A Vaccinia Virus Armed with Interleukin-10 Is a Promising Therapeutic Agent for Treatment of Murine Pancreatic Cancer

Louisa S. Chard1, Eleni Maniati2, Pengju Wang3, Zhongxian Zhang3, Dongling Gao3, Jiwei Wang3, Fengyu Cao3, Jahangir Ahmed1, Margueritte El Khouri1, Jonathan Hughes1, Shengdian Wang4, Xiaozhu Li4, Bela Denes5, Istvan Fodor5, Thorsten Hagemann2, Nicholas R. Lemoine1,3, and Yaohe Wang1,3

Abstract

Purpose: Vaccinia virus has strong potential as a novel therapeutic agent for treatment of pancreatic cancer. We investigated whether arming vaccinia virus with interleukin-10 (IL10) could enhance the antitumor efficacy with the view that IL10 might dampen the host immunity to the virus, increasing viral persistence, thus maximizing the oncolytic effect and antitumor immunity associated with vaccinia virus.

Experimental Design: The antitumor efficacy of IL10-armed vaccinia virus (VVLATK-IL10) and control VVLATK was assessed in pancreatic cancer cell lines, mice bearing subcutaneous pancreatic cancer tumors and a pancreatic cancer transgenic mouse model. Viral persistence within the tumors was examined and immune depletion experiments as well as immunophenotyping of splenocytes were carried out to dissect the functional mechanisms associated with the viral efficacy.

Introduction

Pancreatic cancer is the fourth leading cause of cancer-related death worldwide (1) and remains consistently lethal with a 5-year survival rate of less than 5%. This situation signifies a need for radically new therapeutic strategies that are not subject to cross-resistance with conventional therapies.

Oncolytic viruses have emerged as attractive therapeutic candidates for cancer treatment due to their inherent ability to specifically target and lyse tumor cells and induce antitumor immunity. The antitumor efficacy of VVLATK-IL10 in vitro and in vivo had a similar level of cytotoxicity and replication in murine pancreatic cancer cell lines, but rendered a superior antitumor efficacy in the subcutaneous pancreatic cancer model compared with VVLATK-IL10 resulting in a reduction in virus-specific, but not tumor-specific CD8+ cells compared with VVLATK.

Results: Compared with unarmed VVLATK, VVLATK-IL10 had a similar level of cytotoxicity and replication in vitro in murine pancreatic cancer cell lines, but rendered a superior antitumor efficacy in the subcutaneous pancreatic cancer model and a K-ras-p53 mutant-transgenic pancreatic cancer model after systemic delivery, with induction of long-term antitumor immunity. The antitumor efficacy of VVLATK-IL10 was dependent on CD4+ and CD8+, but not NK cells. Clearance of VVLATK-IL10 was reduced at early time points compared with the control virus. Treatment with VVLATK-IL10 resulted in a reduction in virus-specific, but not tumor-specific CD8+ cells compared with VVLATK.

Conclusions: These results suggest that VVLATK-IL10 has strong potential as an antitumor therapeutic for pancreatic cancer.

Cancer Therapeutics: Preclinical

Clinical Cancer Research

Note: Supplementary data for this article are available at Clinical Cancer Research Online (http://clipcancerres.aacrjournals.org/).

Corresponding Authors: Yaohe Wang, Centre for Molecular Oncology, Barts Cancer Institute, Queen Mary University of London, London, United Kingdom. 2Center for Cancer and Inflammation, Barts Cancer Institute, Queen Mary University of London, London, United Kingdom. 3Sino-British Research Centre for Molecular Oncology, Zhengzhou University, Zhengzhou, China. 4CAS Key Laboratory of Infection and Immunity, Institute of Biophysics, Chinese Academy of Sciences, Beijing, China. 5Center for Health Disparities and Molecular Medicine, Loma Linda University, Loma Linda, California.

©2014 American Association for Cancer Research.

Published Online First November 21, 2014; DOI: 10.1158/1078-0432.CCR-14-0464
Oncolytic virotherapy is beginning to show promise as a realistic alternative to standard cancer therapeutics. To date, clinical trials have proved this strategy safe and well tolerated by patients; however, clinical responses after treatment with virus alone have been modest. A new generation of oncolytic viruses that engage the host immune system in the attack against the tumor are providing more encouraging clinical results. This study demonstrates that vaccinia virus armed with the cytokine interleukin-10 (IL10) is a novel and extremely promising therapeutic for treatment of pancreatic tumors and prevention of disease recurrence. Understanding the mechanisms by which IL10 improves oncolytic virotherapy provides a foundation for the rational design of clinical trials for treatment of pancreatic cancer and other solid tumors with this virus and provides valuable information for the design of future antitumor strategies that aim to combine oncolytic virotherapy with immunotherapeutic approaches.

