TLR7 Ligand Augments GM-CSF–Initiated Antitumor Immunity through Activation of Plasmacytoid Dendritic Cells

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Abstract

Vaccination with irradiated granulocyte macrophage colony-stimulating factor (GM-CSF)–transduced autologous tumor cells (GVAX) has been shown to induce therapeutic antitumor immunity. However, its effectiveness is limited. We therefore attempted to improve the antitumor effect by identifying little-known key pathways in GM-CSF–sensitized dendritic cells (GM-DC) in tumor-draining lymph nodes (TDLN). We initially confirmed that syngeneic mice subcutaneously injected with poorly immunogenic Lewis lung carcinoma (LLC) cells transduced with Sendai virus encoding GM-CSF (LLC/SeV/GM) remarkably rejected the tumor growth. Using cDNA microarrays, we found that expression levels of type I interferon (IFN)–related genes, predominantly expressed in plasmacytoid DCs (pDC), were significantly upregulated in TDLN-derived GM-DCs and focused on pDCs. Indeed, mouse experiments demonstrated that the effective induction of GM-CSF–induced antitumor immunity observed in immunocompetent mice treated with LLC/SeV/GM cells was significantly attenuated when pDC-depleted or IFNα receptor knockout (IFNAR−/−) mice were used. Importantly, in both LLC and CT26 colon cancer–bearing mice, the combinational use of imiquimod with autologous GVAX therapy overcame the refractoriness to GVAX monotherapy accompanied by tolerability. Mechanistically, mice treated with the combined vaccination displayed increased expression levels of CD86, CD9, and Siglec-H, which correlate with an antitumor phenotype, in pDCs, but decreased the ratio of CD4+CD25+FoxP3+ regulatory T cells in TDLNs. Collectively, these findings indicate that the additional use of imiquimod to activate pDCs with type I IFN production, as a positive regulator of T-cell priming, could enhance the immunologic antitumor effects of GVAX therapy, shedding promising light on the understanding and treatment of GM-CSF–based cancer immunotherapy.

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Introduction

In recent clinical trials of patients with diverse solid cancers, cancer immunotherapy such as therapeutic vaccination with granulocyte macrophage colony-stimulating factor (GM-CSF) gene-transduced tumor vaccines (GVAX), as well as sipuleucel-T (Provenge; Dendreon), the first FDA-approved GM-CSF–based therapeutic dendritic cell (DC) vaccine for prostate cancer, induced antitumor immune responses with tolerability (1–3). However, the efficacy of this therapy alone is not satisfactory, raising an urgent need to improve the antitumor effect of GVAX. Although GM-CSF signaling is essential in conventional DC (cDC) maturation, which leads to effective generation of tumor-associated antigen (TAA)-specific T cells and differentiation, the underlying molecular mechanism of how GM-CSF sensitizes and matures DCs (GM-DC, i.e., GM-CSF–sensitized DCs) to trigger host antitumor immunity remains unclear.

