × 10^5 and 1 × 10^6 cells of C26GM and EL-4 tumor lines, respectively. VSSP (CIM) was administered i.p. on days 2, 3 and 7, and all mice were killed on day 20. In this case, the percentage of CD11b+ cells in the splenocyte suspension cultured in the presence of 20 ng/ml recombinant mouse GM-CSF (PeproTech, Rocky Hill, NJ) was determined by FACS. Eighteen hours before harvesting, DCs were matured with 1 μg/ml LPS (Sigma, Milan, Italy) and pulsed with the relevant peptide at 2 μg/ml.

**Real-time PCR analysis**

Total RNA was extracted by TRIzol (Invitrogen) from magnetically purified splenic CD11b+ cells. cDNA were next obtained from total extracted RNA using M-MuLV reverse transcriptase (Invitrogen) according to the manufacturer’s protocol. TaqMan real-time PCR assay was performed with 20 ng template cDNA on an ABI PRISM 7700 (Applied Biosystems, Milan, Italy). The following genes were evaluated, using specific primers (Applera, Milan, Italy: neuronal Nos1; inducible Nos2 and endothelial Nos3; β-Actin and GAPDH were included as housekeeping genes. Data analysis was performed with SDS 2.3 software (Applied Biosystems).

**In vivo differentiation of CD11b+ cells**

A total of 20 × 10^6 to 25 × 10^6 splenocytes (equivalent to 5 × 10^6 CD8+ T cells previously determined by FACS) from OT-I or CL4-Thy1.1 transgenic mice were injected i.v. into naive CD45.1+ or BALB/c recipient mice, respectively (Supplemental Fig. 1A, 1B). Two days later, these mice were vaccinated and within 1 h transferred with purified 3 × 10^5 to 4 × 10^6 CD11b+ cells from different sources. A second adoptive transfer of purified CD11b+ cells was performed on day 4 after vaccination. On day 10 (counting as zero the vaccination day), cells from lymph nodes (LNs) were isolated, restimulated in vitro for 36 h with specific or control peptides, and analyzed for the Ag-specific IFN-γ release by intracellular staining. Different adjuvant or vaccine systems for OVA immunodenominating peptide STIFKEL on the OT-I transgenic model or HA-specific peptide IYSTVASSL for CL4 mice were used to stimulate CD8+ T cells and will be conveniently specified. Specifically, DC vaccination consisted of the injection of 2 × 10^6 bone marrow-derived DCs previously pulsed with 2 μg of the relevant peptide. Additionally, in other experimental groups vaccination consisted of the immunodepletion with 100 μg anti-CD11b mAb (Sigma) or mixed with 100 μg VSSP. Every vaccine was administered s.c. in a single dose except for VSSP vaccine, which was administered following the scheme described previously. CD11b+ cells were isolated from C26GM or EL-4 tumor-bearing mice and treated or not with VSSP, as described earlier for the in vivo experiments. One block of the in vivo experiments (Supplemental Fig. 1C) was performed inoculating 1 × 10^6 EG.7 tumor cells on the CD45.1+ recipient mice, 6 d before vaccination, as a source of natural induced CD11b+ cells. In this particular case, only the first two consecutive doses of VSSP were administered. In those experiments where nonnullized vaccines were compared, the transferred CD11b+ cells were previously pulsed for 90 min with 2 μg of the relevant peptide.

**CD11b+ cell-mediated suppression of specific CD8+ T cells activation**

An total of 5 × 10^6 CD11b+ cells sorted from EL-4 tumor-bearing CD45.1+ congenic mice was injected i.v. into C57BL/6 recipient mice (Supplemental Fig. 1D). The host mice, with a CD45.2+ phenotype, were previously challenged with 1 × 10^6 EL-4 tumor cells and injected or not with 200 μg VSSP. Also, naive and tumor-free VSSP-treated recipient mice were used. On day 3 after adoptive transfer, the recipients’ spleens, LNs, and tumors were collected, and single-cell suspensions of all organs were analyzed by FACS.

**Antitumor activity of VSSP**

C57BL/6 mice were s.c. challenged on day 0 with 3 × 10^6 cells of the EG.7 tumor cell line. Three vaccination systems were tested, OVA/VSSP and calculated from triplicate samples using the formula: 100 × (experimental cpm – spontaneous cpm)/(maximal cpm – spontaneous cpm).