Translational Relevance
Oncolytic virotherapy is beginning to show promise as a realistic alternative to standard cancer therapeutics. To date, clinical trials have proved this strategy safe and well tolerated by patients; however, clinical responses after treatment with virus alone have been modest. A new generation of oncolytic viruses that engage the host immune system in the attack against the tumor are providing more encouraging clinical results. This study demonstrates that vaccinia virus armed with the cytokine interleukin-10 (IL10) is a novel and extremely promising therapeutic for treatment of pancreatic tumors and prevention of disease recurrence. Understanding the mechanisms by which IL10 improves oncolytic virotherapy provides a foundation for the rational design of clinical trials for treatment of pancreatic cancer and other solid tumors with this virus and provides valuable information for the design of future antitumor strategies that aim to combine oncolytic virotherapy with immunotherapeutic approaches.

Materials and Methods

Cell lines and viruses
The murine PDAC cell line DT6606 and the preinvasive pancreatic cancer (PanIN) cell line DT4994 were cultured from LSL-KrasG12D+/–;Pdx-1-Cre mice that had developed PDAC (29). These were kindly provided by David Tuveson (Cancer Research UK Cambridge Research Institute, Cambridge, United Kingdom; now at Cold Spring Harbor Laboratory). The DT6606-ovalbumin (OVA) stable cell line was created by transfection of DT6606 cells at with pCI-neo-cOVA (Addgene) using Effectene transfection reagent (Qiagen) according to the manufacturers’ protocol. CV1 (African monkey kidney) cells and P145 (human pancreatic carcinoma) cells were obtained from the American Type Culture Collection (ATCC).

Construction and production of recombinant vaccinia virus
Lister strains VVLATK-II.10 (rVV-II.10, armed with murine IL10) and VVLATK (rVV-II.15) were previously described (30, 31).

Vaccinia virus replication assay
Appropriate cell lines were seeded in triplicate and infected 16 hours later with VVLATK or VVLATK-II.10 at a multiplicity of infection (MOI) of 1 plaque-forming unit (PFU) per cell. Cells and supernatant were collected at 24, 48, and 72 hours after infection and titers were determined by measuring the median tissue culture infective dose (TCID50) on indicator CV1 cells. The Reed–Muench mathematical method was used to calculate the TCID50 value for each sample (32). Viral burst titers were converted to PFU per cell based on the number of cells present at viral infection. One-way ANOVA followed by Bonferroni post-test was used to assess significance.

Cell cytotoxicity assay
The cytotoxicity of the viruses in each cell line was assessed 6 days after infection with virus using an MTS nonradioactive cell proliferation assay kit (Promega) according to the manufacturer’s instructions, which allowed determination of an EC50 value (dose required to kill 50% of cells).

Real-time quantitative PCR
Subcutaneous tumors collected from treated mice were homogenized before DNA was extracted using the QIAamp DNA Blood Mini Kit (Qiagen Ltd.) according to the manufacturer’s instructions. TaqMan system primers and probes (Supplementary Table S1) were designed using Primer Express v3.0 software (Applied Biosystems) and constructed by Sigma-Aldrich and Applied Biosystems, respectively. Samples, controls, and standards were tested in triplicate by quantitative polymerase chain reaction (qPCR) using 7500 Real-time PCR System. Results were normalized to NanoDrop readings and expressed as genome copy number/0.01 g tumor tissue. One-way ANOVA followed by Bonferroni post-test was used to assess significance.

IL10 and interferon-γ ELISA
IL10 or interferon-γ (IFNγ) protein levels were quantified using an IL10-specific or IFNγ-specific ELISA (R&D Systems) according to the manufacturer’s instructions. Where appropriate, data were normalized to cell number present at time of infection.
Splenocyte preparation

Spleens were extracted from mice, combined with complete T-cell medium (RPMI medium, 10% BCS, 1% penicillin–streptomycin, and 1% sodium pyruvate), and cells were separated using a 70-µm cell strainer. Cells were resuspended in red blood cell lysis buffer (Sigma-Aldrich), washed in PBS, and the pellet was resuspended in T-cell medium.

In vitro splenocyte restimulation

Cells (2 x 10^6) were aliquoted into each well of a 96-well plate in duplicate. Cells were restimulated with either a vaccinia virus–specific B8R peptide (TSYKFESV; Promimmune) at a final concentration of 20 µg/mL or 5 x 10^5 mitomycin C-treated DT6606-OVA cells. Restimulated splenocytes were incubated at 37°C/5% CO₂ for 72 hours and the supernatant was collected.

Tumor cell preparation

Tumor cell suspensions were prepared by incubation with 1 x collagenase/hyaluronidase (STEMCELL TECHNOLOGIES) for 30 minutes at 37°C. Cells were separated using a 70-µm cell strainer and resuspended in complete T-cell medium.