Therefore, in this study, we attempted to improve the antitumor effects of GVAX therapy through identification of the key cluster genes upregulated in GM-DCs that operate T-cell priming in tumor-draining lymph nodes (TDLN) by conducting a cDNA microarray analysis. We used a syngeneic Lewis lung carcinoma (LLC)–bearing mouse, which exhibited remarkable tumor regression following subcutaneous administration of fusion (F) gene-deleted nontransmissible Sendai virus vector–mediated GM-CSF gene-transduced LLC (LLC/SeV/GM) cells (4). Using this experimental system, the expression microarray analysis elucidated that pathways involving Toll-like receptor 7 (TLR7) and interferon regulatory factor 7 (IRF7), which induce type I interferon (IFN) production in plasmacytoid DCs (pDC; ref. 5), were upregulated in GM-CSF–activated mature DCs. Further activation of this pathway using
Figure 1. Tumor development of poorly immunogenic LLC and B16F10 cells modified to produce GM-CSF was markedly inhibited. A, dose-escalation studies to assess GM-CSF production from LLC/SeV/GM cells (MOI = 0, 3, 10, and 100). GM-CSF production levels in the supernatants from the 48-hour culture were measured by ELISA. B and C, tumorigenicity assays using LLC cells. B, a total of 3.0 × 10⁵ LLC and LLC/SeV/GM (MOI of 1, 10, or 100) cells were subcutaneously inoculated into the right flank of C57/BL6N mice (n = 3). C, a total of 2.0 × 10⁵ LLC, LLC/SeV/GFP, or LLC/SeV/GM (MOI = 100) cells were inoculated into the right flank of C57/BL6N mice (n = 6). Significant tumor regression (left) and prolonged survival (right) was shown in mice treated with LLC/SeV/GM cells. D, tumorigenicity assays using B16F10 cells. In total, 1.0 × 10⁵ B16F10, B16/SeV/GFP, or B16/SeV/GM (MOI = 30) cells were inoculated into the right flanks of C57/BL6N mice (n = 6). Significant tumor regression (left) and prolonged survival (right) were observed in mice treated with B16/SeV/GM cells. The asterisks indicate statistically significant differences (*, P < 0.05; **, P < 0.01; ***, P < 0.001). Kaplan–Meier survival curves are shown, and mortality was determined by the log-rank test (LLC vs. LLC/SeV/GM and LLC/SeV/GFP vs. LLC/SeV/GM; P < 0.001, LLC vs. LLC/SeV/GFP; P = 0.67, B16 vs. B16/SeV/GM and B16/SeV/GFP vs. B16/SeV/GM; P < 0.05).
TLR7 agonist enhanced the therapeutic antitumor effects of GVAX therapy using irradiated autologous GM-CSF gene-transduced vaccine cells in both LLC and CT26 tumor-bearing mouse models with augmented pDC activation. These results showed that the combination of GVAX and imiquimod is an effective therapeutic strategy for cancer immunotherapy, and indicate that activated pDCs have a critical role in the GM-CSF–induced induction of antitumor immunity.

Materials and Methods

Mice

Five- to 10-week-old female immunocompetent C57/BL6N and BALB/c/n mice were purchased from Charles River Laboratories Japan and housed in the animal maintenance facility at Kyushu University (Fukuoka, Japan). Type I IFN receptor knockout (IFNAR–/–) mice were purchased from The Jackson Laboratory. All animal experiments were approved by the Committee of the Ethics on Animal Experiments in the Faculty of Medicine, Kyushu University. Mouse experiments were carried out at least twice to confirm results.

Tumor cell lines

LLC and CT26 cells were purchased from the American Type Culture Collection (ATCC) and passaged for 3 to 4 months after resuscitation. The mouse melanoma cell line (B16F10) was a kind gift from Dr. Shinji Okano (Kyushu University) and was validated as free from Mycoplasma infection; no other validations were performed. Both LLC and CT26 cells were validated as free from Mycoplasma infection. No other validations were performed; besides, the former were found as free from ectromelia virus. LLC and B16F10 cells were maintained in Dulbecco’s Modified Eagle Medium (DMEM; Nakalai Tesque) supplemented with 10% heat-inactivated fetal bovine serum (FBS) and 1% antibiotic mixture (Nakalai Tesque). CT26 was maintained in RPMI-1640 (Nakalai Tesque) supplemented with 10% heat-inactivated fetal bovine serum (FBS) and 1% antibiotic mixture.

Gene transduction with nontransmissible recombinant Sendai virus vectors

LLC, B16F10, or CT26 cells were infected with nontransmissible Sendai virus vectors encoding green fluorescence protein (GFP) or mouse GM-CSF (SeV/GFP or SeV/GM, respectively), which were prepared by DNAVAC Corp. (6), at the indicated multiplicity of infection (MOI) for 90 minutes (termed as LLC/SeV/GFP, LLC/SeV/GM, B16/SeV/GFP, B16/SeV/GM, or CT26/SeV/GM cells, respectively). They were cultured for 48 hours after viral gene transduction and used for following mouse studies.
Role of pattern recognition receptors in recognition of bacteria and viruses
Pathogenesis of multiple sclerosis
Activation of IRF by cytosolic pattern recognition receptors
IFN signaling
DC maturation
Hepatic fibrosis / hepatic stellate cell activation
Role of hypercytokinemia/hyperchemokinemia in the pathogenesis of influenza
Communication between innate and adaptive immune cells
Role of tissue factor in cancer

