The Antitumor and Immunoadjuvant Effects of IFN-α in Combination with Recombinant Poxvirus Vaccines

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Abstract

Purpose: IFN-α is a pleiotropic cytokine possessing immunomodulatory properties that may improve the efficacy of therapeutic cancer vaccines. The aim of this study was to evaluate the effectiveness and compatibility of combining recombinant IFN-α with poxvirus vaccines targeting the human carcinoembryonic antigen (CEA) in murine models of colorectal and pancreatic adenocarcinomas, where CEA is a self-antigen.

Experimental Design: The phenotypic and functional effects of IFN-α were evaluated in the draining inguinal lymph nodes of tumor-free mice. We studied the effect of the site of IFN-α administration (local versus distal) on antigen-specific immune responses to poxvirus vaccination. Mechanistic studies were conducted to assess the efficacy of IFN-α and CEA-directed poxvirus vaccines in tumor-bearing CEA transgenic mice.

Results: We identified a dose and schedule of IFN-α that induced a locoregional expansion of the draining inguinal lymph nodes and improved cellular cytotoxicity (natural killer and CD8+ T cells) and antigen presentation. Suppression of the vaccinia virus was avoided by administering IFN-α distal to the site of vaccination. The combination of IFN-α and vaccine inhibited tumor growth, improved survival, and elicited CEA-specific CTL responses in mice with CEA+ adenocarcinomas. In mice with pancreatic tumors, IFN-α slowed tumor growth, induced CTL activity, and increased CD8+ tumor-infiltrating lymphocytes.

Conclusions: These data suggest that IFN-α can be used as a biological response modifier with antigen-directed poxvirus vaccines to yield significant therapeutic antitumor immune responses. This study provides the rationale and mechanistic insights to support a clinical trial of this immunotherapeutic strategy in patients with CEA-expressing carcinomas.
Translational Relevance

Tumor cells avoid immune surveillance by several mechanisms including down-regulation of the MHC, an observation that is inversely correlated with the degree of tumor differentiation and positively correlated with metastatic potential. This research uses IFN-α in a multimodal strategy to improve the efficacy of therapeutic cancer vaccines and render tumors more susceptible to immune cell recognition and lysis. IFN-α is a Food and Drug Administration–approved cytokine reported to up-regulate expression of the carcinoembryonic antigen (CEA) and MHC on tumor cells. The poxvirus vaccines, vaccinia and fowlpox, are novel vaccine platforms that have been used safely and effectively to elicit antigen-specific immune responses in cancer patients. This research addresses the need for combination strategies in clinical cancer immunotherapy by providing phenotypic, functional, and mechanistic data supporting the use of IFN-α as an immune adjuvant in conjunction with CEA-directed poxvirus vaccines in patients with CEA-expressing carcinomas.

Materials and Methods

Tumor cell lines and cell culture conditions. The murine pancreatic adenocarcinoma cell line Panc02 was generously provided by Dr. Michael A. Hollingsworth (University of Nebraska Medical Center, Omaha, NE). The Panc02 cell line was established through the induction of pancreatic tumors with 3-methyl-cholanthrene and serial subcutaneous transplantation in C57BL/6 mice (31). The MC38 murine colon carcinoma cell line was supplied by Dr. Steven Rosenberg (National Cancer Institute, Bethesda, MD). The CEA-expressing Panc02 cells (Panc02.CEA) and MC38 cells (MC38.CEA) were produced by transducing the human CEA gene using the retroviral expression vector pBNC as previously described (32).

Functional assays for lymphocytes were carried out in RPMI 1640 containing 15 mmol/L HEPES (pH 7.4), 10% heat-inactivated fetal bovine serum, 2 mmol/L l-glutamine, 0.1 mmol/L nonessential amino acids, 1 mmol/L sodium pyruvate, 50 units/mL G418 sulfate, and 50 μmol/L β-mercaptoethanol. All cells were maintained in a humidified incubator at 37°C in 5% CO2:95% air atmosphere. Unless otherwise indicated, all media and their components were purchased from Mediatech, Inc.

Animal care and use. All mice were housed in microisolator cages under pathogen-free conditions in accordance with the procedures outlined in The Guide for Care and Use of Laboratory Animals (National Research Council). Female C57BL/6 mice (H-2b) were purchased from Taconic Farms. Mice expressing the transgene for human CEA (CEA.Tg) were generously provided by Dr. John Shively (City of Hope, Duarte, CA). The mice were originally generated by microinjecting a 32.6-kb AarII restriction fragment containing the entire human CEA genomic region into a pronucleus of C57BL/6 zygotes (33). Homozygosity for CEA expression was tested and verified using PCR analysis of DNA isolated from the tails of progeny mice (34).