Immunophenotyping of splenocytes and tumors

All fluorochrome-conjugated antibodies were supplied by eBiosciences and used at a 1:200 dilution. The B8R and OVA H-2kb-restricted, MHC class I pentamers were synthesized by Promimmune and used at a 1:20 dilution.

Splenocytes and tumors were prepared and aliquotted into 96-well U-bottom plates. Pentamer staining was carried out by resuspending cells in FACS buffer (FB; PBS + 1% heat-inactivated BCS + 0.1% NaN₃) plus pentamer and incubating at room temperature for 10 minutes. Cells were washed before being incubated in FB plus appropriate fluorescent marker-conjugated anti-immune cell marker antibodies for 30 minutes on ice. Cells were washed and fixed in 2% formalin before analysis using a BD LSR Fortessa flow cytometer. Data were analyzed using FlowJo software (TreeStar Inc).

In vivo studies

All animal studies were carried out under the terms of the Home Office Project Licence PPL 70/0630 and subject to Queen Mary University of London ethical review, according to the guidelines for the welfare and use of animals in cancer research (33).

The C57/Bl6 mouse is H-2 haplotype-identical to the C57/Bl6 mouse used in the right flank of 3- to 4-week male C57/Bl6 mice by injecting 3 x 10^6 DT6606 cells. When tumors reached around 0.6 cm in diameter, mice were stratified by tumor size into groups of 8 and received 100-µL intratumoral (i.t.) injections of 1 x 10^6 PFU of VVLAKT, VVLAKT-IL10, or PBS daily for 5 days. Tumor size was measured twice weekly until the death of the first animal in each group and volume was estimated [volume = (length x width^2 x π)/6]. Survival analysis was carried out using the Kaplan–Meier survival curves with log-rank (Mantel–Cox) tests used to assess significance. Mice that had cleared tumor after treatment were rechallenged 4 weeks after clearance in the opposite flank with 4 x 10^6 DT6606 cells and tumor volume was estimated as previously. For immune depletion studies, DT6606 subcutaneous tumors were established as described and 1 day before commencement of viral treatment 200 µg of anti-CD4 IgG (antibody clone GK1.5), anti-CD8 IgG (antibody clone TIB210), anti-NK IgG (antibody clone PK136), or control rat IgG was injected intraperitoneally (i.p.) in 200-µL PBS. Injections were continued twice weekly for the duration of the experiment and FACS analysis was used to verify depletion for the duration of the experiment. Five mice per group were treated and the experiment was carried out twice.

Transgenic mice

LSL-KrasG12D/C; LSL-Tp53R172H/+; Pdx-1-Cre (KPC) mice were kindly provided by David Tuveson (Cancer Research UK Cambridge Research Institute) and have been described previously (29). Mice were treated when they reached 2.5 months, previously demonstrated to be the mean age at which PanIN has progressed to PDAC (29). Mice were treated i.p. with 2 x 10^8 PFU/injection VVLAKT or VVLAKT-IL10 on days 1, 3, and 5. Mice were examined daily for signs of disease progression and culled when they showed symptoms of sickness. Survival data were compared using Prism (GraphPad Software) and a log-rank (Mantel–Cox) test was used to determine significance of survival differences.

In vivo imaging

Seven days after treatment of KPC or KP mice, the biodistribution of VVLAKT was determined in anesthetized animals (2% isoflurane inhalation) after i.p. injection of D-luciferin (150 mg/kg; Xenogen) and fluorescence measured with the IVIS camera (Xenogen Corp.).

Histopathologic examination and immunohistochemistry for viral proteins

KPC or control KP mice (2.5-month-old) were treated i.p. with 2 x 10^8 PFU/injection VVLAKT or VVLAKT-IL10 on days 1, 3, and 5. On relevant days, animals were sacrificed, the pancreas removed, snap-frozen, and stored at ~80°C. Frozen tissue was processed for immunohistochemistry (IHC) analysis of vaccinia virus coat protein [1:50 rabbit anti-vaccinia virus coat protein polyclonal antibody (MorphoSys UK Ltd.)], macrophage [1:2,000 anti-F4/80 antibody (Serotech)], CD3⁺ T cell [1:200 anti-CD3 antibody (BioLegend)], and CD8⁺ T cell [1:300 anti-CD8 antibody (BioLegend)] as described previously (31).