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\log (P\text{-value})
\]

\[
\text{Tumor volume (mm}^3\text{)}
\]

\[
\text{Days after tumor challenge}
\]
In vivo experiments

For tumorigenicity assays, syngeneic C57/BL6N mice were subcutaneously challenged with $2.0 \times 10^5$ LLC, LLC/SeV/GFP, or LLC/SeV/GM cells with or without imiquimod (R-837; 50 $\mu$g/mouse; Invivogen) or lipopolysaccharide (LPS; 5 $\mu$g/mouse; Sigma-Aldrich) resuspended in 100-$\mu$L Hanks’ Balanced Salt Solution (HBSS; Life Technologies) in the right or left flank. To dissect the role of type I IFN and pDCs in the tumorigenicity assays, IFNAR$^{-/-}$ or pDC-depleted mice were subcutaneously challenged with $2.0 \times 10^5$ LLC/SeV/GM cells in the right flank. For therapeutic tumor vaccination assays, LLC/SeV/GFP, LLC/SeV/GM, and CT26/SeV/GM cells were irradiated at 50 Gy and were designated as irLLC/SeV/GFP, irLLC/SeV/GM, and irCT26/SeV/GM cells, respectively. On days 2 and 9 after tumor challenge with parental LLC or CT26 cells, C57/BL6N or BALB/cN mice were subcutaneously vaccinated with the indicated tumor vaccine cells in the opposite flank. Tumor volume was measured every 2 to 4 days and calculated with the following formula: $0.4 \times (\text{largest diameter}) \times (\text{smallest diameter})^2$.

ELISA assay

In vitro expression levels of mouse GM-CSF produced from LLC, LLC/SeV/GFP, or LLC/SeV/GM cells at the MOI and time points were measured using mouse GM-CSF enzyme-linked immunosorbent assay (ELISA) kits (R&D Systems).

Flow cytometric analysis

TDLNs, spleen, and tumor vaccine sites (TVS) harvested from the indicated groups of mice ($n = 3–5$) were homogenized and filtered through a 100-$\mu$m cell strainer (BD Biosciences). For splenocyte preparation, smashed spleens were treated with ammonium chloride to lyse red blood. For T-cell detection in TDLNs, cells were stained with either anti-CD317 (PDCA-1, BST2; eBio129c; all eBioscience), anti-CD80–anti-B220 PE (RA3-6B2), anti-CD317 (PDCA-1, BST2; BioLegend), and anti-Siglec-H–FITC (MZ3; BioLegend), and stained with anti-CD4, anti-CD25 APC (JF05-1C2.4.1; Miltenyi Biotec), and anti-FITC MicroBeads (Miltenyi Biotec). Cells were incubated with Abs and analyzed with BD FACSCalibur flow cytometer, CellQuest software (BD Biosciences), and FlowJo software (TreeStar).