Vaccines, adjuvants, and injection schema. Recombinant murine IFN-α was purchased from PBL Biomedical Laboratories and contained ≤0.1 unit/μg of endotoxin. Consistent with its clinical use, IFN-α was administered in our studies s.c. thrice a week (MWF). Recombinant vaccinia (rV) and recombinant fowlpox (rF) vectors that express the transgenes for CEA and a triad of T-cell costimulatory molecules (TRICOM) were administered on the right inner thigh (s.c., ventral surface) at 106 plaque-forming units (pfu) admixed with 107 pfu of the recombinant fowlpox virus expressing murine GM-CSF as previously described (21, 24, 25, 35). In all immune and antitumor studies in which IFN-α was combined with the poxvirus vaccines, a 1-wk course of IFN-α (50,000 IU/injections, 3 × a week, MWF) was initiated on the same day as vaccination with either vaccinia or fowlpox (Monday). As depicted in Supplementary Fig. S1, locally administered IFN-α was given at the site of vaccination (s.c., right, ventral surface) whereas distally administered IFN-α was given on the left side of the lower back (s.c., left, dorsal surface).

In the antitumor studies, 6- to 8-wk-old CEA.Tg mice were injected on the lower back (s.c., right, dorsal surface) with either 3 × 105 MC38.CEA or 1 × 106 Panc02.CEA tumor cells in 100 μL of HBSS (Supplementary Fig. S1). When tumors reached 0.3 to 0.6 cm3 (1 and 3 wk after tumor challenge for MC38.CEA and Panc02.CEA tumors, respectively), mice were randomized to one of six treatment groups: (a) untreated (controls), (b) non-CEA vaccine (105 pfu rV/CEA-TRICOM + 107 pfu rF-GM-CSF), (c) CEA vaccine (105 pfu rF/CEA-TRICOM + 107 pfu rF-GM-CSF), (d) IFN-α (50,000 IU/mouse, 3 × a week, alternating weeks), (e) IFN-α + non-CEA vaccine, and (f) IFN-α + CEA vaccine. Tumor volumes were measured twice per week with digital calipers. The experimental end point for survival was defined as the time point at which the tumor volume reached 2 cm3, whereupon the mice were euthanized.

Phenotypic analyses. Flow cytometry was used in four experiments to conduct phenotypic analyses. In the first experiment, inguinal lymph node cells were isolated from mice 24 h after the last injection of IFN-α (0-50,000 IU/mouse, three injections). The lymph node cells were stained with conjugated antibodies against CD3, CD4, CD8, CD25, CD11c, I-Aβ, CD19, and NK1.1. In the second experiment, proliferating cultures of MC38.CEA and Panc02.CEA cells were treated with titrating doses of IFN-α (0-1,000 IU/mL) for 48 h. Following treatment, the cells were stained for H-2κB, H-2κD, CD80 (B7-1), and CD66 (CEA). In the third experiment, the in vivo tumor cell surface phenotype was studied in mice following a 2-wk course of IFN-α (50,000 IU/mouse, 3 × a week). The mice were sacrificed and their tumors were prepared and
stained for expression of H-2Kb, H-2Db, CD80 (B7-1), and CD66 (CEA). In the experiment, the spleens, inguinal lymph nodes, and tumor infiltrates of mice with Panc02.CEA tumors were analyzed for CD3, CD4, CD8, NK1.1, Gr-1, CD25, and I-Ab expression following a 2-wk course of IFN-α (50,000 IU/mouse, 3× a week). Intracellular expression of FoxP3, IFN-γ, and granzyme B was measured using a BD Cytofix/Cytoperm Fixation/Permeabilization kit following the manufacturer’s recommendations (Becton Dickinson). In all in vitro experiments, the mice were euthanized 24 h after the last IFN-α treatment. All samples (10^5 cells per tube) were incubated with 1 μg of unlabeled antimonouse CD16/CD32 to block nonspecific binding to Fcγ receptors. Isotype control antibodies were matched for each fluorochrome and used to set gate cursors. All flow cytometry experiments were done using a BD LSR II (Becton Dickinson). Data are expressed as the percentage and number of cells positive for each marker and its mean fluorescence intensity.

**Mixed lymphocyte culture.** Draining inguinal lymph node cells from C57BL/6 mice were isolated 24 h after the last injection of IFN-α (50,000 IU/mouse, three injections). The lymph node cells were irradiated and cultured with splenic T cells isolated from naive BALB/c mice at a ratio of 1:5 (1 BALB/c T cell:5 C57BL/6 lymph node cells) in 10 mL for 5 d at 37°C. Viable BALB/c lymphocytes were recovered by centrifugation over lymphocyte separation media (JRH Bio) containing C.Viable BALB/c lymphocytes were used in alloreactive CTL assays.