The suppressive capacity of CD11b+ cells isolated from MCA203 tumor-bearing mice, treated or not with VSSP, was studied in an IFN-γ ELISPOT assay. For IFN-γ ELISPOT assays, cellulo-ester membrane microplates (Millipore, Milan, Italy) were coated with mAb R4-6A2 (BD Pharmingen). Both CD8+ and CD11b+ cells were positively selected from the spleens of tumor-bearing mice using magnetic microbeads (Miltenyi Biotec) following the manufacturer’s instructions. CD8+ T cells (5 × 10^6) were stimulated for 72 h with 1 × 10^5 cells of the MCA203 tumor cell line, and 2 × 10^5 CD11b+ cells were added as suppressive fraction. Syngeneic MB16F10 cell line was used as negative control. MCA203 and MB16F10 cell lines were previously treated for 16 h with culture supernatant containing 1000 U/ml murine IFN-α (CIM) to increase MHC class I expression and Ag presentation. Plates were washed extensively, and spots were visualized with bioin-conjugated mAb XMG1.2 (BD Pharmingen), alkaline phosphatase-conjugated goat anti-biotin (Vector Laboratories, Peterborough, U.K.), and AP Substrate Kit (Bio-Rad Laboratories, Hemstead, U.K.). The number of spots was counted in triplicate and calculated using an automatic ELISPOT counter (ELISPOT Reader System ELRIFL04; AIDS, Straßberg, Germany).
SIINFEKL peptide/VSSP immunization as well as SIINFEKL/IFA control treatment. OVA and SIINFEKL Ags were administered at 50 µg per mouse, whereas VSSP was given at 200 µg protein per mouse. Mouse groups received three doses of each vaccine or PBS, s.c., on days 4, 5, and 11. In a second tumor model, 1 × 10^6 MCA203 cells were inoculated, s.c., on day 0 in C57BL/6 mice. Vaccination was performed only with VSSP on days 11, 12, and 18 using 200 µg protein per mouse. The largest perpendicular diameters of the resulting tumors were measured with a caliper, and tumor volume was calculated using the formula: \( \frac{4}{3} \pi \times \text{length} \times \text{width}^2 \).

**Isolation and analyses of tumor gangliosides**

Primary MCA203 tumors were dissected on day 22 after tumor challenge. Tumor tissue was homogenized and lipids were extracted in chloroform/methanol/water (4:8:3). These extracts were centrifuged (1000 × g, 15 min), and the supernatant was evaporated and dissolved in chloroform/methanol (1:1) for overnight incubation at 4°C. After centrifugation, the supernatant was evaporated and the dry samples dissolved in chloroform/methanol/water (30:60:8) to be applied to a DEAE–Sephadex A-25 column. The acidic lipid fraction was eluted with 0.02 M sodium acetate in methanol. Monosialo gangliosides contained in these fractions were visualized by spraying orcinol reagent and heating at 100°C for 10 min after separation on HPTLC plates.

**Statistics**

Equality of variances was analyzed with Bartlett’s test, and Kolmogorov–Smirnov test was used to verify normal distribution of data. Comparison of spleen weights as well as phenotype of tumor-infiltrating MDSCs and in vivo differentiation of transferred CD11b+ cells at the tumor site was performed with Student’s t-test or ANOVA and Tukey tests depending on the number of groups. IFN-γ production by adoptively transferred Ag-specific CD8+ T cells in C26GM and EG.7 tumor-bearing mice was compared by Student t-test with control (no CD11b+ cell transfer or tumor-free mice) receiving the same immunization system. Analysis of IFN-γ secretion corresponding with the in vivo suppression experiment of the EL-4 tumor model was analyzed with ANOVA and Tukey tests. Statistical differences in the migration of transferred CD45.1+CD11b+ cells were detected in the tumor site or in secondary lymphoid organs with Student t test or ANOVA and Tukey tests, respectively. Analyses of tumor volume were performed by ANOVA and Tukey tests for the EG.7 tumor model and by Mann–Whitney U test for MCA203 tumor-bearing mice.

**Results**

*VSSP recruits CD11b+Gr-1+ cells with poor suppressive capacity*

Subcutaneous administration of VSSP induced splenomegaly in BALB/c and C57BL/6 mice, as revealed by the significant (\( p \leq 0.001 \)) increase in spleen weights after three injections of the adjuvant (Fig. 1A). Further analysis of splenocyte populations in these animals evidenced a relationship between this splenomegaly and the significant (\( p \leq 0.001 \)) increase in CD11b+Gr-1+ cells proportion, from less than 10% of total cell counts in PBS-treated mice to 24.3 ± 4.6% and 29.7 ± 5.8% in BALB/c and C57BL/6 mice treated with VSSP, respectively (Fig. 1B).

A large literature correlated MDSC accumulation in spleens, blood, and tumor environment (12) with tumor-induced immunosuppression (15, 31), therefore the suppressive capacity of CD11b+Gr-1+ cells elicited by VSSP was assessed. Splenic CD11b+ cells, isolated from either tumor-bearing or VSSP-treated mice, were mixed in different proportions with either CL4 or pmel-1 CD8+ T cells specific for influenza HA and gp100 proteins, respectively. After 5 d of culture with cognate peptides, in...
the presence of syngeneic splenocytes as feeder cells, the activity of effector cells was measured in a standard [51Cr] release assay. As shown in Fig. 1C–F, VSSP-induced CD11b+ cells (VSSP-MDSCs) showed a minimal suppressive capacity on Ag-specific T cells compared with that of tumor-induced MDSCs. In fact, CD11b+ cells isolated from animals bearing either EL-4 or C26GM tumors (EL-4-MDSCs and C26GM-MDSCs), added at the final proportion of 24% of total cells in culture, considerably reduced CTL induction, whereas the suppressive action of VSSP-MDSCs was marginal (Fig. 1C, 1E). Accordingly, whereas 12% of EL-4-MDSCs and C26GM-MDSCs still significantly suppressed the generation of cytolitic CD8+ T cells, VSSP-MDSCs were completely inactive (Fig. 1D, 1F).

