Cell Reports
Article

Immune Tolerance to Tumor Antigens Occurs in a Specialized Environment of the Spleen

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http://dx.doi.org/10.1016/j.celrep.2012.08.006

SUMMARY

Peripheral tolerance to tumor antigens (Ags) is a major hurdle for antitumor immunity. Draining lymph nodes are considered the privileged sites for Ag presentation to T cells and for the onset of peripheral tolerance. Here, we show that the spleen is fundamentally important for tumor-induced tolerance. Splenectomy restores lymphocyte function and induces tumor regression when coupled with immunotherapy. Splenic CD11b^{+}Gr-1^{int}Ly6C^{hi} cells, mostly comprising proliferating CCR2^{+}-inflammatory monocytes with features of myeloid progenitors, expand in the marginal zone of the spleen. Here, they alter the normal tissue cytoarchitecture and closely associate with memory CD8^{+} T cells, cross-presenting tumor Ags and causing their tolerization. Because of its high proliferative potential, this myeloid cell subset is also susceptible to low-dose chemotherapy, which can be exploited as an adjuvant to passive immunotherapy. CCL2 serum levels in cancer patients are directly related to the accumulation of immature myeloid cells and are predictive for overall survival in patients who develop a multipeptide response to cancer vaccines.

INTRODUCTION

The interaction between the immune system and transformed cells can result in the elimination of developing tumors, establishment of a growth dormancy state, or selection of neoplastic clones with the ability to survive in immune-competent hosts (Schreiber et al., 2011). On the other hand, cells of both innate and adaptive immunity can promote initial steps of cancer progression by fueling chronic inflammation in the tumor microenvironment (Grivennikov et al., 2010). Most experimental tumor models, as well as clinically diagnosed tumors, are analyzed when malignant cells may have already escaped early immune surveillance by both cell-autonomous and cell-independent mechanisms. At this stage, the almost universal feature of successfully progressive cancers is the activation of abnormal myelopoiesis and the recruitment of immature CD11b^{+}Gr-1^{+} myeloid cells into different tissues (Gabrilovich et al., 2012). This process is governed by tumor-released soluble factors and is dependent upon upregulation of key transcription factors in myeloid cells, such as cEBPβ (Marigo et al., 2010; Sonda et al., 2011). Myelopoiesis during acute infections, stress, or trauma results in rapid terminal differentiation of myeloid cells. In contrast, cancer myelopoiesis is associated with defective cell differentiation, leading to the accumulation and persistence of immature CD11b^{+}Gr-1^{+} myeloid elements (Gabrilovich and Nagaraj, 2009; Gabrilovich et al., 2012; Sica and Bronte, 2007). These cells can also cause profound alterations of antitumor immune responses. In fact, tumors bring on a progressive tolerance toward tumor antigens (Ags) among peripheral CD8^{+} T cells, which is orchestrated by the expansion of CD11b^{+}Gr-1^{+} cells (Dolcetti et al., 2010b; Kusmartsev et al., 2005; Nagaraj et al., 2007). The current view points toward the lymph node as the primary site for tumor Ag presentation and tolerance induction (Nagaraj et al., 2007), but accumulation of immature myeloid cells is extremely limited in these secondary lymphoid organs compared with other organs, such as the spleen. Although it was neglected for many years, the spleen is the main lymphoid organ that undergoes myeloid cell expansion during tumor development, and was recently found to possess unique biological properties. The spleen accumulates monocyte and granulocyte precursors that directly replenish tumor-associated macrophages and neutrophils during lung cancer development (Cortez-Retamozo et al., 2012). Moreover, the cords of the splenic subcapsular red pulp contain a reservoir of a peculiar monocyte subset that is promptly released in the bloodstream following acute injury (Swirski et al., 2009).

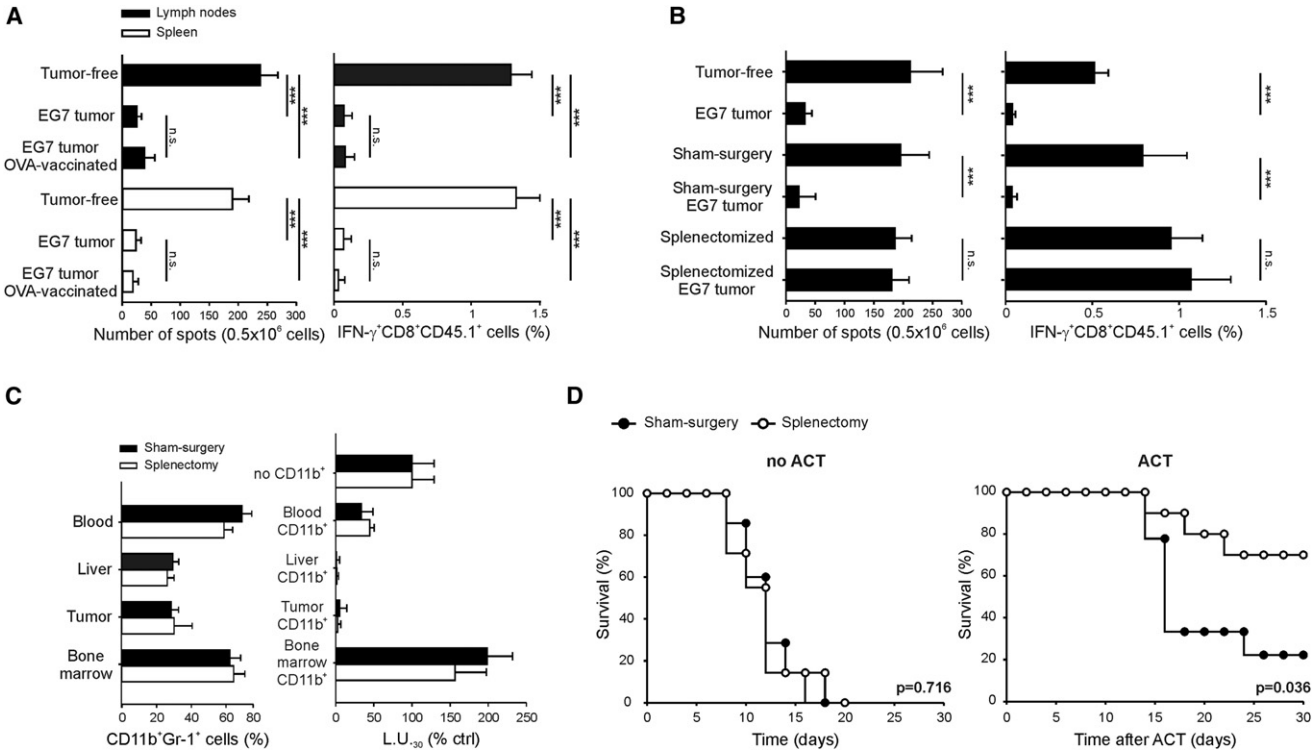

Figure 1. The Spleen Is a Key Organ for Tumor-Induced Tolerance

(A) C57BL/6 mice were either injected with 10^6 EG7 cells or not injected. After 7 days they received i.v. 5 × 10^6 naïve $CD8^+$ T cells isolated from the spleen of OT-1 mice. After 2 days the mice were vaccinated with $OVA_{257-264}$ peptide-pulsed DCs, and 5 days after vaccination, tumor-draining lymph nodes (black bar) and spleens (white bar) were removed, stimulated with either OVA peptide or unrelated peptide, and tested for IFN-γ production (ELISpot assay, left panel; intracellular staining, right panel). Data are presented as the difference in IFN-γ level (either as number of spots or percentage of cells) between OVA-peptide stimulation (specific stimulation) and β-gal peptide stimulation (unspecific stimulation). Data for intracellular stainings are presented as mean ± SD of the percentage of IFN-γ-producing $CD8^+CD45.1^+$ cells, from two independent experiments (n = 6 mice/group for each experiment). Statistical analysis was performed with Student's t test.

(B) C57BL/6 mice were splenectomized or subject to sham surgery. After 14 days, mice were either injected with 10^6 EG7 cells or not injected. Seven days after tumor challenge, the mice received i.v. 5 × 10^6 naïve $CD8^+$ T cells isolated from the spleen of OT-1 mice. After 7 days, the mice were sacrificed and tumor-draining lymph node cells were tested as in (A). Data are represented as mean ± SD of three experiments (n = 5 mice/group for each experiment). Statistical analysis was performed with Student's t test.

(C) When the tumor mass reached 1,000 mm^3, bone marrow, tumor, liver, and blood were collected and single-cell suspensions were analyzed for $CD11b^+Gr\text{-}1^+$ cell accumulation (left panel). $CD11b^+$ cells were immunomagnetically sorted from the same compartments and added in 1:2 serial dilutions (24% to 3% of the effector cells) to an MLPC to test their suppressive properties (right panel). The percentage of $L.U._{30}$ of cultures containing 6% $CD11b^+$ cells is reported as the mean ± SD of two independent experiments. Data were normalized on the average value of $L.U._{30}$ of MLPCs without $CD11b^+$ cells.

(D) Mice were either splenectomized or subjected to sham surgery. After 14 days, the mice were injected with 10^6 EG7 thymoma cells or not injected, and 7 days after tumor challenge the mice received i.v. 5 × 10^6 naïve $CD8^+$ T cells isolated from the spleen of OT-1 mice. A Kaplan-Meier survival analysis (n = 10 mice/group) was performed to compare splenectomy versus sham-surgery groups in the absence (left panel) and presence (right panel) of ACT.

See also Figure S1.