**β-Galactosidase production assay.** In vitro, the cellular production of β-galactosidase (β-gal) protein was measured in MC38 cells following infection with rV-LacZ (0.01 multiplicity of infection) in the presence of increasing concentrations of IFN-α (0-100 IU/ml). After 24 h, MC-38 cells were lysed (lysis buffer containing 100 mmol/L Tris (pH 8.0), 100 mmol/L NaCl, and 0.5% NP40) and whole cell extracts were prepared. In vivo, C57BL/6 mice were vaccinated i.m. with rV-LacZ (10^7 pfu) in both quadriceps followed by administration of either vehicle or IFN-α (50,000 IU/mouse) for 3 consecutive days at the site of vaccination. On day 3, the mice were euthanized and whole cell extracts were prepared from the quadriceps muscles. In both experiments, the production of β-gal protein was measured by ELISA according to the manufacturer’s recommendations (Rockland Molecular Biochemicals).

**Lymphoproliferation assays.** To measure allospecific lymphoproliferative responses, splenocytes from naive BALB/c mice were enriched for T lymphocytes using magnetic murine pan B (B220) Dynabeads (Invitrogen Dynal AS) per manufacturer’s recommendations. Naive BALB/c T cells (2 × 10^5 per well) were incubated with irradiated lymph node cells (0-1 × 10^6 per well) from IFN-α–treated C57BL/6 mice for 4 d at 37°C in flat-bottomed 96-well plates. The plates were pulsed on day 3 with 1 μCi/well of [3H]thymidine (Amersham Corp.).

In vaccinated mice, antigen-specific proliferation assays were initiated 2 to 3 wk following the booster vaccination and performed in a cell culture incubator at 37°C as described previously (25). Splenic CD4+ lymphocytes from each treatment group were stimulated for 5 d. Three days after the booster, the mice were euthanized and whole cell extracts prepared. In both experiments, the production of β-gal protein was measured by ELISA according to the manufacturer’s recommendations (Rockland Molecular Biochemicals) for the last 18 h of incubation. Cultures were
harvested onto glass fiber filter mats (Wallac, Inc.) using a multiple automated sample harvester (Tomtec), and radioactivity was determined by liquid scintillation on a Perkin-Elmer 1450 microbeta plate reader. Results from individual mice in triplicate wells were combined to yield a mean ± SE for each immunization group.

Cytotoxicity assays. All CTL responses were measured using either 4-h ⁵¹Cr or overnight ¹¹¹In release assays as previously described (25, 34, 36). Allospecific CTL responses were evaluated by incubating BALB/c T cells, isolated following a 5-d mixed lymphocyte culture, with ¹¹¹In-labeled MC38 (H-2⁷) or P815 (H-2¹⁰) targets. To measure antigen-specific CTL responses in vaccinated mice, splenocytes from each mouse (25⁰¹⁰⁶) were cultured in an upright T-25 flask containing 10 ug/mL of either CEA 526-533 (EAQNTTYL) peptide or h-gal 96-103 (DAPIYTNV) peptide (CPC Scientific). After 1 wk, lymphocytes were collected on a Histopaque (Sigma-Aldrich) density gradient and quantified. Panco2.CEA target cells were pretreated with IFN-α (2 × 10⁵ IU/mL, 48 h, 37°C) before the CTL assay. On the day of the assay, target cells (4 × 10⁶) were incubated with 50 μCi of ¹¹¹In-labeled oxine (GE Healthcare) for 30 min at 37°C. Target cells were washed twice and pulsed with 20 μg/mL of CEA526-533 peptide, h-gal96-103 peptide, or vesicular stomatitis virus nucleoprotein VSV-NP 52-59 (RGVYQGL) control peptide (CPC Scientific) for 30 min at 37°C. Tumor cells (2,500 per well) were coincubated with 3.13 × 10⁴ to 5 × 10⁵ lymphocytes for 18 h at 37°C. The final peptide concentrations in the CTL assay were 100 μg/mL. The amount of ¹¹¹In released was measured using a gamma counter (Cobra II, Packard Instruments). The percentage of specific lysis was calculated as follows: % specific lysis = [(experimental cpm - spontaneous cpm) / (maximal cpm - spontaneous cpm)] × 100.

NK cell cytotoxicity was assessed in standard 4-h chromium release assay as previously described (37). Experiments were done using 12.5:1 to 200:1 effector-to-target (E/T) ratios and ⁵¹Cr-labeled yeast artificial chromosome-1 target cells. All experiments were done in triplicate.