Furthermore, the inhibition of allogeneic CTLs by VSSP-MDSCs and tumor-induced MDSCs was assessed (Fig. 2A, 2B). Alloantigen-stimulated cytolytic effectors were more susceptible than Ag-specific CTLs to MDSC-mediated suppression, as 12% of C26GM-MDSCs completely abrogated in vitro-generated allogeneic response, whereas the same tumor-induced MDSC percentage reduced Ag-specific response to a still significant but smaller degree (compare Figs. 1D and 2A). However, even in this setting, VSSP-MDSCs were greatly less suppressive than C26GM-MDSCs when added at both 12 and 6% of total cell numbers (Fig. 2A, 2B).

Nos but not Arg is involved in the residual suppressive capacity of VSSP-derived MDSCs

Arg and Nos enzymes have been related to MDSC suppressive capacity. CD11b+Gr-1+ cells isolated from mice inoculated with EL-4 lymphomas and C26 colon carcinomas depend on these two enzymes to exert their functional activity (15, 32, 33). To find out whether Arg and Nos were contributing to the residual suppression exerted by VSSP-MDSCs, an allogeneic MLR culture was set up adding 12% of CD11b+ cells in the presence of either Nos inhibitor L-NMMA or Arg inhibitor Nor-NOHA (Fig. 2C). After 5 d, a [51Cr] release assay was performed to assess the function of effector cells generated in MLR. L-NMMA completely abrogated the suppressive activity of VSSP-MDSCs. In contrast, Nor-NOHA did not modify the reduced generation of allogeneic cytotoxic splenocytes caused by VSSP-MDSCs (Fig. 2C). These experiments suggest that Nos but not Arg is involved in the residual suppressive capacity of VSSP-MDSCs.

We then attempted to identify which Nos isoform was present in VSSP-MDSCs, comparing the relative expression of Nos mRNAs among naive CD11b+ splenocytes and CD11b+ cells from either adjuvant-treated or tumor-bearing mice. Real-time PCR analysis demonstrated that neuronal Nos (Nos1) gene expression was downregulated in CD11b+ cells isolated from the spleens of both VSSP-treated and C26GM tumor-bearing mice (Fig. 2D) compared with that of BALB/c CD11b+ splenocytes from tumor-free mice. However, upregulation of inducible Nos2 was reduced in splenic VSSP-MDSCs in comparison with C26GM-MDSCs (Fig. 2E). On the contrary, the expression of endothelial Nos3 (Nos3) was relatively upregulated in VSSP-MDSCs, suggesting that Nos3 might be involved in the suppressive mechanism of these cells (Fig. 2F). Notably, we recently demonstrated that different MDSC subsets showed varying expression of Nos isoforms in C26GM tumor-bearing mice. In fact, the Gr-1high subset did not express Nos2 protein but had an increased Nos3 mRNA level compared with that of the Gr-1low cell subset. Nevertheless, both subsets were sensitive to Nos inhibitor L-NMMA, supporting

![FIGURE 2](http://www.jimmunol.org/). Analyses of enzymes involved in the suppressive mechanism of VSSP-derived MDSCs. A and B, CD11b+ cells were isolated from spleens of VSSP-treated BALB/c mice and titrated in an MLR culture to final proportions of 12 and 6% of total cells. CD11b+ cells isolated from C26GM tumor-bearing were used as positive control of immunosuppression. Cytotoxicity toward allogeneic targets was evaluated 5 d later in a [51Cr] release assay. C, Arg and Nos enzymes involvement in the suppressive capacity was evaluated by adding L-NMMA and/or Nor-NOHA inhibitors to the MLR culture performed in the presence of 12% VSSP-MDSCs. Data corresponding with the percentage of specific lysis at different effector cell dilutions are expressed as mean ± SD. MLR experiments were repeated twice. D–F, Nos gene expression profiles were studied comparatively in splenic CD11b+ cells from VSSP-treated and C26GM tumor-bearing mice by real-time PCR analysis. Graphs show the logarithm of the differences in threshold cycle, corresponding with the Nos1, Nos2, and Nos3 genes, between CD11b+ cells in the experimental groups and CD11b+ splenocytes from tumor-free BALB/c mice (ΔCTx − ΔCTBALB/c). Real-time analyses were performed with CD11b+ cells from three different experiments with similar results.
the idea that Nos3 could be effective in place of Nos2 in some MDSC subsets (34).