RESULTS

The Spleen Is Essential for Tumor-Induced Tolerance

We adoptively transferred naïve $CD8^+$ T cells from OT-1 mice bearing a T cell receptor specific for ovalbumin (OVA) and traced them in vivo using the congenic marker CD45.1. When we tested the ex vivo activation of peripheral OVA-specific $CD8^+$ T cells in mice bearing a tumor expressing the OVA model tumor Ag, we found that splenic lymphocytes, similarly to those taken from the lymph nodes, underwent Ag-specific tolerance (Figure 1A). Moreover, this state could not be reversed by in vivo immunization with the same tumor Ag delivered by dendritic cells (DCs) in a proper immune-stimulating context (Figure 1A). Therefore, we further investigated the role of the spleen in tumor-induced tolerance by performing the same type of tolerance assay in either splenectomized or sham-surgery-treated mice. Splenectomy completely restored lymphocyte activation by tumor Ag in tumor-draining lymph nodes (Figure 1B), and this effect could be readily observed even when OT-1 lymphocytes were stimulated in vitro with the OVA peptide before the adoptive transfer, or in vivo following vaccination with peptide-pulsed DCs (Figures S1A and S1B). The same results were obtained in mice from another strain, BALB/c, bearing 4T1 mammary carcinoma expressing influenza hemagglutinin (HA) model Ag (Figure S1C).

Of interest, splenectomy did not alter the distribution and suppressive function of CD11b$^+$Gr-1$^+$ myeloid cells in other tissues and blood, in at least three tumor models of different histology (Figure 1C; the results in EG7-bearing mice are shown here, but identical findings were obtained with MCA203 fibrosarcoma and LLC carcinoma, not shown). In contrast to a recent report (Cortez-Retamozo et al., 2012), splenectomy did not affect the rate of tumor growth in our models (Figure 1D, left panel); however, adoptive cell transfer (ACT) of tumor Ag-specific CD8$^+$ T cells in splenectomized mice led to a significant increase in survival compared with mice subjected to sham surgery (Figure 1D, right panel), further highlighting the importance of the splenic compartment in the systemic tolerization of CD8$^+$ T lymphocytes. These results strongly suggest that CD8$^+$ T cells in tumor-bearing mice go through a fundamental step for their inactivation in the spleen, and point to splenic CD11b$^+$Gr-1$^+$ cells as potential tolerogenic effectors.

Chemotherapy Increases the Efficacy of ACT by Eliminating Splenic CD11b$^+$Gr-1^{int} Cells

Chemotherapy can enhance the antitumor efficacy of ACT by several mechanisms, including the elimination of myeloid cells (reviewed in Gabrilovich et al., 2012; Ma et al., 2010; Restifo et al., 2012). To mimic experimentally the effect of splenectomy, we evaluated a large panel of conventional chemotherapeutic drugs for their ability to affect splenic CD11b$^+$Gr-1$^+$ cells and restore immune competence. We previously showed that the suppressive environment created by tumors does not allow the generation of Ag-specific cytotoxic T lymphocytes (CTLs) in alloantigen-stimulated cultures (mixed leukocyte culture [MLC]) set up with splenocytes of tumor-bearing mice (Bronte et al., 1998, 1999). In this initial screening, chemotherapy doses were selected as the lowest effective amount that did not affect tumor growth (Figure S2A). After low-dose chemotherapy, the functional rescue of allogeneic CTLs was achieved with some but not all of the tested drugs, and it was always paralleled by a significant decrease in the CD11b$^+$Gr-1^{int} cell population. In the same mice, CD11b$^+$Gr-1^{hi} and CD11b$^+$Gr-1^{lo} cell subsets were either poorly or not affected (Figures S2B and S2C). Moreover, all of the drugs that reestablished CTL function also rescued the percentages of CD3$^+$CD8$^+$ T cells in the spleen of tumor-bearing mice to the levels present in tumor-free mice, whereas the effects on CD3$^+$CD4$^+$ T cells were more drug dependent (Figure S2D).

Given the relationship between the depletion of the CD11b$^+$Gr-1^{int} cells subset and the recovery of CTL function, we evaluated whether the elimination of this cell subset could improve the efficacy of passive immunotherapy. To use a clinically relevant target, we employed a protocol based on the transfer of oligoclonal CTLs that recognize mouse telomerase (mTERT) Ag (Ugel et al., 2010), in combination with different chemotherapeutic agents. We employed two drugs that in our preliminary screening depleted splenic CD11b$^+$Gr-1^{int} cells and recovered CTL function (gemcitabine and 5-fluorouracil [5-FU]), and one drug that lacked these properties (docetaxel). The adoptive transfer of mTERT-specific CTLs in MCA203 fibrosarcoma-bearing mice had no effect on tumor regression unless it was preceded by treatment with either gemcitabine or 5-FU, but not with docetaxel (Figure 2A). All of these drugs, whether given alone or in combination with CTLs recognizing an irrelevant Ag, had no impact on either tumor growth or mouse survival. From the group of tested drugs, we selected 5-FU for further studies. For ~40 years, this pyrimidine analog has been adopted for the clinical treatment of various solid tumors, and particularly for breast cancer and gastrointestinal malignancies. Moreover, 5-FU does not cause immunogenic cancer-cell death of tumor cells (Vincent et al., 2010), which allowed us to focus on its effect on immune cells. To rule out the contribution of regulatory T lymphocytes and cytokine sinks operated by competing T lymphocytes and NK cells (Gattinoni et al., 2006) as a possible explanation for the immune benefits of 5-FU, we also tested the combinatorial therapy in immunodeficient *Rag2*$^{-/-}\gamma_c^{-/-}$ mice. A prolongation of mouse overall survival (OS) by a single inoculation of 5-FU before mTERT-specific ACT was observed in two different tumor models in *Rag2*$^{-/-}\gamma_c^{-/-}$ mice (Figure 2B). To maximize the adjuvant activity of chemotherapy, we exploited a schedule consisting of repeated administration of 5-FU in combination with mTERT-based ACT. In both immunocompetent and immunodeficient mouse strains, the growth of MCA203 tumor was controlled, resulting in prolonged survival for all of the treated mice (Figure 2C). No toxic side effects were recorded in the cohorts of mice during the duration of the treatment.

To verify that splenic CD11b$^+$Gr-1^{int} cells critically contributed to limit ACT efficacy, we isolated CD11b$^+$Gr-1^{hi} and CD11b$^+$Gr-1^{int} cells from the spleen of *Rag2*$^{-/-}\gamma_c^{-/-}$ tumor-bearing mice and transferred them into *Rag2*$^{-/-}\gamma_c^{-/-}$ tumor-bearing recipients that had received 5-FU 2 days earlier. The next day, the mice were adoptively transferred with mTERT-specific CTLs. Reconstitution with CD11b$^+$Gr-1^{int} cells, but not CD11b$^+$Gr-1^{hi} cells, abrogated the 5-FU immune adjuvant activity (Figure 2D), suggesting that this specific myeloid cell subset is critical for the impairment of antitumor immunity.

CD11b$^+$Gr-1^{int} Splenocytes Comprise Cycling, Committed Precursors that Resemble Inflammatory Monocytes

When we analyzed the kinetics of myeloid repopulation in the spleen of tumor-bearing mice following exposure to either control vehicle or 5-FU, we found that all the myeloid subsets were initially affected by chemotherapy (Figure 3A), as expected. However, after administration of a single dose of 5-FU, CD11b$^+$Gr-1^{hi} and CD11b$^+$Gr-1^{lo} cells reached the numbers of untreated tumor-bearing mice in ~30 days, whereas this did not occur for CD11b$^+$Gr-1^{int} cells. The effect of 5-FU on CD11b$^+$Gr-1^{int} cells was indeed long-lasting, as in treated mice this cell subset was still ~15% of its counterpart in untreated control mice.

We also quantified the proliferative rate of different myeloid subsets in vivo by estimating the percentage of bromodeoxyuridine (BrdU)-incorporating cells after a 48 hr pulse with this synthetic nucleoside. While CD11b$^+$Gr-1^{hi} cells in the bone marrow were cycling, the same cell population was not proliferating in the spleen of tumor-free and tumor-bearing mice. On the contrary, CD11b$^+$Gr-1^{int} and CD11b$^+$Gr-1^{lo} cells were proliferating in the spleen and bone marrow of tumor-free mice, and when the tumor was present, the percentage of BrdU$^+$ cells