Antibody-based immune cell depletion studies. Antibody-based immune cell depletion studies were carried out in tumor-bearing mice to deplete CD4⁷ (rat antibody GK1.5), CD8⁷ (rat antibody 2.43), CD4⁴ and CD8⁸, or NK1.1 (PK136) cells before receiving rV-F-CEA-TRICOM vaccination. Mice were challenged with Panc02.CEA tumors (10⁶ cells per mouse) on day 0. Antibodies were injected i.p. on days 24 to 27, 34, and 41. Mice received a primary vaccination with rV-CEA-TRICOM and rF-GM-CSF on day 28 and a booster vaccination with rF-CEA-TRICOM and rF-GM-CSF on day 42 after tumor challenge. Tumor growth and survival were monitored for up to 100 d following tumor challenge.

Fig. 2. Effect of IFN-α on recombinant vaccinia and fowlpox vaccinations. The route of IFN-α administration and its effect on poxvirus vaccine responses were evaluated in mice receiving vaccine alone (●) or vaccine in combination with IFN-α given either locally (▲; right ventral surface) or distally (◆; left dorsal surface) to the site of vaccination. In rF-LacZ-TRICOM–vaccinated mice, the local administration of IFN-α significantly improved β-gal–specific CD4⁺ T-cell proliferative responses (A) and CD8⁺-mediated lysis of MC38 tumor cells pulsed with β-gal96-103 (DAPIYTNV) peptide (B). In rV-LacZ-TRICOM–vaccinated mice, the local but not distal administration of IFN-α significantly inhibited β-gal–specific CD4⁺ T-cell proliferation (C) and CTL responses (D). Concanavalin A–induced T-cell proliferation was normal in all experiments (Supplementary Fig. S4A and C). Negligible CTL activity was noted in MC38 tumor cells pulsed with the VSV-NP 52-59 (RGVYQGL) control peptide (Supplementary Fig. S4B and D). In each experiment, a 1-wk course of IFN-α (50,000 IU/mouse, 3×/week, MWF) was initiated on the day of vaccination with either vaccinia or fowlpox (Monday). The immune data presented here were generated from the pooled splenocytes of three mice per group and the experiments were conducted thrice with consistent findings.
**Serum cytokine assays.** In tumor-bearing mice treated with either vehicle or IFN-α, serum was collected at sacrifice. ELISA assays were done to measure the serum concentrations of vascular endothelial growth factor and transforming growth factor β1 per manufacturer’s recommendations (R&D Systems).

**Measurement of effector cytokine production.** Intracellular cytokine production of IFN-αγ and granulocyte B, as a percentage of CD8 T cells or NK.1+ cells, was assessed in mice with established Panc02.CEA tumors receiving either no treatment or IFN-α (50,000 IU; 3 × a week for 2 wk; n = 4 mice per group). Following 2 wk of immunotherapy with IFN-α, the mice were sacrificed and single-cell suspensions were prepared from the tumor mass of each animal. Following the manufacturer’s recommendations, tumor samples (10^6 cells/mL) were stimulated for 5 h with a leukocyte activation cocktail containing phorbol 12-myristate 13-acetate, ionomycin, and brefeldin A (Becton Dickinson).

**Statistical analyses.** Differences between treatment groups were determined using ANOVA and Tukey’s multiple comparisons test. All analyses were conducted using the GraphPad Prism software package (Prism 4 for Windows, version 4.03, GraphPad Software, Inc.) and statistical significance was accepted at the P < 0.05 level.

**Results**

**IFN-α induces phenotypic and functional changes in draining lymph node cells.** Titrating doses of IFN-α (0–50,000 IU/mouse × 3 injections) resulted in significant phenotypic and functional changes in the draining inguinal lymph node cells. IFN-α induced a dose-dependent cellular expansion in the total lymph node cells (Fig. 1A; P < 0.0001). The highest dose of IFN-α (50,000 IU/mouse, three injections) significantly elevated antigen presentation function as measured by an allospecific lymphoproliferation assay (Fig. 1B; P < 0.0001). Moreover, IFN-α treatment dose-dependently improved T-cell (Fig. 1C; P < 0.0001) and NK cell (Fig. 1D; P < 0.0002) cytotoxicity. The cellular expansion induced by IFN-α was locoregional because the draining inguinal lymph nodes were expanded by 60% over the contralateral inguinal lymph nodes of the same mice (Supplementary Fig. S2A; P = 0.03). Finally, this IFN-induced cellular expansion was composed of many cell populations including CD19 B lymphocytes (Supplementary Fig. S2B; P < 0.0001), CD3 T lymphocytes (Supplementary Fig. S2C; P < 0.0001), CD11c+/I-Ab+ dendritic cells (Supplementary Fig. S2D; P < 0.0001), and NK.1+ cells (Supplementary Fig. S2E; P < 0.0001).