**VSSP administration changes the phenotype of MDSCs isolated from the spleens of tumor-bearing mice**

The influence of VSSP inoculation on the myeloid populations in tumor-bearing mice was then addressed by administering three doses of VSSP, s.c., to mice previously inoculated with C26GM tumor cells. Splenic MDSCs in mice treated with VSSP accounted for 34.6 ± 5.8% of total splenocytes, similar to the 40.9 ± 2.4% found in the spleens of C26GM tumor-bearing mice. In animals with s.c. growing tumors and treated with VSSP, a higher percentage of MDSCs was detected (61.6 ± 1.5%, p = 0.002).

Flow cytometry analyses of CD11b+ cells sorted from spleens of these mouse groups showed that VSSP-MDSCs expressed increased levels of CD62L compared with those of the C26GM-MDSCs (Fig. 3A, p = 0.001). Notably, CD11b+ cells derived from VSSP-treated C26GM tumor-bearing mice (C26GM+VSSP-MDSCs) showed a percentage of CD62L analogous to that of VSSP-MDSCs (p = 0.939) but different from that of tumor-induced counterparts (p = 0.001). Gr-1 distribution was also different (p = 0.0001) between adjuvant-associated and tumor-induced CD11b+ cells, with 15.9 ± 1.3% and 32.8 ± 1.1% Gr-1low subpopulation, respectively (Fig. 3A). VSSP administration in tumor-bearing mice significantly reduced (20.4 ± 0.8%, p = 0.001) the percentage of CD11b+Gr-1low cells compared with that of nontreated tumor-bearing mice. IL-4Ra was described as a functional marker for MDSCs (15). We also found higher percentages of F4/80+IL-4Rahigh subpopulation within splenic C26GM-MDSCs (29.1 ± 3.9%), in comparison with the 6.10 ± 0.8% and 8.78 ± 0.2% detected in MDSCs isolated from either tumor-free mice (p = 0.001) or C26GM tumor-bearing mice (p = 0.001) treated with VSSP (Fig. 3A). Furthermore, double staining with anti-Ly6C and anti-Ly6G Abs showed that MDSCs sorted from C26GM tumor-bearing mice treated with VSSP were phenotypically closer to MDSCs from VSSP-treated tumor-free mice. In particular, the Ly6GlowLy6Clow population had different abundance in total CD11b+ cells from VSSP-treated mice (either tumor-free or tumor-bearing) and untreated animals implanted with C26GM tumors (p = 0.0001 and p = 0.001, respectively). In fact, Ly6GlowLy6Clow cells represented 7.89 ± 0.6% of VSSP-MDSCs and 10.4 ± 3.9% within C26GM+VSSP-MDSCs compared with 28.1 ± 2.1% in C26GM-MDSCs (Fig. 3A). In tumor-free mice,

![FIGURE 3. Effect of VSSP administration on the phenotype and suppressive capacity of tumor-induced, splenic CD11b+ cells. A. FACS analysis of relevant markers was performed on MDSCs immunomagnetically enriched from the spleens of VSSP-treated tumor-free, C26GM tumor-bearing, and VSSP-treated C26GM tumor-bearing mice. On the dot plot graphs, quadrants were individually set at positions where isotype control Ab signals were less than 1%. Values on quadrants and gates correspond with the mean ± SD of the cell percentages from three different experiments. B–D, Functional suppressive activities of CD11b+ cells sorted from the spleen were evaluated by the inhibition of proliferation and cytotoxicity of CD8+ T cells. B. Bar graph represents proliferative responses of CD8+ T cells from CL4 transgenic mice in the presence of CD11b+ cells (3% of total cells) and the cognate peptide, measured by [3H]thymidine incorporation. Bars represent mean cpm and SD values, and statistically significant differences are represented by letters (ANOVA and Tukey tests): *not significant; †p ≤ 0.05. C and D, To evaluate cytotoxicity inhibition, either CD8+ T cells from CL4 transgenic mice stimulated in the presence of the specific peptide (C) or BALB/c splenocytes stimulated with allogeneic C57BL/6 cells (D) were used as effector cells. Under these experimental settings, CD11b+ cells were added to a final proportion of either 24 or 12% of the total cells, as indicated. Graphs show percentages of specific lysis, measured by [51Cr] release assay, at graded effector cell dilutions, represented as mean ± SD. Data are from one experiment repeated twice with similar results.](http://www.jimmunol.org/)
VSSP-MDSCs contained ~10.9 ± 0.3% Ly6GlowLy6Chigh inflammatory monocytes, which were absent in both C26GM-MDSCs and C26GM+VSSP-MDSCs (Fig. 3A).