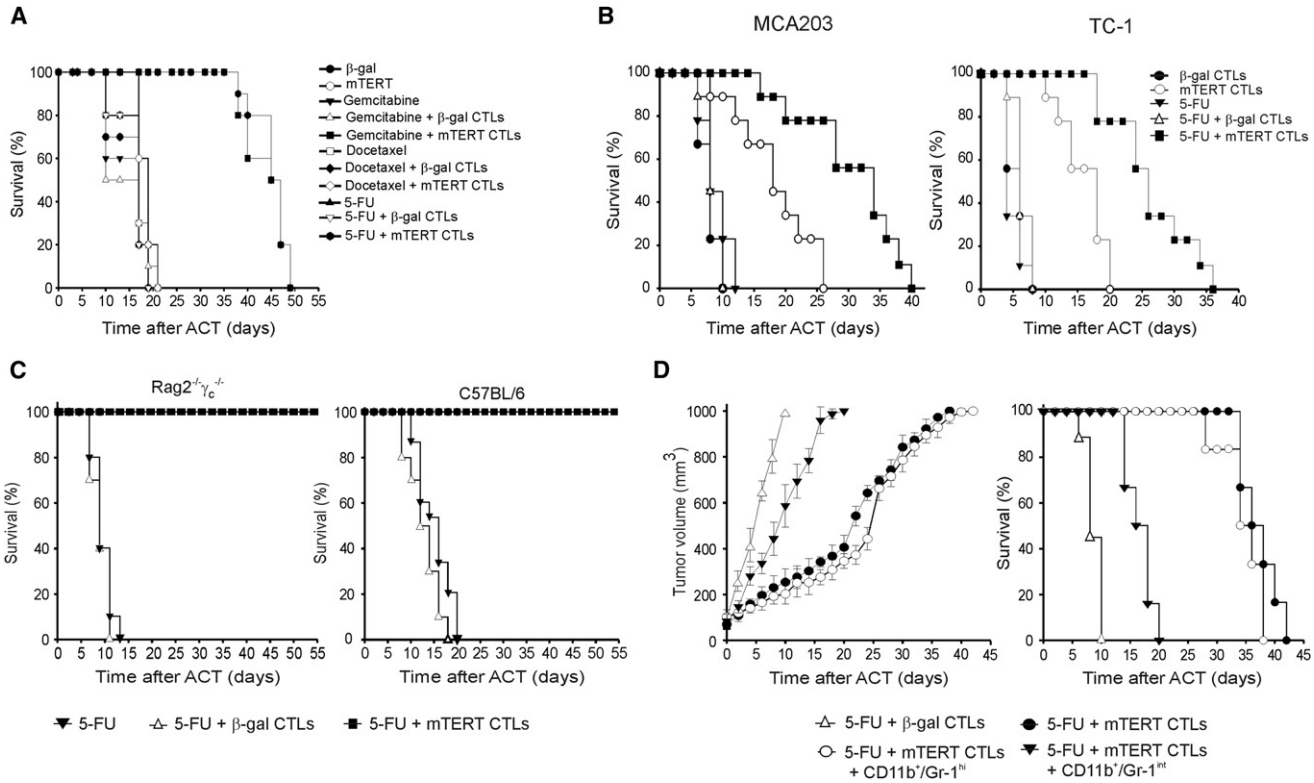

Figure 2. Adjuvant Activity of Low-Dose Chemotherapy on Adoptive Immunotherapy

(A) Therapeutic effectiveness of a single combination of chemotherapy and ACT with $mTERT_{198\text{-}205}$ CTLs. C57BL/6 mice were injected with 10^6 MCA203 sarcoma cells in the right flank. When tumor volume was ~200 mm^3, mice were treated with a single i.p. injection of either 5-FU (40 mg/kg), gemcitabine (120 mg/kg), or docetaxel (10 mg/kg). After 3 days, mice received 5 × 10^6 CTLs i.v. Mice were sacrificed when tumor volume reached 1,000 mm^3. Survival data for one representative experiment (n = 10 for each group) are shown. Kaplan-Meier survival analysis: $mTERT_{198\text{-}205}$ CTLs versus $\beta\text{-gal}_{96\text{-}103}$ CTLs, p = 0.558; mTERT198-205 CTLs versus gemcitabine, p = 0.476; $mTERT_{198\text{-}205}$ CTLs versus docetaxel, p = 0.998; $mTERT_{198\text{-}205}$ CTLs versus 5-FU, p = 0.999; $mTERT_{198\text{-}205}$ CTLs versus $mTERT_{198\text{-}205}$ CTLs + gemcitabine, p = 0.0002; $mTERT_{198\text{-}205}$ CTLs versus $mTERT_{198\text{-}205}$ CTLs + docetaxel, p = 0.998; $mTERT_{198\text{-}205}$ CTLs versus $mTERT_{198\text{-}205}$ CTLs + 5-FU, p = 0.0002; $mTERT_{198\text{-}205}$ CTLs + 5-FU versus $mTERT_{198\text{-}205}$ CTLs + docetaxel, p = 0.0002; and $mTERT_{198\text{-}205}$ CTLs + 5-FU versus $mTERT_{198\text{-}205}$ CTLs + gemcitabine, p = 0.996.

(B) Therapeutic effectiveness of a single combination of 5-FU injection and ACT with $mTERT_{198\text{-}205}$ CTLs in different tumor models. *Rag2*$^{-/-}\gamma_c^{-/-}$mice were s.c. implanted with 10^6 of either TC-1 lung carcinoma or MCA203 sarcoma cells in the right flank. When tumor volume was ~200 mm^3, mice were treated as described in (A). Cumulative data from three separate experiments (n = 15/group) are shown. Kaplan-Meier survival analysis in MCA203 model: $mTERT_{198\text{-}205}$ CTLs versus $\beta\text{-gal}_{96\text{-}103}$ CTLs, p = 0.0031; $mTERT_{198\text{-}205}$ CTLs versus 5-FU, p = 0.0028; and $mTERT_{198\text{-}205}$ CTLs versus $mTERT_{198\text{-}205}$ CTLs + 5-FU, p = 0.0008. Mantel-Haenszel statistic analysis in TC-1 model: $mTERT_{198\text{-}205}$ CTLs versus $\beta\text{-gal}_{96\text{-}103}$ CTLs, p = 0.0049; $mTERT_{198\text{-}205}$ CTLs versus 5-FU, p = 0.0047; and $mTERT_{198\text{-}205}$ CTLs versus 5-FU + $mTERT_{198\text{-}205}$ CTLs, p = 0.0017.

(C) Therapeutic effectiveness of repeated combination of ACT and 5-FU every 15 days. *Rag-2*$^{-/-}\gamma_c^{-/-}$mice (left panel) and C57BL/6 mice (right panel) were implanted with MCA203 sarcoma cells and treated with 5-FU as described in (A). After 3 days, mice received ACT. Treatment was repeated on days 15, 30, and 45 following the first ACT. A survival plot derived from three separate experiments (n = 15 for each group) is shown. Kaplan-Meier survival analysis for *Rag2*$^{-/-}\gamma_c^{-/-}$ model: 5-FU + $mTERT_{198\text{-}205}$ CTLs versus 5-FU + $\beta\text{-gal}_{96\text{-}103}$ CTLs, p = 0.000012. Kaplan-Meier survival analysis for C57BL/6 mice model: 5-FU + $mTERT_{198\text{-}205}$ CTLs versus 5-FU + $\beta\text{-gal}_{96\text{-}103}$ CTLs, p = 0.000036.

(D) *Rag2*$^{-/-}\gamma_c^{-/-}$mice were implanted with MCA203 sarcoma cells and treated with 5-FU as described in (A). After 2 days, 5 × 10^6 $CD11b^+Gr\text{-}1^{int}$ or $CD11b^+Gr\text{-}1^{hi}$ cells, isolated from the spleen of MCA203 tumor-bearing *Rag2*$^{-/-}\gamma_c^{-/-}$ mice, were injected i.v. After 1 day, mice received $mTERT_{198\text{-}205}$ CTLs. A survival plot of one representative experiment (n = 6 for each group) is shown. Mantel-Haenszel statistic analysis: 5-FU + $mTERT_{198\text{-}205}$ CTLs versus 5-FU + $mTERT_{198\text{-}205}$ CTLs + $CD11b^+Gr\text{-}1^{int}$, p = 0.000557; 5-FU + $mTERT_{198\text{-}205}$ CTLs + $CD11b^+Gr\text{-}1^{int}$ versus 5-FU + $mTERT_{198\text{-}205}$ CTLs + $CD11b^+Gr\text{-}1^{hi}$, p = 0.000568; and 5-FU + $mTERT_{198\text{-}205}$ CTLs versus 5-FU + $mTERT_{198\text{-}205}$ CTLs + $CD11b^+Gr\text{-}1^{hi}$, p = 0.490.

See also Figure S2.

increased in the spleen but not in the bone marrow (Figure 3B, left panel). Moreover, a 2 hr BrdU pulse revealed that a fraction of $CD11b^+Gr\text{-}1^{int}$ and $CD11b^+Gr\text{-}1^{lo}$ cells was already proliferating within the spleen of tumor-bearing mice at this early time point (Figure 3B, right panel). Thus, it is likely that the chemotherapeutic drugs found to share immune adjuvant properties in our initial screening are effective in reducing the expansion of highly cycling myeloid cells. As expected, 5-FU reduced proliferation of all the cell subsets when it was given 24–48 hr prior to the BrdU pulse (data not shown); however, even if 5-FU given 28 days earlier strongly affected the $CD11b^+Gr\text{-}1^{int}$ cell numbers (Figure 3A), the percentage of $BrdU^+$ cells in 5-FU treated animals