To evaluate the efficacy of IFN-α as an adjuvant to protein-based vaccination, we measured immune responses in mice vaccinated with β-gal protein (100 μg, s.c.) in the presence or absence of IFN-α (50,000 IU/mouse, three injections) at the site of vaccination (Supplementary Fig. S3). Co-administration of β-gal and IFN-α increased CD4+ proliferative responses ~3-fold (1,500 versus 4,500 cpm/2 × 10^6 CD4+ cells; P < 0.0001). Total IgG serum antibody titers were also increased 3- to 4-fold.

**Table 1. Up-regulation of tumor cell surface MHC class I expression by IFN-α**

(A) *In vitro* cell surface antigen expression

<table>
<thead>
<tr>
<th>Cell Line</th>
<th>IFN-α (IU/mL)</th>
<th>MHC class I (H-2Kb)</th>
<th>CD80 (B7-1)</th>
<th>CD66 (CEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC38.CEA</td>
<td>0</td>
<td>57.5 (36.5)</td>
<td>-</td>
<td>94.6 (139.8)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>99.8 (168.6)</td>
<td>40.5 (33.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>99.8 (200.5)</td>
<td>99.8 (161.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>99.8 (205.5)</td>
<td>99.7 (179.8)</td>
<td></td>
</tr>
<tr>
<td>Panc02.CEA</td>
<td>0</td>
<td>Neg</td>
<td>Neg</td>
<td>94.6 (139.8)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Neg</td>
<td>40.3 (1,687)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>42.8 (527)</td>
<td>54.7 (715)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>70.1 (516)</td>
<td>76.5 (896)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>89.6 (918)</td>
<td>89.9 (1,306)</td>
<td></td>
</tr>
</tbody>
</table>

(B) *In vivo* cell surface antigen expression

<table>
<thead>
<tr>
<th>Tumor</th>
<th>IFN-α (IU)</th>
<th>MHC class I (H-2Kb)</th>
<th>MHC class I (H-2Db)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% Positive (MFI)</td>
<td>% Positive (MFI)</td>
</tr>
<tr>
<td>MC38.CEA</td>
<td>0</td>
<td>94.2 (133.5)</td>
<td>94.5 (110.4)</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>96.4 (335.2)</td>
<td>96.0 (270.3)</td>
</tr>
<tr>
<td>Panc02.CEA</td>
<td>0</td>
<td>23.1 (1,010)</td>
<td>18.7 (270)</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>47.7 (1,058)</td>
<td>43.4 (267)</td>
</tr>
</tbody>
</table>

NOTE: The effect of IFN-α on cell surface MHC class I expression was evaluated in murine pancreatic and colorectal cancer cells. *In vitro* titration of IFN-α (0–1,000 IU/mL) was shown to dose-dependently up-regulate the percentage of cells positive for MHC class I (H-2Kb and H-2Db) in MC38.CEA and Panc02.CEA tumor cells (A). As shown in A, Panc02.CEA, but not MC38.CEA, tumor cells constitutively express the T-cell costimulatory molecule CD80 (B7-1). In mice with established subcutaneous tumors, IFN-α treatment (50,000 IU/injection, 3 × a week, 2 wk) up-regulated MHC class I (H-2Kb and H-2Db) mean fluorescence intensity on MC38.CEA tumors and the percentage of MHC class I–positive cells in Panc02.CEA tumors (B).

Abbreviations: MFI, mean fluorescence intensity; Neg, negative.

*Each cell line was pretreated at the indicated dose of murine IFN-α for 48 h.

†I-Ab, CD54 (intercellular adhesion molecule-1), CD48 (muLFA-3), and CD40 were evaluated but did not respond to titrating doses of IFN-α in the cell lines tested.

‡Mice received six injections (every other day) of either PBS or the indicated dose of IFN-α. The last injections were given 24 h before analysis.
in mice vaccinated with β-gal and IFN-α, compared with those vaccinated with β-gal alone (P < 0.001).