Results

VVLAKT-IL10 replicates efficiently in vitro in murine cancer cell lines derived from a transgenic mouse model of pancreatic cancer

To determine whether inclusion of IL10 affected on characteristics of VVLAKT in vitro, replication and cytotoxicity in three cell lines were examined; DT6606, representing late-stage invasive PDAC and DT4994, representing PanIN, were both derived from the K-ras transgenic mouse model of pancreatic cancer (29), DT6606-OVA, in which the OVA antigen is overexpressed in DT6606 cells, was also examined. All cell lines supported production of infectious virions of VVLAKT and VVLAKT-IL10 (Fig. 1A–C) and IL10 did not act to inhibit nor promote viral replication. The EC₅₀ was comparable between VVLAKT and VVLAKT-IL10 (Fig. 1D). Furthermore, IL10 was expressed in all three cell lines over 72 hours after infection (Fig. 1E). Thus, arming VVLAKT with IL10 does not adversely affect the in vitro oncolytic effect desired for our virotherapy strategy.

VVLAKT-IL10 infection was also assessed in the human pancreatic cancer cell line PT45 to demonstrate potential translation
of this therapy into human cells. VVΔTK-IL10 showed efficient replication, cytotoxicity, and IL10 expression in this cell line (Supplementary Fig. S1).

VVΔTK-IL10 shows superior antitumor efficacy compared with VVΔTK in immunocompetent mouse models of pancreatic cancer

*In vivo* efficacy of VVΔTK-IL10 was examined using a subcutaneously established pancreatic cancer model. DT6606 subcutaneous tumors were established in male C57/BL6 mice and the animals received i.t. injections of $1 \times 10^8$ PFU of VVΔTK, VVΔTK-IL10, or PBS daily for 5 days. The selected viral dose was 10 times lower than the most commonly reported $1 \times 10^9$ PFU/dose in the literature (34). Both VVΔTK and VVΔTK-IL10 demonstrated antitumor efficacy (Fig. 2A). However, treatment with VVΔTK-IL10 resulted in a superior antitumor efficacy by day 44, with 87.5% of mice showing tumor clearance and significantly improved overall survival rates compared with both VVΔTK- and PBS-treated animals (Fig. 2B). The C57/Black6 mouse is H-2 haplotype-identical to the injected DT6606 cells. Growth of tumors in PBS-treated animals confirmed that there was no immunologic rejection of the DT6606 cell line due to MHC or minor antigen mismatches.

To determine whether VVΔTK-IL10 remained efficacious in a more pathologically relevant model of pancreatic cancer, KPC transgenic mice were used. In these mice, pancreas-specific expression of mutant *Kras*G12D and *Trp53*R172H results in progressive development of PDAC (35). Three doses of virus ($2 \times 10^8$ PFU/day) were given i.p. to 2.5-month old, PDAC-bearing mice. To confirm the specificity of virus for pancreatic tumors after i.p. injection, VVΔTK, which expresses a luciferase transgene in the viral TK region, was injected into either experimental KPC mice or control KP mice. Two days later, mice were imaged for luciferase expression (Fig. 2C). Strong luciferase signals were obtained specifically in the pancreatic area of KPC transgenic mice (Fig. 2C, left), while no signal was obtained from control mice (Fig. 2C, right). The vaccinia virus proteins were expressed in cancer cells and proliferative acinar cells in KPC mice (Fig. 2C, left, bottom), whereas no viral protein expression was observed in the ductal epithelial cells and acinar cells in KP mice (Fig. 2C, right, bottom), confirming
Specificity of replication of TK-deleted vaccinia virus for pancreatic tumor cells. Efficacy of viral treatment in this model was assessed by survival (Fig. 2D). Treatment with VVL\textsubscript{\Delta}TK-IL10 resulted in significantly improved survival rates compared with treatment with VVL\textsubscript{\Delta}TK. Mean survival time for VVL\textsubscript{\Delta}TK-IL10-treated animals after commencement of treatment was 138.5 days compared with 69.7 days for VVL\textsubscript{\Delta}TK-treated animals, suggesting VVL\textsubscript{\Delta}TK-IL10 as an extremely effective treatment for PDACs even in the most complex murine models of the disease.
Treatment with VVLΔTK-IL10 results in long-term protection against disease recurrence

Successful OV strategies aim not only to eradicate the primary tumor, but also to induce long-term antitumor immunity to prevent disease recurrence. Thus, animals were rechallenged with \( 4 \times 10^6 \) DT6606 cells 4 weeks after complete regression of the primary tumor (Fig. 3A). Treatment with both viruses resulted in long-term immunity to DT6606 tumor cells as evidenced by rapid clearance of these cells that necessitated no further viral treatments. Interestingly, VVLΔTK-IL10-treated animals were able to clear the secondary tumor more quickly and more consistently than VVLΔTK-treated animals.