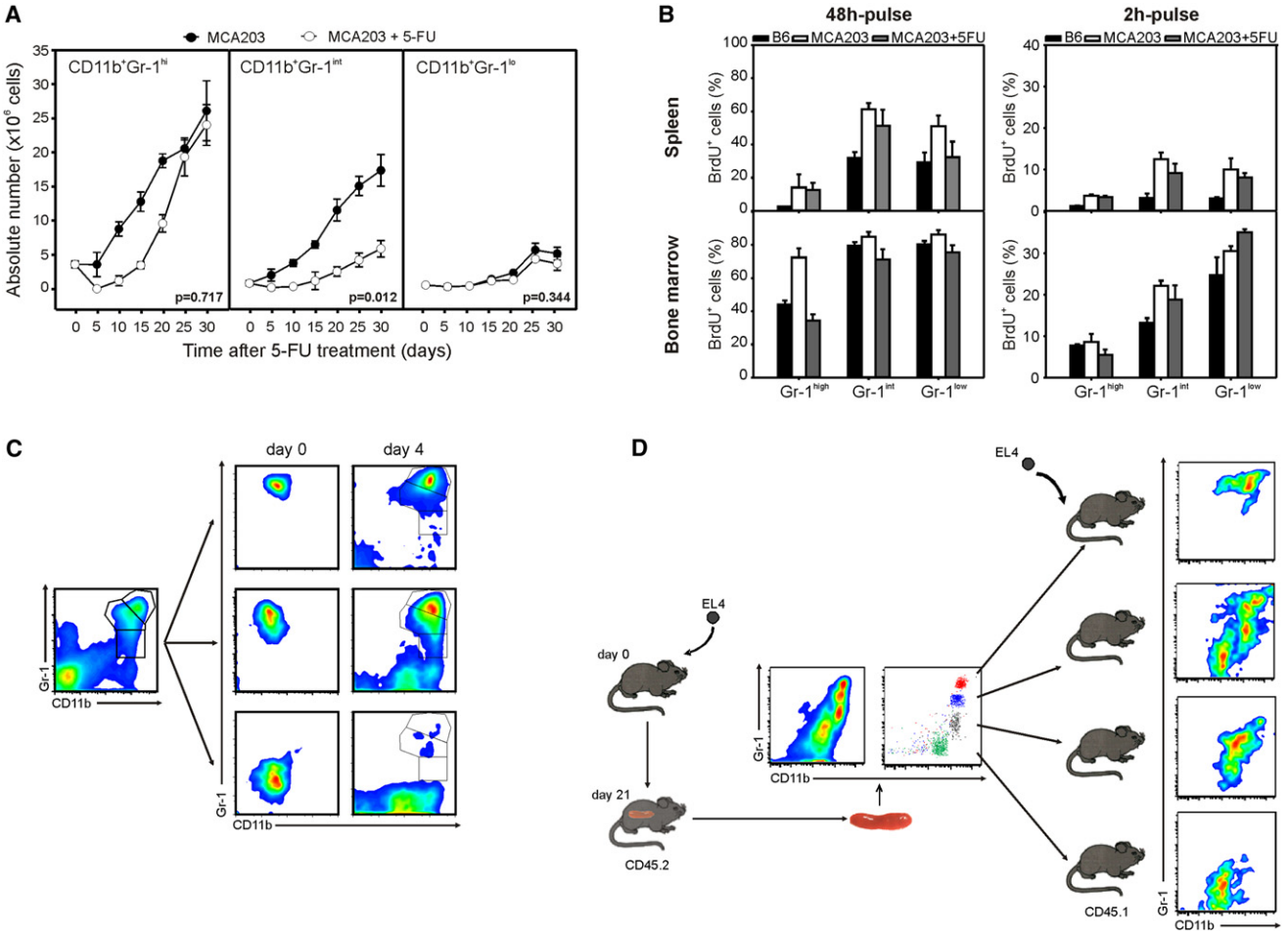

Figure 3. CD11b$^+$Gr-1^{int} Cells Comprise Highly Proliferating Myeloid Progenitors

(A) Kinetics of spleen repopulation of CD11b$^+$Gr-1^{hi}, CD11b$^+$Gr-1^{int} and CD11b$^+$Gr-1^{lo} cells after either 5-FU or PBS treatment. C57BL/6 mice were s.c. injected with 1 × 10^6 MCA203 sarcoma cells in the right flank. After 3 hr, they were treated with a single dose of 5-FU. Mice were sacrificed at different times after chemotherapy. Data are represented as mean ± SD (n = 3 mice) for each time point. Student's t test is reported for day 30.

(B) Proliferative potential of myeloid cell subsets in either spleen (upper panels) or bone marrow (lower panels) was assessed by means of BrdU incorporation, evaluated 48 hr (left panels) or 2 hr (right panels) after its in vivo inoculation. Data are represented as mean ± SE (n = 3 mice) of one representative experiment out of two independently performed experiments.

(C) Splenic CD11b$^+$ cells were FACS-sorted from the spleen of tumor-bearing mice and cultured for 4 days with GM-CSF (40 ng/ml) and IL-6 (40 ng/ml). Representative dot-plot of one of three independent experiments.

(D) Adult CD45.2 C57BL/6 mice were injected with 1 × 10^6 syngeneic EL4 mouse thymoma cells. CD11b$^+$Gr-1^{hi}, CD11b$^+$Gr-1^{int}, CD11b$^+$Gr-1^{lo}, and CD11b$^+$Gr-1$^-$ cells were FACS-sorted from the spleens of tumor-bearing mice 2 weeks following implantation. Then 1 × 10^6 sorted cells were adoptively transferred to adult CD45.1 C57BL/6 mice that had been implanted 1 week before with 1 × 10^6 EL4 cells. The phenotype of CD45.2 cells was analyzed 7 days after adoptive transfer by flow cytometry. Representative dot-plots (n = 4 mice/group).

See also Figure S3.

was not significantly altered within this cell population at such a late time point (Figure 3B), suggesting that the few CD11b$^+$Gr-1^{int} cells conserved their proliferative activity.

Proliferating hematopoietic stem cells and granulocyte/macrophage progenitors were recently shown to accumulate in the spleen of tumor-bearing mice (Cortez-Retamozo et al., 2012). However, these progenitors do not express lineage markers such as CD11b and Gr-1. Thus, we considered the possibility that tumors could also cause the splenic expansion of committed precursors with high proliferative potential.

Purified splenic CD11b$^+$Gr-1^{int} cells are phenotypically homogeneous (i.e., they all express Ly6C and F4/80 monocyte/macrophage markers), bear morphological features of both immature myeloid cells (i.e., doughnut nuclei and CD117 expression; Biermann et al., 1999; Ogawa et al., 1991) and Ly6C^{hi}CCR2$^+$ inflammatory monocytes (Geissmann et al., 2003), and strongly suppress Ag-activated T lymphocytes (Figures S3Aand S3B). To test the potential of this cell fraction to reconstitute the myeloid descendants, we isolated CD11b$^+$Gr-1^{hi}, CD11b$^+$Gr-1^{int} and CD11b$^+$Gr-1^{lo} cells from the spleens of tumor-bearing mice and

cultured them with a combination of GM-CSF and IL-6, which we previously demonstrated to be sufficient to generate in vitro myeloid suppressors from bone marrow cells (Marigo et al., 2010; Sonda et al., 2011). As shown in Figure 3C, only the $CD11b^+Gr\text{-}1^{int}$ fraction was able to give rise to all the other $CD11b^+$ myeloid subsets. Of more importance, when we followed the fate of the same splenic cell subsets in vivo by using congenic markers, after injection into tumor-bearing recipients, only $CD11b^+Gr\text{-}1^{int}$ cells displayed the broadest spectrum of myeloid cell differentiation (Figure 3D). The same behavior could also be observed when cells were transferred to and traced in tumor-free mice (Figure S3C). Moreover, when $CD11b^+Gr\text{-}1^{hi}$, $CD11b^+Gr\text{-}1^{int}$, and $CD11b^+Gr\text{-}1^{lo}$ subsets were tested in a colony-forming unit (CFU) assay, small round colonies, mainly resembling CFU-M, could be detected only in $CD11b^+Gr\text{-}1^{int}$ agar cultures (Figure S3D). These observations led us to conclude that splenic $CD11b^+Gr\text{-}1^{int}$ cells comprise a specific population of inflammatory monocytes with multipotent progenitor features that, although partially committed, may contribute to myeloid replenishment in the spleen during tumor growth.

A Tolerogenic Environment in the Marginal Zone of the Spleen of Tumor-Bearing Hosts

When we performed immunostaining of the spleens for CD19 (lymphoid follicles rich in B cells), CD8 (T cell areas of white pulp), and Ly6C (as a marker of $CD11b^+Gr\text{-}1^{int}$ cells; Figure S4A), we noticed that $Ly6C^{hi}$ myeloid cells were mostly distributed within the marginal zone (MZ) and the outer layers of lymphoid follicles (Figures S4A and S4B), which have been described as the transit areas for memory $CD8^+$ T cells during response to infection (Khanna et al., 2007). The tumor induced an expansion of $Ly6C^+$ cells in the MZ, which appeared hyperplastic (Figure S4B, lower panel). Indeed, although B cell follicles accounted for almost half of the spleen in tumor-free mice, their relative area was strongly reduced in the spleens of tumor-bearing mice, due to the accumulation of myeloid cells (Figure 4A). 5-FU administration reestablished a normal cytoarchitecture in the spleens of tumor-bearing hosts by reducing myeloid cell expansion and consequently MZ hyperplasia. A cytofluorimetric analysis of $CD11b^+Gr\text{-}1^+$ splenocytes confirmed the differences observed by confocal microscopy (Figure 4B; Figure S4C).

Given the relevance of the CCR2 receptor in the inflammatory monocyte egress from bone marrow and recruitment to peripheral tissues under several pathological conditions, including tumor growth (Lesokhin et al., 2011, 2012; Leuschner et al., 2011; Shi and Pamer, 2011), we speculated that it might also play a role in the accumulation of $Ly6C^+$ cells in the MZ of the spleen. Of interest, when we analyzed spleen sections from $Ccr2^{-/-}$ and $Ccl2^{-/-}$ mice, we observed a normal cytoarchitecture and reduced myeloid accumulation despite the presence of the tumor (Figures 4A and 4B; Figures S4B and S4C). CCR2 and CCL2 knockout phenocopied 5-FU treatment in terms of both myeloid subset reduction and the ability to completely abrogate the immunosuppressive influence exerted by the splenic environment on Ag-specific $CD8^+$ T lymphocyte proliferation (Figure 4C).