**IFN-α differentially modulates poxvirus-based vaccines.**

Given the inherent role of type I IFNs in early antiviral defense (38, 39), we were intrigued about whether the observed enrichment of the regional lymph nodes draining the site of IFN-α injection could be exploited to improve host immune responses to poxvirus-based vaccines. A series of experiments was designed to optimize the administration of IFN-α with recombinant vaccinia and fowlpox vaccines. Antigen-specific proliferative and cytotoxic responses were measured in mice vaccinated with either rV-LacZ-TRICOM or rF-LacZ-TRICOM. Administration of IFN-α (50,000 IU/mouse, three injections), whether local or distal to the site of vaccination, significantly improved β-gal–specific CD4+ T-cell proliferative responses (Fig. 2A; P < 0.001). The local administration of IFN-α at the site of rF-LacZ-TRICOM vaccination, significantly improved β-gal–specific CD8+–mediated tumor cell lysis (P < 0.001), whereas distal administration of IFN-α did not alter CTL activity in this system (Fig. 2B). When administered at the site of rV-LacZ-TRICOM vaccination, IFN-α significantly inhibited β-gal–specific proliferative responses (Fig. 2C; P < 0.001) and CTL activity (Fig. 2D; P < 0.001). Distal administration of IFN-α in rV-LacZ-TRICOM–vaccinated mice significantly improved β-gal–specific proliferation (Fig. 2C; P < 0.001) but did not alter CTL activity (Fig. 2D). All controls for these experiments, concanavalin A–induced T-cell proliferation or VSV-NP–specific CTL activity, were normal (Supplementary Fig. S4A-D).

The role of IFN-α–mediated inhibition of replication and/or infectivity by the vaccinia virus was evaluated in vitro and in vivo. Recombinant IFN-α (0-100 IU) was shown to dose-dependently inhibit the production of β-gal protein in cultured MC38 cells infected with 0.01 multiplicity of infection of the rV-based LacZ vaccine (Supplementary Fig. S5A; P < 0.01). Likewise, the i.m. coadministration of rV-based LacZ vaccine (10⁶ pfu) and IFN-α (50,000 IU, 3×) in C57BL/6 mice resulted in significant inhibition of β-gal protein production at the site of vaccination (Supplementary Fig. S5B; P < 0.009). No such activity was observed with rF-LacZ-TRICOM vaccination (Fig. 3A).
inhibition was observed when the fowlpox-based LacZ construct was coinjected with IFN-α (data not shown).

IFN-α alters the tumor cell surface phenotype. Although the baseline cell surface phenotype of MHC class I (H-2Kb and H-2Db) and CD80 (B7-1) expression on MC38.CEA and Panc02.CEA cells are quite different, in vitro titration of IFN-α (0-1,000 IU/mL, 48 hours) dose-dependently up-regulated MHC class I expression to a similar degree (Table 1A). In vivo, the mean fluorescence intensity for MHC class I on MC38.CEA tumor cells increased substantially in mice treated with IFN-α (50,000 IU/mouse, 3× a week for 2 wk; Table 1B). The same dose and schedule of IFN-α, in vivo, up-regulated the percentage of MHC class I–positive cells on the surface of Panc02.CEA tumors (Table 1B).

The combination of IFN-α and rV/F-CEA-TRICOM yields significant antitumor activity. Following 21 days of treatment, the growth of MC38.CEA tumors was significantly delayed only in mice receiving the combination of IFN-α and rV/F-CEA-TRICOM (Fig. 3B; P < 0.001). This treatment combination conferred a significant survival benefit over all other treatment groups (Fig. 3C; P = 0.01). The antitumor efficacy of IFN-α in combination with rV/F-CEA-TRICOM vaccination was CEA dependent because the combination of IFN-α and rV/F-TRICOM (non-CEA vaccine) did not alter the growth of MC38.CEA tumors (Fig. 3A) or improve survival outcomes relative to untreated controls (Fig. 3C). In a subset analysis (n = 4 mice per group) of CTL activity in tumor-bearing mice, only mice vaccinated with rV/F-CEA-TRICOM or the combination of IFN-α and rV/F-CEA-TRICOM generated significant CEA526-533–specific CTL activity against MC38.CEA targets (P < 0.05; Fig. 3D).

In mice with Panc02.CEA tumors, significant antitumor activity and improved survival were observed with rV/F-CEA-TRICOM vaccination (Fig. 4A and C; P < 0.001), IFN-α treatment (Fig. 4B and C; P < 0.001), and the combination of IFN-α and rV/F-CEA-TRICOM vaccination (Fig. 4B and C; P < 0.001). The antitumor efficacy of the vaccine was CEA specific because rV/F-TRICOM (non-CEA) vaccination had no
effect on Panc02.CEA tumor growth (Fig. 4A) or survival (Fig. 4C) relative to untreated controls. In antibody-based immune cell depletion studies, nonsignificant trends for reduced survival were observed in mice depleting CD4+/CD8+ T cells or NK1.1+ cells (Supplementary Fig. S6A). The median survival of mice receiving the CEA vaccine was 52 days after tumor challenge whereas the median survival in vaccinated mice depleted of CD4+/CD8+ T cells or NK1.1+ cells was 42 days ($P = 0.07$) and 45.5 days ($P = 0.27$), respectively. Actuarial survival at 60 days after tumor challenge was 43% (vaccine only), 33% (vaccine + CD4+), 33% (vaccine + CD8+), 0% (vaccine + CD4+/CD8+), and 0% (vaccine + NK1.1+). Significant CEA526-533-specific CTL lysis of Panc02.CEA targets was observed in mice receiving IFN-$\alpha$, rV/F-CEA-TRICOM, and the combination of IFN-$\alpha$ and rV/F-CEA-TRICOM (Fig. 4D; $P < 0.05$). Antibody blockade of B7-1 resulted in a statistically significant decline in Panc02.CEA tumor cell lysis by a CEA526-533-specific CD8+ T-cell line (Supplementary Fig. S6B).