Allogeneic MLR assays

To prepare CD11c$^+$ DCs as stimulators, on day 2 of the tumorigenicity assay, CD11c$^+$ DCs were purified from TDLNs in mice treated with LLC, LLC/SeV/GFP, or LLC/SeV/GM cells using CD11c MicroBeads (Miltenyi Biotec). To prepare the pDC subset as stimulators, total bone marrow cells harvested from naive C57/BL6N mice were cultured in RPMI-1640 supplemented with 50 ng/mL murine Fms-related tyrosine kinase 3 ligand (Flt3L; PeproTech) for 8 days and Siglec-H$^+$–positive cells (pDCs) were purified using anti-Siglec-H–FITC Ab and anti-FITC MicroBeads (Miltenyi Biotec). Sorted pDCs were then incubated overnight with or without 2.5 $\mu$L of imiquimod or 10 ng/mL of murine recombinant GM-CSF (PeproTech). To prepare allogeneic T cells as responders, T cells were sorted from splenocytes harvested from naive BALB/cN mice using a Pan T-cell isolation kit II (Miltenyi Biotec). A total of 5.0 $\times 10^5$ responder T cells labeled with 1.0 $\mu$mol/L CFSE ([6(6)-carboxyfluorescein diacetate N-succinimidylester; Sigma-Aldrich]) were cocultured with an equal number of 30 $\mu$L–irradiated CD11c$^+$ DCs. A total of $2.0 \times 10^5$ T cells labeled with 2.5 $\mu$mol/L of CFSE were cocultured with 4.0 $\times 10^5$ of pDCs for 5 days. The proliferation rate of the gated CD3$^+$ T-cell fraction was visualized by CFSE dilution.

Detection of DCs that engulfed TAAs

LLC, LLC/SeV/GFP, and LLC/SeV/GM cells were labeled with the PKH26 Red fluorescent Cell Linker Mini Kit (Sigma-Aldrich), respectively, according to the manufacturer’s instruction. On day 2 after they were subcutaneously injected into the right flanks of mice, axillary lymph nodes in both TDLNs and CLNs were harvested, incubated with anti-CD86–FITC and anti-CD11c–APC Abs, and subjected to flow cytometric analysis.

cDNA microarray

Dead cells were excluded from CD86$^+$ CD11c$^+$ DCs using 7-AAD viability dye (Beckman Coulter), which were sorted by
FACSaria (BD Biosciences) from TDLNs of mice on day 2 during the tumorigenicity assay. Cells were transferred to RNA later (Life Technologies) to stabilize and protect intact cellular RNA. RNA isolation was performed according to the TRIzol Reagent technical manual (Life Technologies). Total RNA (50 ng) was amplified and labeled using the Agilent Low-Input QuickAmp Labeling Kit, one color (Agilent Technologies). Labeled cRNA was hybridized to Agilent Whole Mouse Genome Oligo DNA microarray (4 × 44 K) v2 (Agilent Technologies). The raw signal microarray slides and were scanned by an Agilent scanner.

In three groups (DCs from mice treated with LLC, LLC/SeV/GFP, and LLC/SeV/GM cells). Lists of genes with statistically significant expression in GM-DCs in comparison with GFP-DCs were submitted to Ingenuity Pathway Analysis (IPA; Ingenuity Systems) and analyzed for overrepresented general functions and the resulting networks. Microarray data were deposited in Gene Expression Omnibus (GEO: http://www.ncbi.nlm.nih.gov/geo/; accession number GSE43169).

In vivo depletion experiments

To deplete pDCs, mice were injected intraperitoneally with 100 μg of anti-PDCA-1 mAb (JF05-IC2.4.1; Miltenyi Biotec) or control Ab (rat IgG; Jackson Immunoresearch), as previously described (7). Effective depletion of PDCA-1⁺ cells was confirmed by flow cytometric analysis (Supplementary Fig. S1). CD4⁺ T or CD8⁺ T cells were depleted by using GK1.5 or 2.43 mAbs, as previously described (8). Briefly, mice received intraperitoneal injections of anti-mouse GK1.5 mAb, anti-mouse 2.43 mAb (50 μg/mouse), or control Ab 6, 4, and 2 days before tumor challenge, and once every 3 days thereafter. Effective depletion of CD4⁺ and CD8⁺ T cells was confirmed by flow cytometric analysis (data not shown).