Spontaneous CCL2 production by whole splenocytes is strongly increased in tumor-bearing mice, and isolated $CD11b^+$ cells clearly participate in the increase in chemokine production, likely creating a positive feedback loop that enhances monocyte recruitment to this organ (Figure 4D). Nestin-positive bone marrow mesenchymal stem cells were recently shown to release CCL2 rapidly in response to circulating toll-like receptor ligands or bacterial infection, and cause inflammatory monocyte trafficking from the bone marrow into the bloodstream (Shi et al., 2011). In addition to myeloid $Ly6C^+$ cells (Figure S4D), $Nestin^+$ splenocytes (but not $CD31^+$ endothelial cells) also express CCL2 in the spleen of tumor-bearing hosts, as shown in Figure 4E and Figure S4E. These cells were rarely detectable in the spleen of tumor-free mice (not shown).

Splenic Immature Monocytes Cross-Present Tumor Ag and Tolerize $CD8^+$ T Lymphocytes

The relevant expansion of $CD11b^+Gr\text{-}1^{int}Ly6C^{hi}$ cells in the spleen makes a direct interplay with $CD8^+$ T cells highly probable, and indeed, recurrent contacts between these two cell types were observed. In particular, we noticed that $Ly6C^+CD8^+$ T cells, which display a $CD62L^+CD44^+CD127^+CD25^-$ T central memory phenotype (T_{CM}) and a strong cytotoxic activity (Figure S5A), are preferentially surrounded by $Ly6C^+$ (monocytes) rather than $Ly6G^+$ (granulocytes) cells, in contrast to $Ly6C^-CD8^+$ naïve T lymphocytes (Figures 5A–5E; Figures S5B and S5C). Memory $CD8^+$ T lymphocytes could also be tracked as $CD11b^-Gr\text{-}1^{int}Ly6C^{hi}$ cells (Figure S5A; in these $CD8^+$ T lymphocytes, Gr-1 expression is entirely due to the presence of the Ly6C), and their percentages in the spleen were inversely related to the percentages of $CD11b^+Gr\text{-}1^{int}Ly6C^{hi}$ monocytes during tumor development (Figures S2C, S2D and, S5D), suggesting that these two cell types may interfere with each other for spleen occupancy. We speculated that the prolonged and selective loss of $CD11b^+Gr\text{-}1^{int}Ly6C^{hi}$ cells in the spleen following 5-FU treatment (Figure 3A) could be explained by the occupancy of the MZ by drug-resistant $Ly6C^+Gr\text{-}1^{int}CD8^+$ T cells, which are poorly proliferating (Figure S5E) and thus are not likely affected by a low-dose chemotherapy. Indeed, in $Rag2^{-/-}\gamma_c^{-/-}$ immunodeficient mice, which lack B and T lymphocytes, myeloid cell subsets were largely unaffected 30 days after 5-FU treatment, in comparison with wild-type littermates (Figures S5F and S5G). Moreover, when $Ly6C^+Gr\text{-}1^{int}CD8^+$ T cells, but not $CD4^+$ and $Ly6C^-CD8^+$ (naïve) T cells, were transferred to tumor-bearing $Rag2^{-/-}\gamma_c^{-/-}$ recipients following low-dose chemotherapy, the myeloid cell numbers were significantly reduced, highlighting the role of memory $CD8^+$ T lymphocytes in hampering myeloid expansion and spleen replenishment (Figure 5F).

It has been suggested that splenic $CD11b^+Gr\text{-}1^+$ cells can process and present tumor Ags (Kusmartsev et al., 2005). We hypothesized that contacts between $CD11b^+Ly6C^{hi}$ cells and memory $CD8^+$ T lymphocytes in the spleen could result in the direct cross-presentation of tumor Ags in a tolerogenic manner. Indeed, splenic $CD11b^+$ cells isolated from OVA-EG7 tumor-bearing mice initially primed OVA-specific $CD8^+$ T lymphocytes to proliferate in the absence of the exogenous peptide (Figure 5G, left panel), whereas $CD11b^+$ splenocytes from mice bearing the same tumor lacking OVA Ag (EL4) were inactive, indicating that the proper OVA peptide was processed and presented. However, after the first stimulation by $CD11b^+$ cells,

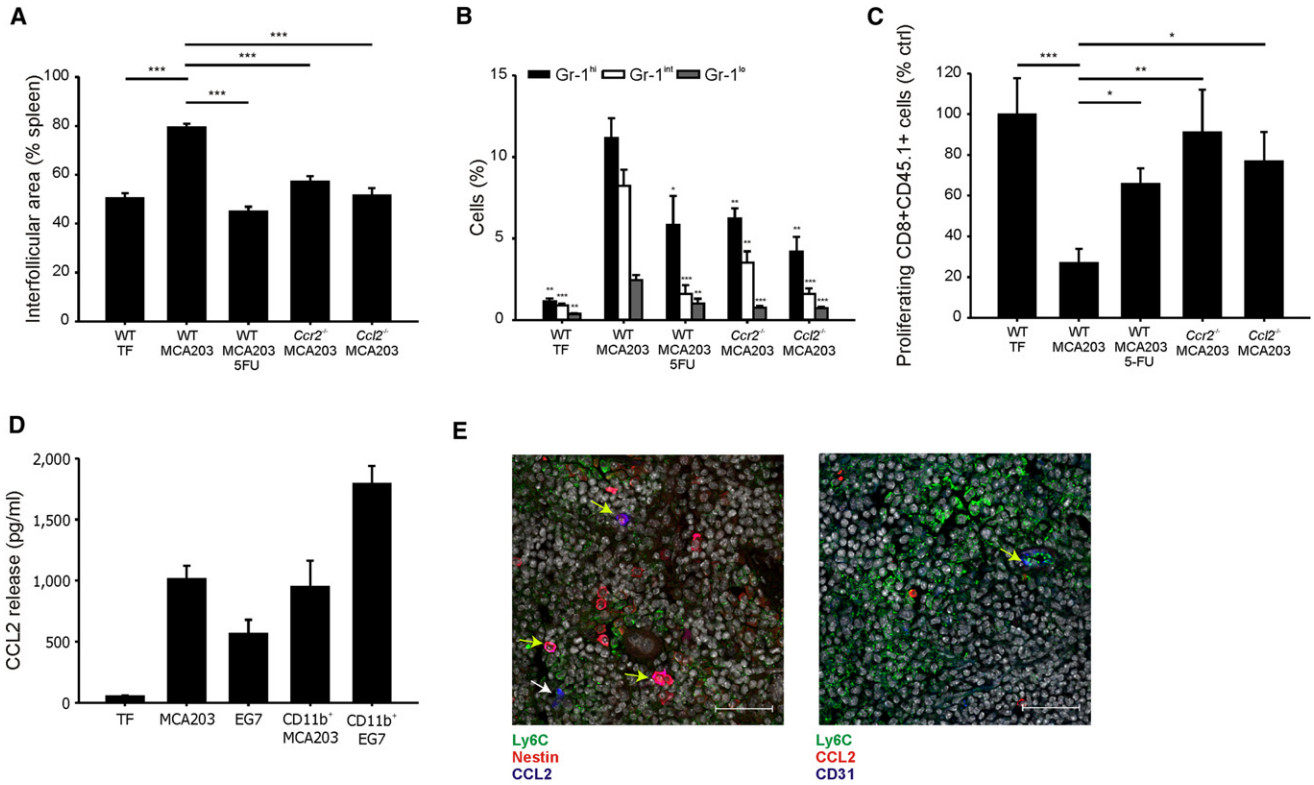

Figure 4. The CCL2/CCR2 Axis Is Crucial for CD11b$^+$Gr-1^{int}Ly6C^{hi} Monocyte Recruitment to the Spleen

(A) Interfollicular area was calculated as the percentage of the whole spleen section by collecting 30 images from at least three different MCA203-bearing mice for each of the indicated groups. Mean ± SD.

(B) Splenic distribution of myeloid subsets, determined by FACS staining of splenocytes for CD11b and Gr-1 markers in tumor-free and MCA203 tumor-bearing mice from the indicated groups. Tumor-bearing mice were sacrificed 25 days after tumor injection. Data represent mean ± SE of three separate experiments (n = 4 mice/group for each experiment). Comparisons among myeloid subsets from either tumor-free or MCA203 tumor-bearing mice were performed with Student's t test.

(C) CFSE-labeled, OVA-specific CD8$^+$ T cells were cultured in the presence of splenocytes from the indicated experimental groups. Proliferation was compared and normalized to MLPC setup with splenocytes from tumor-free mice. Data represent mean ± SE of three independent experiments (n = 3 mice/group for each experiment). Statistical analysis was performed with Student's t test.

(D) CCL2 release was measured in the supernatants of 48 hr cultures of either total or CD11b$^+$-sorted splenocytes, isolated from either tumor-free or (MCA203, EG7) tumor-bearing mice, by ELISA. Data are presented as mean ± SE of three independent experiments.

(E) Immunofluorescence was performed on thin spleen cryosections from MCA203 tumor-bearing mice. Scale bars are 50 μm. In the left panel, yellow arrows point to Nestin$^+$CCL2$^+$ cells and white arrows point to Ly6C$^+$CCL2$^+$ cells. In the right panel, arrowheads point to CD31$^+$CCL2$^-$ cells.