To better understand the mechanism(s) by which IFN-$\alpha$ therapy inhibited Panc02.CEA tumor growth, we treated mice ($n = 6$ mice per group) for 2 wk with IFN-$\alpha$ (50,000 IU, 3× a week) and then examined their tumor infiltrates (Fig. 5A-D) and lymphoid organs (Supplementary Fig. S7A and B) using six-color flow cytometry and measured serum cytokine levels by ELISA (Supplementary Fig. S7C and D). When compared with untreated controls, IFN-$\alpha$ treatment significantly suppressed tumor growth (Fig. 5A; $P = 0.03$) and increased the percentage of CD8+ (Fig. 5B, 6.7% versus 11.2%; $P = 0.03$), NK1.1+ (Fig. 5C, 1.8% versus 3.2%; $P = 0.03$), and Gr-1+ (Fig. 5D, 2.4% versus 4.5%; $P = 0.03$) tumor infiltrates. IFN-$\alpha$ treatment did not alter the percentage of CD4+ tumor infiltrates (data not shown). Nonsignificant trends were noted for normalization of the spleen size (Supplementary Fig. S7A; $P = 0.22$) and expansion of the draining inguinal lymph nodes (Supplementary Fig. S7B; $P = 0.25$) in these tumor-bearing mice. Treatment with IFN-$\alpha$ significantly reduced serum vascular endothelial growth factor levels (Supplementary Fig. S7C; $P = 0.03$) whereas serum transforming growth factor-$\beta$ concentrations were unchanged (Supplementary Fig. S7D; $P = 0.44$). To assess effector cytokine production by tumor infiltrates, tumor samples from control and IFN-$\alpha$-treated mice were stimulated in vitro with a leukocyte activation cocktail. Intracellular IFN-$\gamma$ and granzyme B expression was higher in the tumor-infiltrating CD8+ T cells (46.1% versus 55.7%; $P < 0.05$) and NK1.1+ cells (14.7% versus 25.8%; $P < 0.05$) of IFN-$\alpha$–treated mice.

**Discussion**

Previous studies have enumerated the pleiotropic adjuvant actions of IFN-$\alpha$ including cellular enrichment of the draining regional lymph nodes as well as the ability to up-regulate antigen expression on tumor targets (9, 10, 40). The locoregional changes brought on by IFN-$\alpha$ can be argued to improve priming of the cellular host immune response, whereas the systemic distribution of IFN-$\alpha$ may improve the effector arm of host immunity by improving immune cell target recognition. In this study, we identified a dose and schedule of IFN-$\alpha$ (50,000 IU, 3× a week) that induced a locoregional expansion of the draining lymph nodes and functional improvements in antigen presentation and cellular cytotoxicity. These findings...
are consistent with previous reports about the adjuvant characteristics of IFN-α on dendritic cell (16, 41) and NK cell (42) functions.

Our studies show that inhibition of infectivity and/or replication of the vaccinia virus observed with coadministration of IFN-α can be avoided by injecting IFN-α at a site distal to the site of vaccination. These data suggest that the systemic effects of IFN-α allow for its continued use as a biological response modifier in antitumor studies (i.e., to up-regulate tumor MHC class I expression) by anatomically separating the administration of IFN-α from the site of primary vaccination with recombinant vaccinia. Fowlpox vectors, being replication defective and resistant to IFN-induced suppression of viral replication, yielded improved lymphoproliferative and CTL responses when coadministered with IFN-α at the site of booster vaccinations.

Based on these observations, we designed antitumor studies to evaluate the combination of poxvirus vaccines with the optimal dose, schedule, and site of IFN-α administration. In mice with MC38.CEA tumors, vaccination alone generated MC38.CEA tumor-specific CD8 + T-cell responses but was not sufficient to yield therapeutic antitumor responses. One interpretation of these findings is that IFN-α potentiated the action of the vaccine regimen in mice with MC38.CEA tumors through one or more of its immunomodulatory effects (activation of dendritic cells and NK cells or MHC up-regulation).