CD8\(^+\) and CD4\(^+\), but not NK cells, are required for VVLΔTK-IL10 efficacy in vivo

Long-term immunity suggests an activation of specific antitumor immune responses after treatment. To assess the contribution of different immune cells to treatment efficacy, CD8\(^+\), CD4\(^+\), or NK immune subsets were depleted from mice before treatment of subcutaneous DT6606 tumors with VVLΔTK-IL10 (Fig. 3B). Depletion of both CD4\(^+\) and CD8\(^+\) cells had a significantly detrimental effect on the efficacy of treatment, suggesting VVLΔTK-IL10 is acting via these immune subsets to eliminate the tumor. Surprisingly, given previous reports that IL.10 can activate NK cells to mediate tumor clearance (17), depletion of NK cells in our experiment had no effect on treatment efficacy.

Tumor-associated activated T-cell and macrophage populations are altered after treatment with VVLΔTK-IL10 compared with VVLΔTK, which affects viral persistence

Given the involvement of T cells in VVLΔTK-IL10 treatment efficacy, tumor T-cell populations were analyzed in more detail. Pancreatic tumors of KPC transgenic mice treated as previously were harvested posttreatment and T-cell populations analyzed by IHC. We noted a significant increase in CD3\(^+\)CD8\(^+\) infiltrate after treatment with both viruses compared with PBS (Supplementary Fig. S2) and a significant increase in CD3\(^+\)CD8\(^+\) cells in VVLΔTK-IL10-treated animals at day 22 after infection compared with VVLΔTK–treated animals.

DT6606 subcutaneous tumors were also harvested for analysis of T-cell populations by FACS. In accordance with data obtained from KPC mice, we found a significant increase in tumor T-cell infiltrate after treatment with both viruses, with a significant increase in CD8\(^+\) infiltrate into tumors of VVLΔTK-IL10–treated animals (Fig. 4A). However, most interesting was that in CD4\(^+\) (data not shown) and, more significantly, CD8\(^+\) populations (Fig. 4B), the proportion of activated (CD45RB\(^+\)/CD44\(^hi\)) T cells in tumors treated with VVLΔTK was higher than those treated with VVLΔTK-IL10. IFN\(\gamma\) expression within VVLΔTK-IL10–treated tumors was also significantly reduced compared with VVLΔTK–treated tumors (Fig. 4C).

Tumor-associated macrophage populations were also assessed in KPC (Supplementary Fig. S3) and DT6606 tumor-bearing mice (Fig. 4D) after infection. We found that treatment with either virus increased macrophage infiltrate into tumors of KPC mice compared with PBS, but that treatment with VVLΔTK-IL10 resulted in a reduced macrophage tumor infiltrate compared with treatment with VVLΔTK. This result was mirrored in DT6606 tumor-bearing mice. Further assessment of macrophage activation status in the DT6606 subcutaneous model revealed that VVLΔTK-IL10 induces a downregulation of MHCII expression compared with VVLΔTK (Fig. 4E).

To assess the impact of these phenomena on viral persistence, viral DNA load in the tumors (6 mice/group/time point) was analyzed after i.t. treatment at days 8, 16, and 24 after infection using qPCR (Fig. 4F, i) and TCID\(_{50}\) (Fig. 4F, ii). We found that by day 24, both viruses had been cleared from the tumor to the same extent, but at days 12 and 16, significantly more VVLΔTK-IL10 was recovered from tumors than VVLΔTK, indicating a delay in clearance of VVLΔTK-IL10 compared with VVLΔTK. These results were confirmed by IHC analysis of viral load in pancreatic tumors of KPC mice (Supplementary Fig. S4).

The splenic CD4\(^+\) and CD8\(^+\) cell populations are altered after treatment with VVLΔTK-IL10 compared with treatment with VVLΔTK

It is clear that VVLΔTK-IL10 treatment efficacy involves modulation of the immune system, thus splenic immune cell population dynamics in response to treatment were assessed in greater detail.

**Figure 3.** Immune system involvement in the efficacy of VVLΔTK-IL10 in vivo. A, mice that had cleared tumors after i.t. treatment with VVLΔTK or VVLΔTK-IL10 during efficacy experiments were rechallenged 4 weeks later in the opposite flank with \( 4 \times 10^6 \) DT6606 cells and tumor growth measured as previously. VVLΔTK \( n = 3 \), VVLΔTK-IL10 \( n = 6 \). Mean tumor size \( \pm \) SEM are displayed and compared by one-way ANOVA with post hoc Bonferroni testing. \(*\) \( P < 0.05; \) ** \( P < 0.005; \) *** \( P < 0.001 \). B, DT6606 tumors were established in male C57/Black6 mice as described previously and 1 day before commencement of viral treatment, rat anti-mouse CD4, CD8, NK, or control monoclonal antibodies were injected i.p. Injections were continued twice weekly for the duration of the experiment and FACS analysis used to confirm depletion. Mean tumor size \( \pm \) SEM are displayed and compared by one-way ANOVA with post hoc Bonferroni testing. \(*\) \( P < 0.05; \) ** \( P < 0.005; \) *** \( P < 0.001 \) (\( n = 5 \) /group).
DT6606 tumor-bearing mice were treated as described and their spleens collected and assessed for presence of various immune cell subsets. No differences were found in splenic B cell (B220+ cells), Treg (CD4+ , CD25+ cells), NK (CD3+, CD49b+ cells), or NKT populations (CD3+, CD49b+ cells) after treatment with either virus compared with PBS-treated animals (Supplementary Fig. S5).