See also Figure S4.

the same OVA-specific T lymphocytes were no longer able to respond to the cognate Ag upon restimulation with the Ag presented by Ag-presenting cells (Figure 5G, right panel). We observed that cross-presentation and tolerance induction involved, at least partially, the uptake of tumor Ags from blood circulating exosomes, as the exosome inhibitor dimethyl-amiloride (DMA) (Chalmin et al., 2010) was shown to limit the extent of both cross-presentation and tolerance when administered in vivo to tumor-bearing mice. Intriguingly, Ag cross-presentation and consequently cross-tolerance were abrogated in *Ccr2*$^{-/-}$ mice, indicating that splenic CD11b$^+$CCR2$^+$ myeloid cells are responsible for cross-tolerization of peripheral CTLs (Figure 5G). This functional behavior was fully mirrored by the ability of splenic CD11b$^+$ cells to cross-present tumor-derived OVA peptide on MHC I class molecules on their surface, since either DMA treatment or CCR2 deficiency strongly impaired Ag presentation (Figure 5H). CD11b$^+$Gr-1^{int}Ly6C^{hi}CCR2$^+$ monocytes positive for MHC I-OVA peptide complexes were also detected among tumor-infiltrating leukocytes, but were not observed in tumor-draining lymph nodes, bone marrow, or blood (data not shown). The splenectomy experiments described above thus indicate that even if tumor Ag presentation occurs within the tumor environment, it is not sufficient to induce Ag-specific tolerance.

CCL2 Serum Levels Are Predictive of the Clinical Outcome in Patients Responding to Cancer Vaccination

Using *Ccl2*$^{-/-}$ mice, we noticed that CCL2 deficiency helped the endogenous immune response to eradicate tumor cells exclusively when mice were implanted with highly antigenic tumor cells, as in the case of 4T1-HA mammary carcinoma (Figure 6A). To investigate whether this observation could be relevant for clinical purposes, we assessed CCL2 serum levels in patients

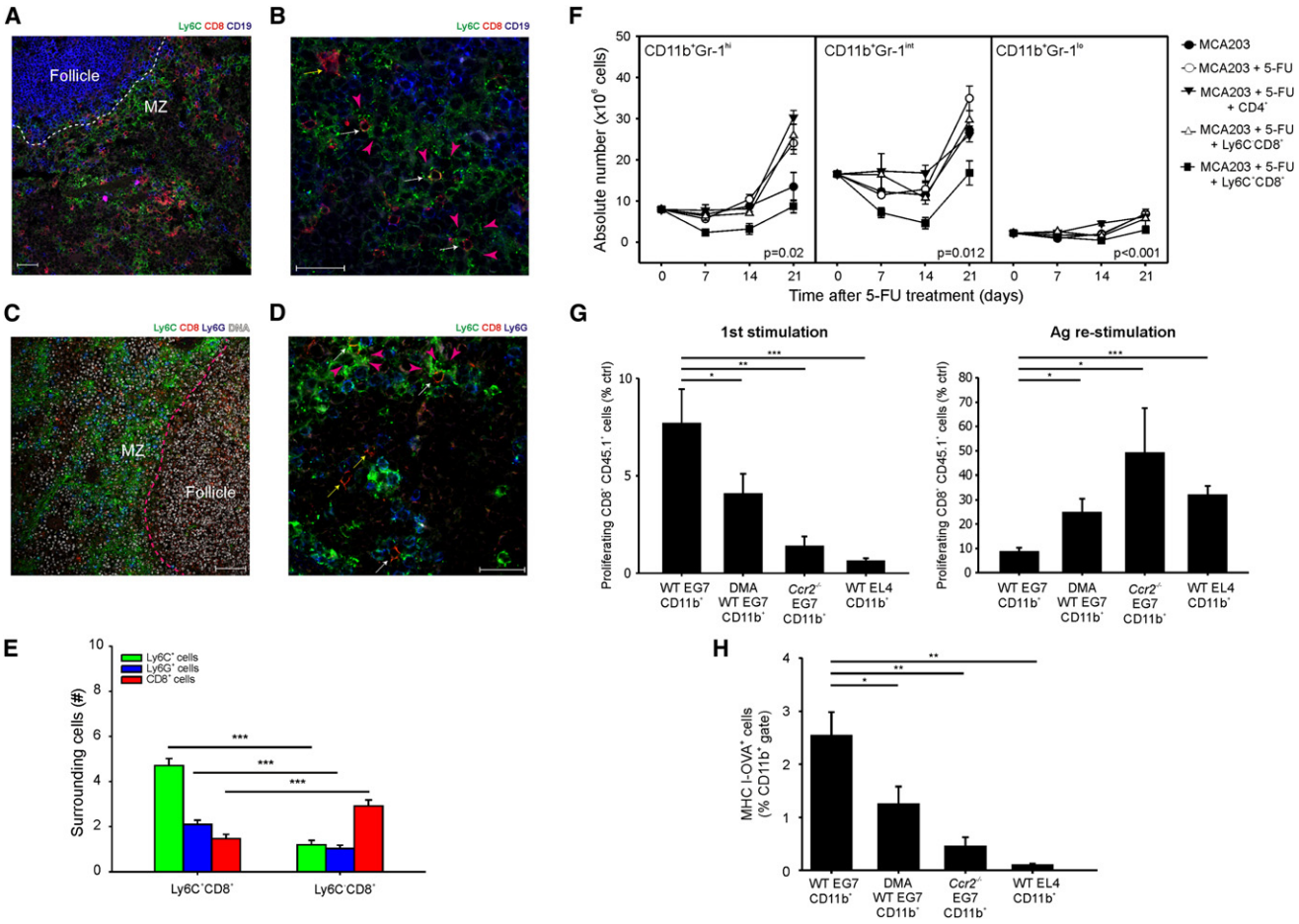

Figure 5. Splenic CD11b$^+$Ly6C^{hi} Monocytes Are in Close Contact with and Cross-Present Tumor Ags to CD8$^+$ T Cells

(A–D) Distribution of Ly6C$^+$CD8$^+$ (memory T lymphocytes), Ly6C$^+$CD8$^-$ (monocytes), and Ly6C$^-$CD8$^+$ (naïve T lymphocytes) cells in the spleen of MCA203 tumor-bearing mice. White arrows point to Ly6C$^+$CD8$^+$ cells, yellow arrows point to Ly6C$^+$CD8$^-$ cells, and pink arrowheads point to Ly6C$^+$ myeloid cells. Scale bars are 50 μm for (A) and (C), and 25 μm for (B) and (D).

(E) The numbers of Ly6C$^+$Ly6G$^-$CD8$^-$ (green bars), Ly6C$^{+/-}$Ly6G$^+$CD8$^-$ (blue bars), and Ly6C$^-$Ly6G$^-$CD8$^+$ (red bars) cells surrounding either Ly6C$^+$CD8$^+$ or Ly6C$^-$CD8$^+$ lymphocytes were calculated as described in Figure S5B. Data are presented as mean ± SE (n = 70 cells/group). Statistical analysis was performed with Student's t test.

(F) *Rag2*$^{-/-}\gamma_c^{-/-}$ mice were s.c. implanted with MCA203 sarcoma cells and after 3 hr were treated with a single dose of 5-FU. After 2 days, 10^6 of CD8$^+$Ly6C$^+$, CD8$^+$Ly6C$^-$, or CD4$^+$ T cells were injected i.v. in the same mice. *Rag2*$^{-/-}\gamma_c^{-/-}$ mice were sacrificed at different time points after chemotherapeutic treatment. Statistical analysis was performed with Student's t test; p values for the comparison between MCA203 + 5-FU and MCA203 + 5FU + CD8$^+$Ly6C$^+$ groups on day 21 are shown.

(G) CD11b$^+$ cells were isolated from the spleen of either wild-type or *Ccr2*$^{-/-}$ EG7 or EL4 tumor-bearing mice and cultured for 3 days together with CFSE-labeled, OVA-specific CD8$^+$ T cells (left panel) in the absence of exogenous peptide. The values reported refer to cultures with 24% CD11b$^+$ cells on total cell counts. When required, mice received daily i.p. injection of DMA for 1 week before sacrifice. OVA-specific CD8$^+$ T cell proliferation, measured by CFSE dilution, was normalized to the values obtained in the presence of OVA peptide-pulsed feeder cells (ctrl). Lymphocytes from the former cultures were restimulated with Ag-pulsed feeder cells (right panel), and CFSE dilution was measured 3 days after the second stimulation. OVA-specific CD8$^+$ T cell proliferation was normalized to the values obtained in control cultures. Data represent mean ± SE of three independent experiments (n = 3 mice/group for each experiment). Statistical analysis for the indicated comparisons was performed with Student's t test.

(H) MHC class I-OVA complexes were labeled on splenic CD11b$^+$ cells used in the previous cultures. Data represent mean ± SE of three independent experiments (n = 3 mice/group for each experiment). Statistical analysis for the indicated comparisons was performed with Student's t test.