Results

Production of GM-CSF from LLC and B16F10 cells remarkably impaired the tumorigenicity

To test the possibility that substantial secretion of GM-CSF from syngeneic mouse cancer cells facilitates the development of antitumor immune responses, we used recombinant nontransmissible Sendai virus vectors expressing GM-CSF (SeV/GM) at various MOI. Abundant GM-CSF production from the infected LLC (LLC/SeV/GM) cells was observed and was MOI dependent (Fig. 1A). The proliferation rate of LLC cells was not affected by transduction with SeV/GM, as previously described (6). We next performed tumorigenicity assays in which each LLC and LLC/SeV/GM cells (MOI = 1, 10, and 100) were subcutaneously injected into the left flank of syngeneic mice. All mice treated with LLC/SeV/GM cells exhibited significant suppression of the tumor outgrowth in an MOI-dependent manner (Fig. 1B). We thus determined MOI = 100 for gene transduction as an optimized infection dose. Notably, mice treated with LLC/SeV/GM cells showed significantly suppressed tumor growth and prolonged survival of mice, compared with control groups (P < 0.001; Fig. 1C). Similar suppression of tumor growth and prolongation of mouse survival were observed when SeV/GM-infected B16F10 melanoma cells were injected to C57BL/6N mice (Fig. 1D).

Increased ability of GM-CSF–sensitized DCs to stimulate T-cell proliferation, accelerate their maturation, and deliver phagocytosed TAAAs in TDLNs

To determine a putative phase when GM-CSF–sensitized DCs from TDLNs of mice treated with LLC/SeV/GM cells (GM-DCs) effectively prime naive T cells, we performed allogeneic MLR assays. GM-DCs exhibited a significantly marked response on day 2 compared with DCs from mice treated with LLC/SeV/GFP cells (GFP-DCs), and stimulated the proliferation of allogeneic CD3⁺ CD4⁺ T and CD3⁺ CD8⁺ T cells (Fig. 2A). Furthermore, GM-DCs harvested on day 2 elicited higher expression levels of costimulatory maturation markers CD80 and CD86 than those from control mice (Fig. 2B), suggesting that day 2 could be the putative phase to mount optimum immunologic responses by GM-DCs. To explore the migratory capacity of GM-DCs that phagocytosed TAAAs at the tumor injection site, we inoculated PKH26-labeled LLC, LLC/SeV/GFP, or LLC/SeV/GM cells into the right flank of mice, and evaluated PKH26⁺ DC numbers in both TDLNs and contralateral LNs (CLN). The frequencies of PKH26⁺ DCs in TDLNs, but not CLNs, harvested from mice treated with LLC/SeV/GM cells were significantly increased, indicating that GM-CSF production potentiated the migration of PKH26⁺-labeled LLC/SeV/GM cells (TAA)–phagocytosed DCs from the tumor injection site into TDLNs (P < 0.05; Fig. 2C). PKH26⁺ GM-DCs derived from TDLNs, but not from CLNs, showed significantly higher CD86 expression than controls (P < 0.001; Fig. 2D).

cDNA microarray analysis revealed the involvement of type I IFN–related pathways in GM-CSF–induced antitumor immunity