Analysis of CD4+ and CD8+ populations revealed that frequencies of these populations were altered at early time points (Fig. 5A and D; Supplementary Fig. S6). At days 8 and 16, a significant increase in the frequency of total CD8+ cells was seen after treatment with either virus; however, VVLΔTK–IL10 treatment resulted in fewer total CD8+ cells than treatment with VVLΔTK (Fig. 5D). This phenomenon was also observed in the CD4+ populations at day 16 after treatment (Fig. 5A).

Further examination revealed that after treatment with VVLΔTK–IL10 or VVLΔTK, T-cell populations shifted toward an effector/memory phenotype (Fig. 5B–F) at days 8 and 16. However, VVLΔTK–IL10 induced statistically fewer activated CD4+ and CD8+ T cells than VVLΔTK at days 8 and 16 after infection (Fig. 5B–F), as noted previously within the tumor.

VVLΔTK–IL10 treatment results in reduced antiviral immune responses compared with treatment with VVLΔTK, but an increased frequency of tumor-specific T cells

To clarify the proportions of virus-specific and tumor-specific splenic effector CD8+ cells elicited after treatment with VVLΔTK and VVLΔTK–IL10, splenocytes from DT6606-OVA tumor-bearing animals were analyzed. For virus-specific T cells, an MHCI-specific pentamer against an immunogenic vaccinia virus antigen, B8R, was used (Fig. 6A and Supplementary Fig. S7A). As expected, viral treatment resulted in detection of B8R-specific CD8+ cells in both treatment groups. However, VVLΔTK-treated animals had a significantly higher proportion of B8R-specific T cells than VVLΔTK–IL10–treated animals at all time points, suggesting a decreased virus-specific immune response after treatment with VVLΔTK–IL10, which could account for the fewer effector CD8+ cells noted after VVLΔTK–IL10 treatment. We confirmed the decreased frequency of antivirus-specific T cells using an in vitro restimulation assay, in which IFNγ production from splenocytes in response to B8R peptide restimulation was measured (Fig. 6B). At all time points, significantly less IFNγ was detected from VVLΔTK–IL10 treatment groups compared with VVLΔTK treatment groups.

To assess T-cell reaction to tumor antigens, an MHCI OVA-specific pentamer was used in FACS staining (Fig. 6C and Supplementary Fig. S7B). At day 8, no differences in OVA-specific CD8+ T cells was observed after treatment with either virus when compared with PBS; however, by day 16, VVLΔTK–IL10–treated animals showed an increase in production of OVA-specific antigens compared with VVLΔTK–treated animals. This result was reflected in restimulation assays (Fig. 6D).

Taken together, these results indicate that although VVLΔTK–IL10 treatment resulted in a reduction in antiviral T-cell production, the frequency of antitumor-specific CD8+ T cells was comparable or even increased compared with VVLΔTK–treated mice.

Discussion

Efficacy of oncolytic vireotherapy is dependent on both the oncolytic action of the virus itself and the effective stimulation of a local immune response to viral infection (36, 37). Oncolytic viruses may represent a method of achieving vaccination in situ, enabling the adaptive arm of the immune system to clear residual disease and provide long-term surveillance against relapse. To date, however, the use of oncolytic viruses alone has proved unsuccessful in clinical trials and this is likely due to their early clearance preventing their oncolytic effects and an effective immune-stimulating release of tumor-associated antigens (TAA). Many viruses encode homologs of the cytokine IL10, generally considered immunosuppressive, to dampen the antiviral immune response and circumvent early viral clearance (11, 38). We aimed to adopt this natural strategy of viruses by arming vaccinia virus with IL10, which has been reported to be effective at prevention of vaccinia virus clearance (39). We hypothesized that prolonging viral persistence in the host would improve the antitumor efficacy by enhancing both the direct oncolytic effect and release of TAA.

The pancreatic cancer subcutaneous tumor model we developed was based on the use of a DT6606 cell line, which was originally derived from the transgenic KPC spontaneous model of pancreatic cancer (29), and therefore accurately reflect the PDAC populations of cells within these mice. Previous study has demonstrated that these cancer cells resemble human PDAC in many respects, including their expression of oncogenic KrasG12D and the TAA mesothelin, and both spontaneous and subcutaneous tumors show similar histopathologic features such as the presence of FAP+ stromal cells (40).