See also Figure S5.

who had undergone active immunotherapy. We considered patients with renal cell carcinoma (RCC) and colorectal cancer (CRC) who were enrolled in phase I/II studies and had received two therapeutic vaccines, IMA901 and IMA910, respectively, which consist of naturally presented tumor-associated peptides (TUMAPs; Walter et al., 2012). In these trials, CCL2 serum levels measured prior to vaccination were used to classify the patients into two subgroups. There was no difference in the number of multipeptide immune responders versus nonresponders among patients with either low or high CCL2 serum levels. In

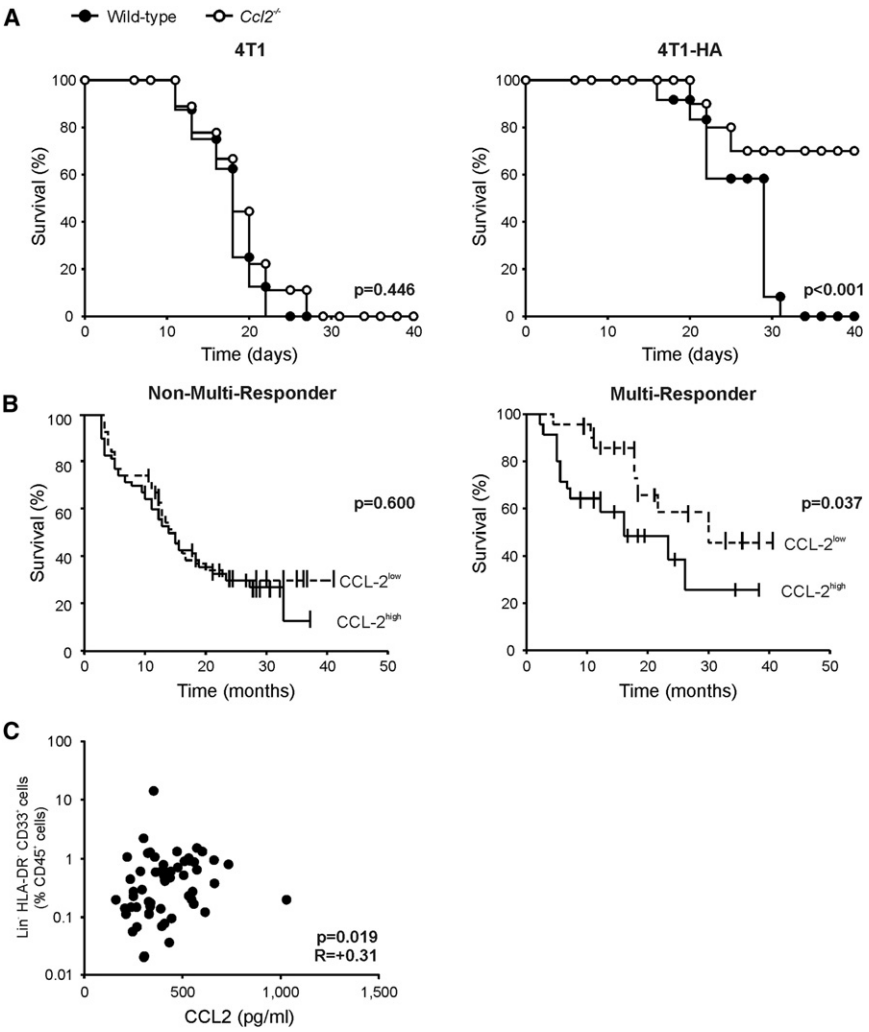

Figure 6. CCL2 Serum Levels Correlate with Myeloid Cell Accumulation and Response to Immunotherapy in Renal Cell and Colorectal Cancer Patients

(A) BALB/c (left panel) or *Ccl2*$^{-/-}$ (right panel) mice were subcutaneously injected with either 4T1 or 4T1-HA cell lines. Mice survival (n = 12 mice/group) was analyzed by means of the Kaplan-Meier method.

(B) Combined analysis of OS in RCC and CRC patients of two immunotherapy trials with multipeptide vaccines. Shown is a survival analysis of immune- and CCL2-evaluable patients without (left panel, n = 88) or with (right panel, n = 48) vaccine-induced multipeptide responses, grouped by CCL2 levels above (solid line) or below (dashed line) the median value.

(C) Spearman's rank correlation analysis of serum CCL2 and Lin$^-$HLA-DR$^-$CD33$^+$ myeloid cell levels among PBMCs, determined prior to immunotherapy, in individual RCC patients (● represents individual patients, n = 58).

See also Figure S6 and Table S1.

agreement with our preclinical results, however, only in patients who developed multiple T cell responses to peptide vaccination were high CCL2 serum levels predictive of worse prognosis in terms of OS (Figure 6B). Pretreatment levels of distinct subsets of myeloid cells were significantly increased in the blood of these patients relative to healthy controls (Walter et al., 2012). Of interest, we observed that, at least in the patients with RCC, CCL2 serum levels directly correlated with peripheral blood mononuclear cell (PBMC) frequencies of an immature Lin$^-$HLA-DR$^-$CD33$^+$ myeloid cell subset (Figure 6C), which was recently described as highly proliferating, strongly immunosuppressive, and predictive of disease progression in CRC and breast cancer (Solito et al., 2011). Correlations of pretreatment CCL2 serum levels with other human myelomonocytic cell subsets were less robust (Figure S6; Table S1).

DISCUSSION

It has recently become clear that the immune system has a crucial role in modulating tumor progression and response to therapy. Numerous anticancer agents that were used in the past for their cytotoxic properties can modulate the host immune system, and sometimes induce a long-term protective memory T cell response. We unveiled a previously unknown environment in the MZ of the spleen of tumor-bearing hosts in which immunoregulatory monocytes coexist with memory CD8$^+$ T cells. These multipotent inflammatory monocytes are recruited to the MZ by CCL2 and cross-tolerize Ag-specific lymphocytes, at least in part by sampling tumor-released exosomes. Because of the high proliferative rate of these monocytes, some chemotherapeutic agents are very active in depleting them while sparing poorly proliferating lymphocytes, and the subsequent occupation of the splenic environment by CD8$^+$ T cells hampers the replenishment of myeloid cells following chemotherapy. The contribution of both depletion of regulatory T lymphocytes and induction of immunogenic cancer cell death by chemotherapy to the described phenomena was negligible. These findings provide a rational explanation for the often empirical and paradoxical observation that chemotherapy is one of the most effective adjuvants for ACT, and suggest that an extensive lympho-myeloablation before ACT is likely unnecessary or even detrimental. We propose that our findings lay the foundation for defining both the dose and class of chemotherapeutic agents that will have the greatest impact on ACT.

Our data depict two scenarios for future approaches aimed at enhancing ACT therapeutic impact. First, metronomic chemotherapy treatment could be exploited to maintain a long-term contraction of the immunosuppressive monocyte expansion. Metronomic chemotherapy was originally developed to

overcome drug resistance; however, low-dose cyclophosphomide was reported to limit regulatory T lymphocytes and increase innate immune response (Ghiringhelli et al., 2004; Ghiringhelli et al., 2007). Second, chemotherapeutic drugs with distinct immunomodulatory properties could be combined with cancer immunotherapy. As recently reviewed, in fact, some agents can induce immunogenic cancer-cell death (Galluzzi et al., 2012; Zitvogel et al., 2011). Of interest, many of the drugs that alter the splenic immunoregulatory environment do not affect the immunogenic context of cancer death. Future developments could thus be based on optimizing low-dose chemotherapy to eliminate immunosuppressive monocytes before administering a specific drug that is able to elicit immunogenic death and increase tumor-Ag uptake by APCs present in the tumor microenvironment.

A prediction based on our data is that adoptive transfer of Ag-specific $CD8^+$ T_{CM} would be the best choice for passive immunotherapy, because these cells may be able to interfere with myeloid cell expansion in the spleen following chemotherapy. Indeed, this hypothesis is supported by some published experimental data showing that adoptively transferred $CD8^+$ T_{CM} were more potent than effector memory $CD8^+$ T cells specific for a melanoma Ag in causing the eradication of large established tumors (Klebanoff et al., 2005). Of interest, this greater efficacy achieved with $CD8^+$ T_{CM} was related to the ability of tumor-reactive T cells to traffic better to secondary lymphoid organs than to tumor sites (Klebanoff et al., 2005).

In mouse studies, a relationship between the extent of lympho- and myelodepletion and the magnitude of the in vivo antitumor effect of the transferred cells seemed to emerge (Wrzesinski et al., 2010; Wrzesinski and Restifo, 2005). However, our data suggest that myeloablative chemotherapy may not be necessary for an optimal adjuvant activity of ACT. In the case of 5-FU, for example, relatively low doses of drugs were administered (40 mg/kg versus 100 mg/kg, which is commonly used in preconditioning regimens). On the basis of our data, we can hypothesize that high-dose chemotherapy can be either detrimental or beneficial depending on its prevailing effects on the myeloid or lymphoid compartment.

CCL2 has multiple roles in cancer progression. Gr-1^+ inflammatory monocytes were not found at primary mammary tumor lesions, and instead were preferentially recruited by CCL2 to pulmonary metastases to assist tumor spreading. Moreover, CCL2 expression and macrophage infiltration were shown to correlate with poor prognosis and metastatic disease in human breast cancer (Qian et al., 2011). Recent evidence, however, shows that the antitumor effects of CCL2 blockade in vivo are dependent on the host immune system. In fact, administration of anti-CCL2 monoclonal antibody (mAb) induced tumor-specific $CD8^+$ T cell activation and expansion rather than a decrease in the number of tumor-associated macrophages (Fridlender et al., 2010, 2011). Moreover, the antitumor effects of CCL2 blockade was completely lost in immunodeficient mice or after $CD8^+$ T cell depletion, clearly enforcing the concept that CCL2 blockade reestablishes the immune response in the tumor-bearing host, in similarity to the data we obtained with either 5-FU administration or *ccl2*/*ccr2* gene knockout ablation. Moreover, we show here that CCL2 serum levels correlate with the expansion of immature myeloid cells in the blood of cancer patients, and, more importantly, with the clinical response to cancer vaccination in patients who develop broad immune responses to the tumor Ags present in the vaccine. The spleen is not easily accessible in patients, but our findings indicate that blood may be used to provide information relevant for the clinical outcomes of cancer immunotherapy.