EL-4-induced CD11b+ cells were also analyzed to corroborate further the phenotypic changes caused by VSSP inoculation in mice from a different genetic background. In this tumor model as well, administration of VSSP increased the number of CD11b+Gr-1+ T cells infiltrating the spleens of tumor-bearing mice, from 14.3 ± 2.4% in untreated animals to 37.4 ± 2.1% in those inoculated with the adjuvant (p = 0.0001). Similar to the results obtained in the C26GM tumor model, CD11b+ cells isolated from the spleens of EL-4 tumor-bearing mice (EL-4-MDSCs) showed higher percentages of Gr-1low population (population = 0.046) and F4/80IL-4Rx+ cells (p = 0.001) than those of CD11b+ cells coming from adjuvant-injected tumor-bearing mice (EL-4+VSSP-MDSCs) (Supplemental Fig. 2A). In contrast, the percentage of CD62L+Gr-1+ cells was increased in EL-4+VSSP-MDSCs compared with that of EL-4-MDSCs (p = 0.001). Furthermore, Ly6GlowLy6Chigh inflammatory monocytes accounted for 31.6 ± 1.2% of CD11b+ cells in the spleens of VSSP-treated tumor-inoculated mice, whereas they represented only 19.2 ± 2.3% in untreated animals with EL-4 tumors (Supplemental Fig. 2A; p = 0.001).

Suppressive ability of tumor-induced splenic MDSCs is reduced when VSSP is given as adjuvant

To test whether the differences in phenotype between tumor-induced MDSCs, isolated from tumor-bearing mice either treated or not with VSSP, were related to changes in functional activity, a new set of experiments on C26GM and EL-4 tumor models was performed. Initially, we tested the ability of MDSCs to inhibit the proliferation of Ag-specific CL4 CD8+ T cells. Cell proliferation was measured by [3H]thymidine incorporation after stimulation with cognate peptide or cytidylic acid (poly I:C) adjuvant, a known inductor of strong CD8+ T cell responses (35, 36). As shown in Supplemental Fig. 4, the effect of VSSP on the capacity of CD11b+ cells sorted from the spleens of mice, were added during alloantigen or antigen presentation generation of functional CTLs in vitro. CD11b+ cells, sorted from the spleens of mice, were added during allograft or peptide-mediated stimulation of effector cells, and CTL function was evaluated in a [3Cr] release assay. C26GM-MDSCs induced an almost complete suppression of both HA Ag-specific (Fig. 3C) and alloantigen-specific (Fig. 3D) lytic responses, whereas either VSSP-MDSCs or C26GM+VSSP-MDSCs only partially affected CTL generation, and no difference could be seen among these two groups. Analogous results were obtained with CD11b+ cells purified from EL-4 tumor-bearing mice. Spleenic EL-4–MDSCs abolished, almost completely, the lytic activity of Ag-specific CD8+ T cells, and treatment of EL-4 tumor-bearing mice with the adjuvant reduced the inhibitory capacity of the corresponding MDSC population, mimicking the activity of VSSP-MDSCs (Supplemental Fig. 2B). In this model, the effect of VSSP seems to be transient, as 7 d after the last VSSP dose there was a reduction in the VSSP-dependent accumulation of MDSCs; however, MDSCs present in the spleens of EL-4 tumor-bearing mice treated with VSSP still had a reduced suppressive activity on Ag-activated CD8+ T lymphocytes (Supplemental Fig. 3A, 3B).

VSSP prevents in vivo T cell unresponsiveness induced by CD11b+ cells isolated from tumor-bearing mice

To confirm in vivo the modulatory activity of VSSP on tumor-conditioned CD11b+ cells, we performed different adoptive transfer experiments. Basically, in these models Ag-specific CD8+ T cells were adaptively transferred to tumor-free mice that were then vaccinated with the Ag; some of the mice also received an adoptive transfer of tumor-conditioned CD11b+ cells to evaluate their in vivo immunoregulatory function. IFN-γ production by transferred CD8+ T cells was assessed 10 d after vaccination by cytokine intracellular staining.

First, we compared the suppressive capacity of CD11b+ cells isolated from EL-4 tumor-bearing mice treated or not with VSSP, which were transferred to CD45.1+ congenic mice previously injected with OVA-specific CD8+ T cells and vaccinated with SIINFEKL peptide emulsified in IFA. As shown in Fig. 4A and 4B, Ag-specific IFN-γ+ cells were detected in LNs from recipient mice that had received no MDSC injection, whereas the response of LN cells isolated from mice after transfer of EL-4-MDSCs was significantly reduced (p = 0.013). In accordance with the in vitro results, CD11b+ cells isolated from VSSP-treated mice, independently of the presence of the tumor, produced no suppression of the IFN-γ secretion in Ag-specific CTLs (Fig. 4A, 4B).