The long-held paradigm of IL10 function suggests it as an immunosuppressive cytokine, commonly investigated therapeutically in the context of treatment for inflammatory autoimmune conditions and allograft survival (41, 42). However, using these two different murine models of pancreatic cancer, we observed significantly enhanced therapeutic responses after treatment with our IL10–armed vaccinia virus compared with unarmed virus. In both models, low doses of the virus were sufficient to induce objective responses and in agreement with previous reports, no IL10–related toxicity was observed (43). Treatment also resulted in rejection of tumors after rechallenge, confirming the development of effective long-term immunity against tumor antigens. These results are consistent with those of others investigating the antitumor properties of IL10 in which systemic administration of recombinant protein or tumor cells transfected with IL10 induced tumor clearance and long-term memory responses in mice bearing sarcoma (16), melanoma (16, 44), colorectal cancers (16), breast cancers (45), and prostate cancers (20).

In vitro studies indicated that IL10 did not alter vaccinia virus replication or cytotoxicity and no effect on cell proliferation was observed. To determine other possible mechanisms for the superior efficacy associated with this virus, viral persistence within tumors was assessed. Although both IL10–armed and unarmed viruses were effectively cleared from animals, greater titers of VVLΔTK–IL10 were recovered at days 12 and 16 compared with VVLΔTK in both the transgenic and subcutaneous models of pancreatic cancer, suggesting that IL10 could significantly delay viral clearance.

Given previous reports of the ability of IL10 to stimulate NK cells (17) and as a cytotoxic T-cell differentiation factor (46), we examined reliance of our treatment on these immune subsets. Depletion of NK cells had no effect on treatment efficacy in vivo and we found no evidence of altered splenic or tumor (data not shown) NK populations after treatment with VVLΔTK–IL10. In contrast, depletion of CD4+ and CD8+ T-cell populations had a negative impact on treatment efficacy. It has previously been
Figure 4.
Analysis of activated T cells, IFNγ expression, macrophage populations, and viral persistence in tumors. DT6606-OVA tumors were established and mice treated i.t. with VVLΔTK or VVLΔTK-IL10 following the same regimen as described for efficacy experiments. At days 10 and 15, tumors were harvested and analyzed using FACS analysis (n = 3/group). A, CD8⁺ T cells as assessed by analysis of CD3⁺/CD8⁺ populations within CD45⁺ populations. Mean populations ± SEM are displayed and compared by one-way ANOVA with post hoc Bonferroni testing. B, activated CD8⁺ cells as assessed by analyzing CD44RBloCD44hi populations within the CD8⁺ population. Mean populations ± SEM are displayed and compared by one-way ANOVA with post hoc ANOVA testing. *, P < 0.05; **, P < 0.01. C, IFNγ expression within tumors was assessed by ELISA using tumor homogenates after treatment. Mean concentration/0.1 g tumor ± SEM are displayed and compared by one-way ANOVA with post hoc Bonferroni testing. D, DT6606-OVA tumors were established and mice were treated i.t. with VVLΔTK or VVLΔTK-IL10 following the same regimen as described for efficacy experiments. At days 8 and 16, tumors were harvested and analyzed for total macrophage populations using FACS analysis (n = 3/group). Macrophage activation status was also assessed using an MHCII marker, with MHCIIhi populations regarded as activated macrophages (E, i) and MHCIIlo populations regarded as naive macrophages (E, ii). (Continued on the following page.)
reported that progression from PanIN to PDAC is accompanied by progressive infiltration of T cells into the tumor in KPC transgenic mice (47, 48); however, no antitumor response is induced by this infiltrate. Our analysis of T-cell populations in spleens and tumors revealed that treatment with both unarmed and IL10-armed viruses induced a high level of adaptive immunity in mice.

Figure 5.
Analysis of CD4+ and CD8+ populations and activation status in splenocytes of VVLΔTK-IL10- or VVLΔTK-treated mice. DT6606-OVA tumors were established and mice treated i.t. with VVLΔTK or VVLΔTK-IL10 following the same regimen as described for efficacy experiments. At days 8, 16, and 24, spleens were harvested and analyzed using FACS analysis (n = 6/group). A, CD4 populations as a percentage of live cells in splenocytes of treated mice assessed by gating on CD3+CD4+ populations. B, naive CD4 cells as assessed by analyzing CD44RBhiCD44lo populations within the CD4+ population. C, activated CD4 cells as assessed by analyzing CD44RBloCD44hi populations within the CD4+ population. D, CD8 populations in splenocytes of treated mice assessed by gating on CD3+CD8+ populations. E, naive CD8 cells as assessed by analyzing CD44RBhiCD44lo populations within the CD8+ population. F, activated CD8 cells as assessed by analyzing CD44RBloCD44hi populations within the CD8+ population. Mean populations ± SEM are displayed and compared by one-way ANOVA with post hoc Bonferroni testing. * P < 0.05; ** P < 0.01; *** P < 0.001. Representative FACS profiles with gating criteria are shown in Supplementary Fig. S6.