EXPERIMENTAL PROCEDURES

Splenectomy

The abdominal cavity of mice under general anesthesia (Rompum and Zoletil) was opened and the spleen vessels were cauterized. The spleen was carefully removed and placed in cold phosphate-buffered saline (PBS) solution. For control experiments, the abdomen was opened but the spleen was not removed (sham surgery).

In Vivo Tolerance Assay

C57BL/6 mice were either splenectomized or subjected to sham surgery. After 10 days, 0.5×10^6 EG7 cells were injected subcutaneously (s.c.) into the flank of $CD45.2^+$ mice. Seven days later, the mice were adoptively transferred with 2×10^7 splenocytes derived from OT-1 transgenic mice ($CD45.1^+$), corresponding approximately to 5×10^6 OVA-specific $CD8^+$ T cells. Two weeks after tumor injection, the animals were euthanized and cells from lymph nodes and spleens were tested by ELISpot and intracytoplasmic cytokine staining (ICS) as previously described (Dolcetti et al., 2010a, 2010b; Marigo et al., 2010). Where indicated, tumor-bearing mice were s.c. vaccinated with 1×10^6 $OVA_{257-264}$ peptide-pulsed DCs 2 days post lymphocyte transfer (Dolcetti et al., 2010a). When Ag-experienced $CD8^+$ T cells were adoptively transferred, OT-1 splenocytes were cultured with the cognate peptide and 20 U/ml IL-2 for 5 days (>97% $CD8^+$ cells after stimulation). Similar experiments were performed on a BALB/c background, with s.c. injection of 1×10^6 4T1-HA tumor cells 10 days after surgery. After 20 days, the mice were transferred with 2×10^7 splenocytes derived from CL4 mice and were vaccinated with 1×10^6 $HA_{512-520}$-peptide pulsed DCs 2 days after ACT. The mice were sacrificed at day 26 and lymph nodes were stimulated as previously described.

ACT

ACT in mouse transplantable tumor models was performed in $Rag2^{-/-}\gamma_c^{-/-}$ and C57BL/6 mice after subcutaneous challenge with 1×10^6 tumor cells. When the tumor volume was ~200 mm^3, the mice were treated with 40 mg/kg 5-FU. After 3 days, 5×10^6 Ag-specific CTLs were intravenously (i.v.) injected. At the time of CTL transfer, mice were intramuscularly (i.m.) injected with 5×10^8 PFU of a recombinant adenoviral vector coding for the relevant Ag recognized by transferred T cells and then intraperitoneally (i.p.) treated with 30,000 IU rIL-2 twice a day for 3 consecutive days. Blind measurements of tumor mass were carried out with the use of digital calipers. Mice were euthanized when the tumor volume reached 1,000 mm^3. In some experiments, OVA-specific $CD8^+$ T cells were administered to EG7-bearing recipients, as described previously (Molon et al., 2011).

Cell Isolation

$CD11b^+Gr\text{-}1^{hi}$ and $CD11b^+Gr\text{-}1^{int}$ cells were isolated with the use of Miltenyi Biotec antibodies and microbeads as previously described (Dolcetti et al., 2010a, 2010b). The purity of cell populations was evaluated by flow cytometry and exceeded 90%. For fluorescence-activated cell sorting (FACS) sorting, splenocytes were labeled with PERCP-Cy5.5 anti-CD11b and APC anti-Gr-1 mAb, and sorted to >98% purity with a FACSAria (BD) flow cytometer.

Cytotoxicity Assay

After 5 days, the cultures were tested for the ability to lyse an allogenic target (MLR) or target cells pulsed with a specific peptide (MLPC) in a 5 hr ^{51}Cr-release assay as previously described (Dolcetti et al., 2010a).

In Vitro Cross-Tolerance Assay

To evaluate myeloid-induced tolerance, $CD11b^+$ cells were immunomagnetically sorted from the spleens of EG7- or EL4-bearing mice and cultured, ranging from 24% to 3% of the whole culture, together with C57BL/6 and carboxyfluorescein succinimidyl ester (CFSE)-pulsed 1% OVA-specific splenocytes. $OVA_{257-264}$ peptide was added only to control cultures. After 3 days, proliferation was assessed by CFSE dilution in half of the cultures, and CTLs were recovered from the remaining cultures and plated with peptide-pulsed splenocytes for another 3 days. After 6 days from the initial culture, CFSE dilution was assessed in restimulated CTLs to evaluate the induction of tolerance. When required, EG7-tumor-bearing mice received daily i.p. injection of 1 μmol/kg DMA (Sigma-Aldrich) for 1 week before they were sacrificed.

Phase II Study of IMA901 in Renal Cell Cancer

IMA901 (Walter et al., 2012) is a therapeutic cancer vaccine based on the selection of naturally presented TUMAPs (nine HLA-A*02 and one HLA-DR binding). In the multicenter phase II study IMA901-202, 68 HLA-A*02-positive patients (intent-to-treat [ITT] group) with advanced clear-cell type RCC and documented progression during or after standard first-line therapy were randomized 1:1 to receive up to 17 intradermal vaccinations of IMA901 over 9 months, together with 75 μg granulocyte-macrophage colony-stimulating factor (GM-CSF) plus/minus a single infusion of cyclophosphamide (CY; 300 mg/m^2) 3 days before the first vaccination. A total of 64 patients were treated per protocol (PP). Blood for PBMCs isolation was collected at day −3, 1, 15, 22, and 36 relative to the first vaccination. Blood for serum analysis was collected at day −3.

Phase I/II Study of IMA910 in Colorectal Cancer

IMA910 is a peptide-based vaccine consisting of 10 HLA-A*02 binding and three HLA-DR binding TUMAPs presented on colorectal tumors and overexpressed relative to healthy tissues. The multicenter clinical phase I/II study IMA910-101 enrolled 92 HLA-A*02 ITT patients with advanced/metastatic CRC who were at least clinically stable after 12 weeks of first-line oxaliplatin-based therapy. The patients were infused with a single dose of CY (300 mg/m^2) 3 days prior to first vaccination and thereafter were repeatedly immunized intradermally (up to 16 vaccinations over 8 months) with IMA910 in combination with GM-CSF (75 μg, cohort 1; n = 66) or, in a second cohort, with GM-CSF plus topically applied imiquimod (2 × 12.5 mg, cohort 2; n = 26) as an additional adjuvant. A total of 82 patients were treated PP. Blood for PBMC isolation was collected at days −3, 1, 8, 15, 22, 36, and 57 relative to the first vaccination. Blood for serum analysis was collected at days −42 to −4.

Both clinical studies (IMA901-202 and IMA910-101) were conducted in accordance with the Declaration of Helsinki, current International Conference on Harmonisation of Technical Requirements for Registration of Pharmaceuticals for Human Use (ICH) guidelines, and all applicable regulatory and ethical requirements. Approvals by the relevant Institutional Review Boards were given and all subjects provided written informed consent before study-related procedures were performed.

Statistics

A two-tailed Student's t test or Wilcoxon's test was used to compare data sets, with an α-level of 0.05 (in the figures, significance is indicated as * $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$). A Kaplan-Meier survival analysis was performed for the comparison of survival curves. An unpaired, two-sided Welch's t test was used to test the association of serum CCL2 levels with T cell responses in both clinical trials. Because CCL2 was measured using different assays in both trials, differences between RCC and CRC CCL2 serum values may be due to differences in serum levels between the two diseases, or to differences between the two assays. To assess the influence of CCL2 serum levels on OS in a combined analysis of RCC and CRC patients (PP populations), we dichotomized continuous serum levels within each tumor entity by cutting at the medians of the respective ITT populations (median CCL2 RCC 396.5 pg/ml, CRC 1196.6 pg/ml) and assigning every patient to the $CCL2^{low}$ or $CCL2^{high}$ subgroup. We performed OS analyses using R (GNU) programming language version 2.14.2 with the "coin" package. We conducted a stratified log-rank test to assess the difference in OS between $CCL2^{low}$ and $CCL2^{high}$ patients using surv_test. Each trial (RCC or CRC) was included as a stratification factor to calculate the p values within multipeptide-responders and nonmultipeptide responders (PP). The correlation between CCL2 and MDSC levels was analyzed with Spearman's rank correlation. Kaplan-Meier curves and correlation analyses were generated with GraphPad Prism 5 software.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Extended Experimental Procedures, six figures, and one table and can be found with this article online at http://dx.doi.org/10.1016/j.celrep.2012.08.006.

LICENSING INFORMATION

ACKNOWLEDGMENTS

We thank Arben Dedja, Serena Zilio, Martina Piccoli, Maurizio Buggio, and Barbara Molon for technical help and critical discussions. This work was supported by grants from the Italian Ministry of Health; Italian Ministry of Education, Universities, and Research; Italian Association for Cancer Research (AIRC, grants 6599 and 12182); and Fondazione Cassa di Risparmio di Verona, Vicenza, Belluno e Ancona. T.W. is co-founder and employee of and holds shares and stock options of Immatics Biotechnologies. S.W. is an employee of and holds stock options of Immatics Biotechnologies.

Received: January 24, 2012
Revised: July 9, 2012
Accepted: August 13, 2012
Published online: September 6, 2012

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