In the second model, the effect of VSSP was evaluated by using it as adjuvant for the HA peptide (IYSTVASSSL) formulation to stimulate transferred Ag-specific CD8+ T cells (Fig. 4C, 4D). As a control vaccine, bone marrow-derived, peptide-pulsed DCs were used. In these experiments, adoptively transferred C26GM-MDSCs were still able to suppress Ag-specific CD8+ T cell responses when mice were vaccinated with DCs (p = 0.027). However, in recipient mice immunized with VSSP and HA peptide, suppression mediated by C26GM-MDSCs was prevented (Fig. 4C, 4D; p = 0.086). In the last model, EG.7 tumor cells expressing OVA were implanted 6 d before vaccination to induce suppressive CD11b+ cells presenting OVA, and the two vaccination approaches discussed before were compared. Fig. 4E illustrates that DC vaccination was prone to EG.7-induced suppression, as IFN-γ production by specific CD8+ T cells was reduced 2-fold in comparison with that of tumor-free mice (p = 0.001). In contrast, VSSP vaccination stimulated similar IFN-γ production in tumor-free and EG.7 tumor-bearing mice (Fig. 4E; p = 0.770).

The capacity of VSSP to shelter Ag-specific CTL responses in tumor-bearing mice was compared also with polyinosinic:polycytidylic acid (poly I:C) adjuvant, a known inductor of strong CD8+ T cell responses (35, 36). As shown in Supplemental Fig. 4A, immunization with OVA in VSSP generated an in vivo CTL response against SIINFEKL peptide in EL-4 tumor-bearing mice comparable with that observed in tumor-free mice (p = 0.304). However, the presence of this MDSC-recruiting tumor significantly reduced the cytotoxic response induced by the administration of three doses of OVA admixed with poly I:C (Supplemental Fig. 4B; p = 0.008).

Myeloid populations within the tumor microenvironment are modified by VSSP treatment

Previous experiments have shown that VSSP influenced the functional capacity and phenotype of tumor-induced, splenic MDSCs. To understand whether a similar situation could be found at the tumor site, C26GM tumor-infiltrating CD11b+ cells were isolated from mice either treated or not with VSSP. As shown in Fig. 5A, the expression of CD62L, IL-4Rx, and F4/80 ligands was comparable in both experimental groups. Even the Gr-1 distribution among low and high populations did not change after VSSP inoculation. Notably, tumor-infiltrating as well as splenic MDSCs did not contain a CD11b+Ly6GlowLy6Chigh monocytic subpopulation, irrespective of the treatment with VSSP (Fig. 5A). Similar results were obtained with tumor-infiltrating MDSCs from EL-4 tumor-bearing mice inoculated or not with VSSP (Supplemental Fig. 5). The functional capacity of tumor-infiltrating MDSCs was then evaluated in an Ag-specific CTL experimental setting. In contrast with the results obtained in the spleen, treatment with VSSP did not
modify the suppression exerted by CD11b+ cells isolated from the tumor (Fig. 5B). 

Apparently, VSSP administration did not modify, phenotypically and functionally, tumor-induced MDSCs within the tumor microenvironment. However, in experiments where equivalent amount of EL−4-MDSCs isolated from the spleen were adoptively transferred into congenic EL−4 tumor-bearing mice, a significant reduction of injected CD45.1+ cells was observed within the tumor in VSSP-treated mice (Fig. 5C; p = 0.001). This result suggests that VSSP treatment reduces MDSC capacity to infiltrate tumors. In contrast, as shown in Supplemental Fig. 6A, a higher number of the transferred CD11b+ cells migrated to LNs in VSSP-treated recipient mice, with nearly 3-fold the amount of CD45.1+ cells observed in both tumor-free (p = 0.014) and tumor-bearing (p = 0.04) mice. No differences in the migration could be detected in the spleens of treated (Supplemental Fig. 6B).

Furthermore, in this experimental setting, tumor-infiltrating transferred EL−4-MDSCs were found to be more differentiated into APCs in VSSP-treated congenic mice, as shown by the increased number of transferred cells with high levels of MHC class II molecules (Fig. 5D; p = 0.05). Also at the tumor site, a decreased expression of CD11b marker among total MHCII+ CD45.1+ cells was observed (Fig. 5D; p = 0.02). Moreover, in VSSP-treated tumor-bearing recipient mice, a higher percentage of CD11c+ cells became CD11b− (Fig. 5E; p = 0.003), a phenotypic change associated with terminal differentiated mature DCs (37, 38). In the spleen, the percentage of MHCII+ F4/80+ macrophages within the transferred population showed no differences between tumor-free and EL−4 tumor-bearing mice, either treated or not with VSSP (Supplemental Fig. 6C, 6E; p = 0.889 and p = 0.720, respectively). Nevertheless, a significant increase in total CD11c+ cells, widely employed as a marker of murine DCs (39), was detected in VSSP-treated mice compared with that in both tumor-free mice (p = 0.022) and untreated tumor-bearing mice (p = 0.011) (Supplemental Fig. 6D, 6F).

Taken together, these results suggest that VSSP administration reduces the migration of tumor-induced MDSCs toward the tumor site while it accelerates the differentiation of this immature myeloid population into mature APCs within the tumor microenvironment and secondary lymphoid organs.
VSSP diminishes the suppression of tumor-specific CTL responses by MDSCs and contributes to reduce tumor growth

We speculated that the effect of VSSP on both splenic and tumor-infiltrating MDSCs might contribute to reduce tumor growth. Indeed, administration of OVA protein or SIINFEKL peptide with VSSP, but not SIINFEKL peptide emulsified in IFA, caused a significant reduction of EG.7 tumor growth in a therapeutic experimental setting (Fig. 6A; *p = 0.01 and *p = 0.014, respectively), indicating the usefulness of VSSP as adjuvant in tumors triggering an MDSC-dependent immunosuppression.

