Therapeutic Efficacy of Antigen-Specific Vaccination and Toll-Like Receptor Stimulation against Established Transplanted and Autochthonous Melanoma in Mice

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Abstract

Malignant melanoma is an attractive model disease for the development of antigen-specific immunotherapy because many antigens recognized by tumor-specific T cells have been identified. In C57BL/6 mice, genetic immunization with recombinant adenovirus encoding xenogeneic human tyrosinase-related protein 2 (Ad-hTRP2) induces protective but not therapeutic cellular immunity against growth of transplanted B16 melanoma cells. Here, we additionally applied CpG DNA and synthetic double-stranded RNA, which activate the innate immune system via Toll-like receptors (TLR). Both adenoviral vaccination and peritumoral injections of TLR ligands were required for rejection of established B16 melanoma in the skin. To more closely mimic the clinical situation in patients with melanoma, we evaluated this combined immunotherapeutic strategy in genetically modified mice, which overexpress hepatocyte growth factor (HGF) and carry an oncogenic mutation in the cyclin-dependent kinase 4 (CDK4)R24C. HGF × CDK4R24C mice rapidly develop multiple invasive melanomas in the skin following neonatal carcinogen treatment, which spontaneously metastasize to lymph nodes and lungs. Vaccination with Ad-hTRP2 followed by injections of TLR ligands resulted in delayed growth of autochthonous primary melanomas in the skin and reduction in the number of spontaneous lung metastases but did not induce tumor regression. Carcinogen-treated HGF × CDK4R24C mice bearing multiple autochthonous melanomas did not reject transplanted B16 melanoma despite treatment with Ad-hTRP2 and TLR ligands, suggesting the development of tumor immunotolerance. Further investigations in our novel genetic melanoma model may help to better understand the role of the immune system in the pathogenesis and treatment of this life-threatening disease. (Cancer Res 2006; 66(10): 5427-35)

Introduction

Antigen-specific immunotherapy for melanoma has been primarily investigated for many years using the transplantable B16 melanoma cell line in C57BL/6 mice (1). Vaccination strategies targeting melanocyte-specific proteins, such as the tyrosinase enzyme family or the gp100 protein, which are naturally expressed by melanoma cells, have shown the existence of peripheral immunotolerance against these weakly immunogenic self-antigens. Use of dendritic cells, immunogenic viruses, or linked helper determinants as vaccine adjuvants are required for the induction of protective cellular immunity against this clinically relevant category of antigens (2–5). However, immunomediated destruction of established B16 melanoma has thus far been difficult to achieve with vaccine approaches. IFN-α secreted locally in the tumor microenvironment by genetically engineered transplanted tumor cells supports the induction as well as the therapeutic efficacy of cellular tumor immunity (6–9). Synthetic immunostimulatory oligonucleotides, such as CpG-containing DNA and double-stranded RNA (dsRNA), are able to strongly activate innate immunity via Toll-like receptors (TLR) and induce the production of type I IFNs as well as other proinflammatory cytokines and chemokines. Peritumoral injections of CpG DNA and polyinosinic acid-poly-CMP (polyIC), which engage TLR9 and TLR3, respectively, have been shown to promote tumor immune responses in several tumor models (10–13). These TLR agonists therefore seem promising candidates to enhance the efficacy of antigen-specific immunotherapy.