On the basis of the aforementioned results, we determined day 2 to be an adequate time point for the peak in T-cell priming by TAA-phagocytosed CD86⁺ DCs. To address the important factor of DC/T-cell priming, we isolated CD86⁺ DCs from mice treated with LLC/SeV/GM cells and control groups, and compared the comprehensive gene expression patterns of isolated CD86⁺ DCs in TDLNs. After normalization of microarray data and statistical analysis, 1,318 genes were found to be differentially expressed between GM-DCs and GFP-DCs with statistical significance (upregulated genes; Z-score ≥ 2 and ratio > 1.5, downregulated genes; Z-score ≤ − 2 and ratio < 0.66; data not shown). A list of the genes significantly upregulated in the top 10 canonical pathways in CD86⁺ GM-DCs in comparison with CD86⁺ GFP-DCs is shown in Table 1. As expected, these genes composed immunologic response–related pathways (Fig. 3A). Among the activated pathways triggered by GM-CSF, we focused on the following representative molecules: IRF7, OAS3 (2′-5′-oligoadenylate synthetase 3), and TLR7, which constitute type I IFN (IFN-α/IFN-β)–associated pathways (Fig. 3B and C;
Figure 4. Combined imiquimod and irLLC/SeV/GM cells exert significant therapeutic antitumor effects compared with irLLC/SeV/GM cells alone. A, a total of $2.0 \times 10^5$ LLC and LLC/SeV/GM cells with or without LPS or imiquimod were subcutaneously inoculated into the right flanks of C57/B6N mice. Bar graphs, mean + SEM of tumor volumes. Combined data from two independent experiments with similar results are shown (*, $P < 0.05$). B, schematic diagram of the experimental protocol of therapeutic GM-CSF--based tumor vaccination. Briefly, $2.0 \times 10^5$ LLC cells or $3.0 \times 10^5$ CT26 cells were inoculated subcutaneously to C57/B6N or BALB/c mice. LLC-bearing mice were divided into the following groups: untreated, imiquimod alone, irLLC/SeV/GFP, irLLC/SeV/GM, or irLLC/SeV/GM cells plus imiquimod. CT26-bearing mice were divided into the following groups: untreated, imiquimod alone, irCT26/SeV/GM or irCT26/SeV/GM cells plus imiquimod. On days 2 and 9, mice were inoculated subcutaneously with the indicated vaccine cells. For imiquimod administration, mice were subcutaneously inoculated with imiquimod on days 2, 4, 6, and 9. Represented are tumor growth curves observed in either LLC- (C) or CT26-bearing (D) mice (*, $P < 0.05$; **, $P < 0.01$).
cells, whereas control mice treated with irLLC/SeV/GM marked suppression of tumor growth of preestablished LLC cells or imiquimod alone manifested negligible antitumor immunity. Imiquimod and irLLC/SeV/GM cells elicited a significant induction of IFNα/β via IFNAR 

LPS attenuated the GM-CSF–induced antitumor immunity (10), we speculated that pDCs could be positively involved in the induction of effective GM-CSF–sensitized DC/T-cell priming (11). Indeed, the numbers of pDCs, CD11b+ cDCs, and CD8+ cDCs subsets from total GM-DCs from TDLNs harvested on days 2 and 4 were greater than the equivalent subsets from total GFP–DCs (Fig. 3D). Furthermore, the results of in vivo experiments using IFNα receptor knockout (IFNAR−/−) mice demonstrated that IFNAR−/− mice inoculated with LLC/SeV/GM cells significantly abrogated the impairment of tumorigenicity seen in the corresponding wild-type (WT) mice (Fig. 3E). Importantly, similar results were also obtained when pDC-depleted mice were used (Fig. 3F). These results collectively demonstrate the positive role of type I IFN–producing pDCs in the induction of GM-CSF–mediated antitumor immunity.

Combination of TLR7 ligand and GM-CSF–secreting LLC cells enhanced the induction of antitumor immunity in both tumorigenicity and therapeutic vaccination models

TLR7-dependent type I IFN pathways are activated by binding with their corresponding ligand, imiquimod (12). To examine the impact of the TLR7–mediated activation of type I IFN–related pathways primarily in pDCs on GM-CSF–induced antitumor immunity, we performed a gain-of-function assay by evaluating the tumorigenicity of LLC/SeV/GM cells with or without imiquimod or TLR7 ligand, LPS, as an irrelevant control. Mice treated with LLC/SeV/GM cells combined with imiquimod showed significantly suppressed tumor development accompanied with complete tumor regression (P < 0.05). Conversely, treatment with LLC/SeV/GM cells combined with LPS attenuated the GM-CSF–induced antitumor effects (Fig. 4A), and these mice exhibited no significant changes in body weight (Supplementary Fig. S3). We next attempted to translate these findings into a tumor vaccination therapy adding by binding imiquimod to the subcutaneous administration of irradiated LLC/SeV/GM (irLLC/SeV/GM) cells to investigate the synergistic effect. Notably, mice treated with combined imiquimod and irLLC/SeV/GM cells elicited a significantly marked suppression of tumor growth of preestablished LLC cells, whereas control mice treated with irLLC/SeV/GM cells or imiquimod alone manifested negligible antitumor effects (P < 0.05; Fig. 4B and C). Similarly, mice vaccinated with irradiated GM-CSF gene-transduced (MOI = 100) CT26 colon cancer cells in combination with imiquimod showed significantly suppressed tumor development (P < 0.01; Fig. 4D).