Furthermore, we decided to study the antitumor effect of VSSP as an adjuvant of a more physiological tumor-associated Ag (TAA). The sarcoma MCA203 is an MDSC-recruiting tumor (15, 34), and GM3 ganglioside was detected in the primary tumor by chemical isolation and HPTLC identification, as shown in Fig. 6B. Vaccination of MCA203 tumor-bearing mice with VSSP, which contains GM3 ganglioside, reduced significantly the tumor growth (Fig. 6B). This vaccination setting was started on day 11, when s.c. tumors were palpable, indicating a therapeutic effect of VSSP using GM3 ganglioside. Notably, CD11b+ cells isolated from tumor-bearing mice by FACS. Contour graphs show one representative mouse for each experimental group. Statistical differences on dot graphs were detected with two-tailed t-test: *p = 0.01 and ***p = 0.0001, respectively. Results are representative of two experiments with similar results.
CTL response against MCA203 tumor, even when the nominal Ag in the vaccine was the GM3 ganglioside.

**Discussion**

Adjuvants have been frequently used in cancer vaccines to potentiate antitumor immune response. However, some adjuvants can induce MDSC accumulation into tumor-bearing mice and cancer patients. For example, whereas low doses of GM-CSF potentiate antitumor activity, higher doses impaired efficacy of antitumor vaccines through MDSC accumulation (40, 41). These findings highlight the importance of studying the immune modulatory mechanisms of cancer vaccine adjuvants. VSSP is an adjuvant developed at CIM that has been used in a randomized phase II clinical trial on renal carcinoma patients and in three phase I clinical trials on breast cancer, hormone-sensitive prostate cancer, and cervical intraepithelial neoplasia grade III (unpublished data). Notably, some of these clinical tumors have been associated with the recruitment of MDSCs, for instance breast cancer, renal carcinoma, and prostate cancer (42–44).

In this work, we demonstrated that VSSP adjuvant is able to recruit CD11b+Gr-1+ cells in the spleens of treated mice. Association between infection and CD11b+Gr-1+ cell recruitment has been reported: *Trypanosoma cruzi* and *Taenia crassiceps* infections are linked with T cell unresponsiveness mediated by immature CD11b+Gr-1+ cells (45, 46). Because VSSP contains bacterial molecules, we presumed that it could induce MDSCs through the physiological mechanisms responsible for the control of anti-infectious response. Another important component of VSSP is GM3 ganglioside. Gangliosides inhibit DC differentiation, and they have been linked to MDSC accumulation (47, 48). The expansion of MDSCs after VSSP inoculation appears to depend on both bacterial and GM3 molecules, because outer membrane vesicles from *N. meningitidis* without the ganglioside recruited a smaller number of MDSCs than did VSSP (Supplemental Fig. 7A, 7B).

Notably, the splenic CD11b+Gr-1+ population induced by VSSP had a lower capacity to suppress Ag-specific CTL response than that of tumor-induced MDSCs, both in C26GM and EL-4 tumor models. Previous in vivo experiments using similar dosage and schedule of VSSP suggested that VSSP potentiated Ag-specific CTL responses (27). These results suggest that MDSCs recruited during acute exposure to VSSP might exert a less suppressive function than that of counterparts induced during a chronic inflammation and tumor growth. The residual suppressive capacity of VSSP-MDSCs seemed to be more dependent on Nos than Arg, in contrast with tumor-induced MDSCs in which both Arg and Nos might play a role (15, 32, 33). Moreover, whereas Nos3 was more upregulated than Nos1 or Nos2 in VSSP-MDSCs compared with that in tumor-free
an experimental autoimmune encephalomyelitis model. In contrast, inflammatory monocytes can efficiently suppress T cell responses in differentiated to a greater extent toward MHCII+ APCs. In addition, the tumor site, and those cells that effectively reached it differ-

populations within VSSP-MDSCs, which could account for their characterization also demonstrated changes in the main sub-