Genetically modified mice are currently being generated, which recapitulate the molecular pathogenesis of melanoma and develop autochthonous primary tumors in the skin. These experimental models may be more suitable for the evaluation of novel therapeutic strategies. Previously, we evaluated a candidate vaccine approach against autochthonous primary melanoma in mice, which carry an oncogenic mutation in the cyclin-dependent kinase 4 (CDK4)R24C mice, a protein critically involved in cell cycle regulation (14, 15). This CDK4R24C mutation is of particular immunologic interest because it was originally identified with melanoma-specific cytolytic T cells and could subsequently also be detected in the germ line of some families with hereditary melanoma (16, 17). To further improve this experimental model, we crossed mice overexpressing the hepatocyte growth factor (HGF) with CDK4R24C mice. Deregulated receptor tyrosine kinase signaling is frequently observed in human melanoma and supports the development of spontaneous and UV-inducible cutaneous melanoma in HGF mice (18–20). The CDK4R24C mutation strongly promotes growth of melanoma in HGF mice. Neonatal carcinogen treatment of HGF × CDK4R24C mice results in a dramatic tumor phenotype characterized by many primary melanomas in the skin, which grow rapidly within the first 3 months of life and spontaneously metastasize to the draining lymph nodes and lungs.1 This new experimental mouse model is ideally suited to evaluate new treatment modalities. Here, we show that both

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adenoviral vaccination against the model melanocytic self-antigen tyrosinase-related protein 2 (TRP2) and peritumoral injections of synthetic CpG DNA and dsRNA are required for rejection of established B16 melanoma in the skin. Application of this immunotherapeutic regimen in carcinogen-treated HGF × CDK4R24C mice bearing multiple autochthonous primary melanomas resulted in delayed tumor growth and reduction in the number of spontaneous lung metastases but did not induce tumor regression. Importantly, engrafted B16 melanoma cells grew progressively in carcinogen-treated HGF × CDK4R24C mice with primary cutaneous melanomas despite vaccination with recombinant adenosvirus encoding human TRP2 (Ad-hTRP2) and application of TLR ligands, suggesting the induction of tumor immunotolerance.

Materials and Methods

Mice. C57BL/6 mice (H-2b) were purchased from Charles River Laboratories (Sulzfeld, Germany). CDK4R24C mice were originally generated on a mixed 129Sv × CD1 background using a knock-in strategy ensuring physiologic regulation of the mutant CDK4R24C protein during the cell cycle (21). CDK4R24C mice used in the experiments reported here were crossed back with C57BL/6 mice for more than eight generations. HGF mice were originally generated on the FVB background using a transgenic strategy by placing HGF under the control of the metallothionein promoter (22). HGF mice used in the experiments here were crossed back with C57BL/6 mice for at least five generations and mated with CDK4R24C. C57BL/6 mice. Overexpression of HGF on the C57BL/6 background leads to a "chocolate point phenotype" due to melanocytes in the epidermis. HGF × CDK4R24C mice can easily be distinguished from wild-type (WT) littermates by their dark noses, ears, and paws. All animal experiments were done at the Central Animal Facility of the University of Bonn (Bonn, Germany) in adherence to the standards of the German law for the care and use of laboratory animals.

Engraftment of B16 melanoma in the skin or the lungs. B16 (H-2b) is a spontaneous murine melanoma and was maintained in DMEM supplemented with 10% heat-inactivated FCS, 2 mM L-glutamine, 50 μM/L 2-mercaptoethanol, 100 IU/mL penicillin, and 100 μg/mL streptomycin (all reagents were from Life Technologies GmbH, Eggenstein, Germany). Engraftment of melanoma in the skin was done by intracutaneous injection of 10^7 B16 melanoma cells. Tumor growth was assessed twice weekly by palpation. Tumor size was measured using a caliper and calculated as the maximal product of two bisecting diameters in mm^2. Mice with tumors >100 mm^2 were sacrificed. Engraftment of melanoma in the lungs was done by i.v. injection of 4 × 10^7 B16 melanoma cells. The number of macroscopically visible melanoma metastases on the surface of the lungs was counted with the help of a dissecting microscope 14 days after challenge. Experiments were done in groups of five mice and repeated two to four times.