Admixed use of TLR7 ligand in combination with GVAX therapy induced pDC activation leading to generation of T-cell–mediated antitumor immunity

To elucidate the effect of imiquimod on GM-CSF–induced initial immune responses, we performed phenotypic immunanalyses. Six hours after the first tumor vaccination, mice treated with irLLC/SeV/GM cells plus imiquimod showed a significantly higher frequency and number of cells expressing CD86, a pDC-specific marker, than control mice in both TVSs and TDLNs (Fig. 5A and Supplementary Fig. S4). Furthermore, pDCs (CD11c+PDCA-1− cells) derived from mice treated with irLLC/SeV/GM cells plus imiquimod expressed increased levels of CD86 and sialic acid binding Ig-like lectin (Siglec)-H, a functional pDC-specific receptor (Fig. 5B; ref. 13), accompanied with significantly higher levels of serum IFNα (Supplementary Fig. S5). Because CD9+ pDCs stimulated with TLR agonists induced higher amounts of IFNα and provoked protective T-cell–mediated antitumor immunity (14), we compared CD9 expression levels on pDC subsets. Mice treated with irLLC/SeV/GM cells plus imiquimod had significantly increased frequency and mean fluorescence intensity (MFI) of CD9+PDCA1+CD11c+ pDCs in TDLNs (Fig. 5C and D). However, the frequency of CD4+CD25+FoxP3+ Tregs was decreased in TDLNs from mice treated with irLLC/SeV/GM cells and imiquimod, whereas the frequency of CD4+CD25−FoxP3− T cells was increased in mice treated with combined therapy (Fig. 5E). To investigate the effect of imiquimod and GM-CSF on the T-cell proliferation capacity of pDCs, we performed an allogeneic MLR assay. pDCs stimulated with GM-CSF and imiquimod elicited the most pronounced proliferative activity of CD8+ T cells, but not CD4+ T cells, when compared with controls (Fig. 5F). Moreover, the synergistic therapeutic efficacy of irLLC/SeV/GM cells and imiquimod was significantly inhibited when the corresponding mice were depleted of CD4+ or CD8+ T cells (Fig. 5G).

Discussion

This study demonstrates that SeV/GF–mediated exogenous expression of GM-CSF caused poor growth of cancer cells in...
syngeneic mice, concomitant with an early appearance of mature DCs in TDLNs. We used SeV/dF vectors for the gene transduction of vaccine cells because they have relatively higher capacities in terms of gene transduction, induction of antitumor immunity, and safety (6, 15). Expression microarray analyses of the GM-CSF–sensitized CD86+ DCs revealed increased expression of the TLR7–IRF7 pathway components, which induce type I IFN production in pDCs (5). Furthermore, the addition of imiquimod was found to be an effective potential approach to improve the antitumor effects of GVAX therapy (Fig. 4).

As LLC cells have been considered as poorly immunogenic in lung cancer (16), it was surprising that tumor challenge with LLC/SeV/GM cells markedly impaired its tumorigenicity with complete tumor disappearance in half of the mice tested (Fig. 1). In addition, prophylactic vaccination with irLLC/SeV/GM cells also significantly inhibited subsequent tumor challenge with LLC cells (Supplementary Fig. S6). However, therapeutic vaccination using irLLC/SeV/GM cells alone failed to exert significant antitumor immunity (Fig. 4C). We, therefore, attempted to potentiate the therapeutic antitumor effects of irLLC/SeV/GM cells through scrutinizing the gene expression signature of GM-CSF–sensitized DCs in TDLNs from mice that strongly rejected the tumor challenge with LLC/SeV/GM cells. We confirmed that GM-CSF facilitated the maturation of DCs into antigen-presenting cells with enhanced ability to prime naïve T cells to proliferate, and to increase expression of CDS0, CD86, MHC class I, MHC class II, and CD40 (Fig. 2B and Supplementary Fig. S7), consistent with the previous finding that GM-CSF promotes DCs maturation and differentiation (17). Herein, transcriptome analyses revealed that GM-CSF also modulated signal transduction in pDCs by upregulation of the TLR7–IRF7 pathway related to type I IFN production (Fig. 3), consistent with a previous report that GM-CSF stimulation upregulated TLR7 expression in mouse immune cells (18). Our observation that the pDC subset was markedly increased in GM-DCs from TDLNs was unexpected, as the GM-CSF receptor is mainly expressed on subset was markedly increased in GM-DCs from TDLNs was mouse immune cells (18). Our observation that the pDC