(Continued.) Mean populations ± SEM are displayed and compared by one-way ANOVA with post hoc Bonferroni testing. F, to assess viral persistence, DT6606 tumors were established and 18 mice per group treated i.t. with VVLΔTK or VVLΔTK-IL10 following the same regimen as described previously. At days 8, 16, and 24, tumors were harvested, viral DNA extracted, and viral DNA levels quantified in relation to a standard curve using qPCR (i). Mean vaccinia virus copy number ± SEM is displayed and analyzed at each time point using a Student unpaired t test. * P < 0.05; ** P < 0.01. Infectious virus recovered from homogenized tumors was also analyzed (ii). Mean viral replication ± SEM was determined by TCID50 assay on CV1 cells. Statistical analysis was carried out using a Student unpaired t test at each time point. * P < 0.05.
compared with untreated mice. However, an interesting finding was that the magnitude of the activated splenic CD4+ and CD8+ population response in VVLΔTK-IL10-treated mice was lower compared with the unarmed virus. This difference correlated with a reduction in virus-specific CD8+ T cells and IFNγ recovery from tumors after VVLΔTK-IL10 treatment, which accounted for the delayed viral clearance from tumors. Interestingly, although VVLΔTK-IL10 treatment reduced antiviral CD8+ populations, IL10 had no inhibitory effect on production of antitumor CD8+ cells. Indeed, at day 16 after injection, an increase in anti-OVA CD8+ cells was observed, which we postulate is a result of the increased oncolysis occurring with VVLΔTK-IL10 treatment, which improves TAA release.

These results suggest that IL10 improves the efficacy of OV by modulation of the early immune response to infection, resulting in dampening of antiviral, but not antitumor immunity. However, the mechanism by which IL10 elicits this alteration remains unclear. Our investigations revealed that local IL10 expression results in modification of the tumor macrophage population, which is highly sensitive to IL10 exposure (49). Numerous investigators have reported that IL10 can negatively regulate macrophages by (i) inhibiting their infiltration into tumors, and (ii) downregulating MHCII expression and suppressing production of proinflammatory cytokines and reactive nitrogen oxides (50).

Although we found that VVLΔTK-IL10 treatment increased macrophage infiltration into tumors in both the spontaneous and subcutaneous models of pancreatic cancer, we found that in accordance with previous data, VVLΔTK-IL10 treatment results in a significant downregulation of MHCII expression. Thus, it is feasible that in our model, tumor macrophages are responsible for viral antigen presentation to T cells and a reduction in macrophage activation by IL10 leads to reduced cross-priming of the antiviral immune response. A further consideration is that this model suggests distinct pathways of viral and tumor antigen presentation, which are the subject of ongoing investigation in our laboratory.

These findings demonstrate that IL10 armed vaccinia virus shows great promise as a novel therapeutic for pancreatic cancer, and that IL10 in combination with oncolytic virotherapy is clearly able to enhance tumor rejection through modulation of the innate and adaptive immune responses.

**Disclosure of Potential Conflicts of Interest**

No potential conflicts of interest were disclosed.
Study supervision:
- Writing, review, and/or revision of the manuscript: L.S. Chard, E. Maniati, Y. Wang
- Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): L.S. Chard, E. Maniati, Z. Zhang, D. Gao, J. Wang, J. Ahmed, M. El Khouri, J. Hughes, B. Denes

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis):
- L.S. Chard, E. Maniati, J. Hughes, B. Denes, I. Fodor, Y. Wang

Writing, review, and/or revision of the manuscript:
- L.S. Chard, E. Maniati, J. Hughes, I. Fodor, N.R. Lemoine, Y. Wang

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases):
- L.S. Chard, J. Wang, S. Wang, X. Li, T. Hagemann, Y. Wang

Study supervision: I. Fodor, Y. Wang

References
27. McCarty JW, Reed CM, J. Hu Y, Alexander RF, Libutti SK, et al. Systemic cancer therapy with a tumor-selective vaccinia virus mutant lacking...
A Vaccinia Virus Armed with Interleukin-10 Is a Promising Therapeutic Agent for Treatment of Murine Pancreatic Cancer

Louisa S. Chard, Eleni Maniati, Pengju Wang, et al.

Clin Cancer Res  Published OnlineFirst November 21, 2014.

Updated version  Access the most recent version of this article at:
doi:10.1158/1078-0432.CCR-14-0464

Supplementary Material  Access the most recent supplemental material at:
http://clincancerres.aacrjournals.org/content/suppl/2014/11/22/1078-0432.CCR-14-0464.DC1

E-mail alerts  Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions  To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions  To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.