Our immune cell depletion studies in mice with Panc02.CEA tumors suggest that CD4+ and CD8+ T cells and NK1.1+ cells are important mediators of vaccine efficacy. These findings are consistent with the work of Sivinski et al. (43) who reported a significant role for these cell populations in generating antitumor immunity against parental Panc02 tumors. The absence of synergy between IFN-α and CEA vaccine in mice with Panc02.CEA tumors was surprising considering the efficacy of the individual treatments and the synergistic effects of this combination in mice with MC38.CEA tumors. One possible explanation is that in mice with Panc02.CEA tumors, IFN-α and CEA vaccine may operate through shared immunologic pathways such as the activation of CEA526-533-specific CTL activity.

The phenotypic differences in Panc02.CEA (MHC-I+/CD80−) and MC38.CEA (MHC-I+/CD80+) tumor cells allowed us to ask fundamental questions about immunosurveillance and response to immunotherapy in these two model systems. The functional consequences of these phenotypic differences may explain why IFN-α seems to activate adaptive immune responses in mice with Panc02.CEA but not MC38.CEA tumors. One might infer from our studies that the treatment of Panc02.CEA tumor-bearing mice with IFN-α induces CEA526-533-specific CTL activity and the accumulation of CD8+ tumor-infiltrating lymphocytes by up-regulating MHC class I expression (signal 1) in a tumor cell with constitutive CD80 expression (signal 2). The Panc02 model recapitulates some of the conditions reported by Hiroishi et al. (11, 12) in which MC38 cells transduced with either IFN-α or CD80 generated MC38-specific CTLs and long-lasting antitumor immunity. Our antibody blockade experiments support a role of CD80 expression in mediating antitumor immunity. Costimulation through CD80 is likely an important mediator of adaptive immunity in the Panc02 system because CD28−/− mice show markedly reduced survival following a challenge with the parental Panc02 cell line (43). The role of CD80 in mediating the interaction between tumor and the immune system is complex, however, because low CD80 expression is reported to contribute to tumor escape through preferential engagement of CD152 (CTLA-4) on T cells (44). The findings by our laboratory and others would suggest that a threshold may exist above which CD80 expression induces positive costimulation resulting in therapeutic responses to IFN-α therapy.

Our data also support a role for immune surveillance of Panc02 tumors by NK cells. Panc02.CEA tumors remained 50% to 60% MHC class I negative following IFN-α therapy and, thus, may also be more susceptible than MC38.CEA cells to recognition and lysis by NK cells. The activation of NK1.1+ cytotoxicity in tumor-free mice and the accumulation of NK1.1+ infiltrates in tumor-bearing mice would suggest that activation of the innate immune system is another mechanism by which IFN-α regulated Panc02.CEA tumor growth in our experiments. To summarize our findings in mice with Panc02.CEA tumors, IFN-α therapy was shown to stimulate CEA-specific CTL activity, increase CD8+ and NK1.1+ tumor infiltrates and their effector cytokine production (IFN-γ and granzyme B), slow tumor growth, and improve survival.

Clinically, IFN-α is well documented to enhance the expression of CEA and MHC antigens on freshly isolated human adenocarcinomas (40) and improve monoclonal antibody-targeting of carcinoma lesions following systemic administration in patients (45, 46). In patients with CEA-expressing carcinomas, therefore, we would expect the full repertoire of immunomodulatory properties of IFN-α to improve the clinical efficacy of our vaccine strategy. In a phase I study of patients with advanced CEA-expressing carcinomas (primarily colorectal), Marshall et al. (26) used recombinant poxvirus vaccines to elicit CEA-specific T-cell responses without significant toxicities. In a recent phase I study of advanced pancreatic cancer, recombinant poxvirus vaccines expressing CEA and MUC-1 (termed PANVAC-TRICOM) were successful in generating antigen-specific immune responses in 62.5% of evaluable patients (27). Overall survival was significantly better in those patients who developed antigen-specific immune responses to vaccine (15.1 versus 3.9 months, respectively; P = 0.002). In pancreatic cancer patients who undergo pancreaticoduodenectomy, an adjuvant IFN-α-based chemoradiation protocol has led to 5-year survival rates of 55% despite a high incidence of nodal involvement and advanced tumor stage before surgery (47). These studies suggest that recombinant poxvirus vaccines and IFN-α can be potentially used as effective forms of immunotherapy in patients with gastrointestinal malignancies. Our research provides both a rationale and mechanistic insights to support a clinical trial evaluating the combination of IFN-α and CEA-directed poxvirus vaccines in patients with CEA-expressing carcinomas.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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