CD4+ T cells (32), and cross-present antigens with an efficiency comparable with CD11b+ cDCs (33), implicating their potential as promising antigen-presenting cells for cancer immunotherapy. Indeed, imiquimod or CpG, a TL R9 agonist, reverted immunotolerant pDCs to antitumor pDCs (34), resulting in clinical antitumor effects (35, 36). Importantly, results of our in vivo experiments using pDC depletion and/or IFNAR−/− mice demonstrated the positive impact of the pDC subset and/or type I IFN signaling on the effective generation of GM-CSF–induced antitumor immunity (Fig. 3E and F). Thus, there may be a functional dichotomy in pDC biology between immune tolerance and antitumor phenotype, where their redirection is dependent on the tumor microenvironment.

Imiquimod, a TLR7 ligand, could be regarded as the most effective adjuvant among all approved immunomodulators based on the following: (i) topical imiquimod is currently FDA approved with a good safety profile; (ii) it potently activates antigen-presenting cells to release type I IFNs and Th1-skewing cytokines; and (iii) imiquimod treatment leads to CCL2-dependent recruitment of pDCs and their transformation into killer DCs (37). The underlying mechanism of substantial antitumor efficacy by the combined vaccination may be due to generation of functionally mature pDCs in TDLNs (Fig. 5A and Supplementary Fig. S4). IFNα, mainly produced from pDCs upon exposure to viruses via TLR7 or TLR9 (38), acts directly on memory T cells, which potentiate the antigen presentation and cross-priming capacities of CD11b+ cDCs (39, 40). We detected CD9+ pDCs, which produce abundant IFNα (14), in TDLNs from mice injected with irLLC/SeV/GM cells (Fig. 5C and D). Furthermore, GM-CSF–sensitized pDCs expressed higher CD86 and Siglec-H (Fig. 5B), a regulator of pDC differentiation (1). Indeed, depletion assays revealed that CD4+ and CD8+ T-cell responses (13, 41). Moreover, pDCs activated with GM-CSF plus imiquimod further enhanced the proliferation of CD8+ T cells (Fig. 5F), indicating that GM-CSF–activated pDCs with or without imiquimod could serve as functional antigen-presenting cells to prime the potent generation of TAA-specific adaptive immunity. ELISPOT assay demonstrated that the number of IFNγ-producing splenocytes from mice treated with irLLC/SeV/GM cells plus imiquimod was increased compared with control mice (data not shown). Indeed, depletion assays revealed that CD4+ and CD8+ T cells significantly contributed to the augmentation of the antitumor efficacy by combination GVAX therapy (Fig. 5G), thus reflecting the imiquimod-driven accelerated TAA-specific Th1 responses.

Although other researchers showed that the addition of imiquimod negates the antitumor efficacy of a GM-CSF–based vaccine (42), these conflicting results may stem from the difference in doses and administration schedule. It is noteworthy that the ability of imiquimod to potentiate the antitumor effect of GVAX therapy in two different types of cancers and in two different host strains might confirm the generality of our findings (Fig. 4C and D).

In conclusion, we, for the first time, elucidated that the beneficial roles of the pDCs and relevant type I IFN pathway...
in GM-CSF–induced antitumor immunity and that the combinational use of imiquimod with GVAX therapy produced synergistic antitumor effects, underscoring its potential as a promising approach for the treatment of cancer.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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pDCs as Positive Regulator in GM-CSF–Based Antitumor Effect

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