Induction of primary autochthonous melanoma in the skin. Litters of newborn mice were painted once at day 4 of life with either 20 or 200 μg 7,12-dimethylbenz(a)anthracene (DMBA). Two weeks later, tumor growth was promoted by treatment with 5 μg 12-O-tetradecanoylphorbol-13-acetate (TPA) twice weekly for a total of 5 weeks. Development of melanocytic neoplasms as well as other skin tumors was carefully recorded on a weekly basis after completion of TPA treatment. Nevi and melanomas were counted, and the size of the largest tumor was measured using a caliper. Tumor sizes were calculated as the maximal product of two bisecting diameters in mm^2. Additionally, mice were photographed with a digital camera. When progressively growing melanomas exceeded 100 mm^2, mice were sacrificed. Occasionally, mice also had to be sacrificed because of weight loss and apparent sickness. Autopsy was done in all mice. Lungs were retrieved, and the number of black nodules on their surface indicating metastatic spread of melanoma was counted.

Histopathologic and immunohistochemical analyses. Samples of skin, lymph nodes, and lungs were obtained when mice were sacrificed. Tissue specimens were in part fixed in 10% buffered formalin, embedded in paraffin, and routinely stained with H&E. For immunohistopathologic investigations, a zinc-based fixative was used as an alternative to formalin (DAKO, Hamburg, Germany). To confirm the melanocytic origin of tumor cells, sections were immunostained with the TRP2-specific polyclonal rabbit antibody Pep8 (a kind gift from Vincent Hearing, NIH, Bethesda, MD) followed by a biotin-conjugated anti-rabbit secondary antibody and the LSAB-2 color development system (both from DAKO). To determine the proliferative activity of tumor cells, a Ki67-specific polyclonal rabbit antibody was used.

Plasmids, recombinant adenosviruses, and genetic immunization. Plasmid DNA was grown in Escherichia coli strain DH5α and purified using Qiagen Plasmid Maxi kits (Qiagen, Hilden, Germany). E1- and E3-deleted adenosviral vectors were propagated on 293 cells, purified by cesium chloride density gradient centrifugation and subsequent dialysis according to standard protocols, and stored at −70°C. Genetic immunization with recombinant adenosvirus was done by i.p. injection of 5 × 10^5 plaque-forming unit recombinant adenosvirus suspended in 100 μL PBS. Genetic immunizations with corresponding expression plasmids using the gene gun was done by transfecting the skin of the shaved abdomen in vivo by two shots with the Helios gene gun (Bio-Rad, Munich, Germany) resulting in the delivery of ~2 μg plasmid DNA as described previously (3).

Treatment with TLR ligands. The synthetic phosphothioate-stabilized CpG oligodeoxynucleotide 1826 with the sequence 5′-TCCATGACGTTCCT-GACGT-3′ was purchased from TIB Molbiol (Berlin, Germany). Synthetic polyIC was purchased from Amersham Biosciences (Freiburg, Germany). Treatment of mice was done by injecting 50 μg CpG DNA and 50 μg polyIC dissolved in 100 μL PBS in and around cutaneous melanomas. Alternatively, CpG DNA and polyIC were injected intraocularly in the flank for the treatment of lung metastases.

Detection of antigen-specific T cells and antibodies. The induction of peptide-specific CD8+ T cells was measured using the IFN-γ enzyme-linked immunosspot (ELISPOT) technique with commercially available antibodies (PharMingen, Heidelberg, Germany) as described previously (3). The H-2Kb-binding peptide SVYDFFVWL (TRP2 aa180-188) derived from TRP2 and the H-2Kb-binding peptide ICPMYAVR (β-galactosidase-binding peptide) derived from β-galactosidase were purchased from Genosphere (Paris, France). The induction of humoral immunity to β-galactosidase was determined using the ELISA technique with recombinant E. coli-derived protein as a solid-phase antigen. The induction of humoral immunity to TRP2 was assessed using the Western blot technique with lysates of B16 melanoma cells or 293-S cells infected with Ad-TRP2 as described previously (3).

Statistical analyses. The significance of differences in the number of lung metastases was assessed with the nonparametric Mann-Whitney U test using the SPSS 11 computer program.