ponential capacity (34, 50). The lower accumulation of F4/80+IL-4R+ cells in VSSP-MDSCs was demonstrated with that of tumor-induced MDSCs, as IL-4R+ is important for MDSC activity in vitro and in vivo (15), Zhu et al. (51) demonstrated that only a small population of CD11b+Ly6C\text{high} inflammatory monocytes can efficiently suppress T cell responses in an experimental autoimmune encephalomyelitis model. In contrast, VSSP induced a higher amount of CD11b+Ly6C\text{high} cells than EL-4 and C26GM tumors, but tumor-derived MDSCs had a superior suppressive activity. Thus, CD11b+Ly6C\text{high} cells might not be the population responsible for the efficient suppression of T cell responses exerted by MDSCs under different pathological conditions, and other subpopulations could exert suppression depending on the stimulus, type of tumor, or genetic background. Finally, VSSP inoculation in tumor-bearing mice generated a splenic CD11b+ population with a reduced suppressive ability compared with that of tumor-associated counterparts, both in EL-4 and C26GM tumor models. Further in vivo experiments corroborated the diminished function of VSSP-MDSCs and the ability of VSSP to modulate the suppressive activity of tumor-derived MDSCs. Adoptive transfer of tumor-induced MDSCs into tumor-free VSSP-treated mice demonstrated the capacity of this adjuvant to create a particular environment able to restrain their suppressive activity on T cell responses. Moreover, the positive effect of VSSP on tumor-induced MDSCs was shown to be dominant, as a reduced suppressive function was observed after EL-4+VSSP-MDSC adoptive transfer. VSSP inoculation in EG.7 tumor-bearing mice restored the IFN-γ secretion by adoptively transferred OT-1 CD8\textsuperscript{T} cells to levels similar to those obtained in tumor-free mice. The restorative action of this adjuvant seems to be unique because DC vaccination was ineffective. In addition, VSSP and not poly I:C inoculation protected Ag-specific CTL response in EL-4 tumor-bearing mice. Although other mechanisms might contribute, it appears that the VSSP adjuvant activity could be associated with its capacity to promote differentiation of tumor-induced MDSCs into APCs, as demonstrated by the in vivo differentiation experiments. Previous results from Kusmartsev and Gabrilovich (52) showed that, when transferred into naive recipients, Gr-1\textsuperscript{+} cells isolated from tumor-free mice differentiated in vivo more quickly than tumor-derived counterparts into functional DCs and macrophages, indicating a delay in the differentiation program of these tumor-induced MDSCs. Our results suggest that also MDSCs iso-

lated from VSSP-treated tumor-bearing mice differentiated more rapidly into APCs than tumor-induced counterparts. Thus, immu-
nization with VSSP could be a better choice than DC vaccination or poly I:C adjuvant to develop a potent immune response in immu-
nocompromised tumor-bearing hosts.

CD11b\textsuperscript{+} cells sorted from tumor infiltrate showed similar immunosuppressive properties in vitro on a per-cell basis, irrespec-
tive of adjuvant treatment. However, when tumor-induced splenic MDSCs were adoptively transferred to tumor-bearing mice inoculated with the adjuvant, these CD11b\textsuperscript{+} cells migrated less to the tumor site, and those cells that effectively reached it differ-

tiated to a greater extent toward MHCII\textsuperscript{+} APCs. In addition, a higher percentage of DCs lost CD11b\textsuperscript{+} marker in VSSP-inoculated mice. De Smedt et al. (37) demonstrated that DCs matured in vivo in response to LPS expressed high levels of B7 molecules and lost CD11b marker, and this phenotype was asso-
ciated with a reduced capacity to process proteins and an in-
creased efficiency to stimulate T cells. One hypothesis could be that VSSP administration modulates the tumor microenvironment facilitating the differentiation of the infiltrating MDSC population to mature APCs while the functionality of the remaining MDSCs is not changed. When VSSP was inoculated together with a TAA (either OVA or GM3), it caused a significant decrease in EG.7 and MCA203 tumor growth (Fig. 6A, 6B), confirming the antitumor efficacy of several vaccine candidates when admixed with VSSP adjuvant, previously demonstrated in other tumor models (4, 24– 26). In contrast, administration of VSSP in tumor-bearing mice did not change tumor-growth kinetics in EL-4 and C26GM tumor models (Supplemental Fig. 8A–C), probably due to a low expression level of GM3 in the first case and an inappropriate ex-
posure of this ganglioside on the surfaces of C26GM tumor cells (data not shown). These results suggest that modification of tumor-induced MDSCs by VSSP is not sufficient to change pri-
mary tumor development, and a simultaneous stimulation of an effector CTL response against TAA is also needed.

Chemical compounds like NO-aspirin and phosphodiesterase-5 inhibitors (e.g., sildenafil, vardenafil, and tadalafl) can reduce MDSC function, restoring T cell function and improving efficacy of antitumoral treatments (53, 54). However, these inhibitors do not change MDSC accumulation. In contrast, inoculation of CpG ad-

juvant induces CD11b\textsuperscript{+}Gr-1\textsuperscript{+} cell accumulation in the spleens of treated mice, which efficiently suppresses T cell-mediated allo-
reactivity and graft-versus-host disease in a murine model of allogeogenic cell therapy (55). Our results with VSSP demonstrate that an increased frequency of MDSCs is not necessarily corre-
lated with the strongest immunosuppression, as VSSP reduced the suppressive ability of tumor-derived MDSCs. Finally, this work indicates that VSSP could be a cancer vaccine adjuvant able to target tumor-induced immunosuppression while stimulating a po-
tent immune response against tumor Ags.

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