Results

Both antigen-specific vaccination and peritumoral injection of synthetic CpG DNA and polyIC are required for rejection of established B16 melanoma in the skin. In our previous studies, we observed that genetic immunization with Ad-hTRP2 was able to provide protective immunity against subsequent transplantation of B16 melanoma cells. The xenogeneic human TRP2 protein is 80% homologous to the murine sequence. It contains the H-2Kb-binding peptide SVYDFFVWL (TRP2aa180-188) recognized by melanoma-reactive CTL and provides linked immunogenic CD4 helper determinants in the divergent amino acid sequences. However, genetic immunization with Ad-hTRP2 is not effective against established B16 melanoma in the skin or the lungs. To promote the therapeutic efficacy of vaccine-induced antigen-specific cellular immunity, we additionally did peritumoral injections of immunostimulatory CpG DNA and polyIC, which mimic a viral infection and strongly activate innate immunity via TLRs. Groups of five mice were first challenged intraocularly with B16 melanoma
cells and subsequently vaccinated with Ad-hTRP2 or Ad-β-gal either alone or in combination with local injections of TLR ligands according to the schedule depicted in Fig. 1A. Mice with either Ad-hTRP2 alone or Ad-β-gal and TLR ligands showed a slight delay in tumor growth compared with the control group of mice receiving Ad-β-gal alone (Fig. 1A and B). Growth of melanoma in the skin was not affected by injections of Ad-β-gal as evidenced in experiments with mice, which were either left untreated or treated with CpG and polyI:C only (data not shown). Importantly, vaccination with Ad-hTRP2 followed by treatment with TLR ligands induced tumor rejection in a significant percentage of mice with a total of 18 of 30 animals being tumor-free after 50 days. Induction of TRP2-specific cellular and humoral immunity could be verified in this experimental group (data not shown). In selected experiments, mice who rejected B16 melanoma were followed for up to 120 days. Some of these mice developed vitiligo-like fur depigmentation. In alternative experiments, we assessed the efficacy of our combined immunotherapeutic strategy against B16 melanoma lung metastases. Groups of five mice were challenged i.v. with B16 melanoma cells, vaccinated with recombinant adenovirus, and treated with TLR ligands according to the schedule depicted in Fig. 1C. Metastatic growth of B16 melanoma cells was prevented in the lungs of all mice receiving TLR ligands (Fig. 1C).

**Genetic vaccination of HGF × CDK4R24C C57BL/6 mice induces effective cellular antimalanoma immunity.** Before investigating the efficacy of our combined immunotherapeutic strategy against carcinogen-induced autochthonous primary melanoma in the skin, we wanted to confirm the ability to induce antigen-specific immunity against the melanocytic self-antigen TRP2 in HGF × CDK4R24C C57BL/6 mice. Groups of HGF × CDK4R24C mice were injected with Ad-hTRP2 or Ad-β-gal and subsequently shot five times at weekly intervals with the corresponding plasmid DNA pCI-hTRP2 or pCI-β-gal using the gene gun. Similar to WT mice, this strategy led to *in vivo* induction of TRP2 aa180-188 peptide–specific T cells and TRP2-reactive antibodies associated with vitiligo-like fur depigmentation in HGF × CDK4R24C mice immunized against TRP2 (Fig. 2A). Subsequently, groups of five HGF × CDK4R24C mice were challenged intracutaneously with B16 melanoma cells, vaccinated with Ad-hTRP2 or Ad-β-gal, and injected with TLR ligands according to the schedule depicted in Fig. 1A. As shown in Fig. 2B and C, treatment with

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**Figure 1.** Peritumoral injections of CpG and poly:C enhance the therapeutic efficacy of a genetic melanoma vaccination with recombinant adenovirus. **A,** groups of five C57BL/6 mice were engrafted intracutaneously with $10^5$ B16 melanoma cells. Four days later, mice were therapeutically vaccinated with Ad-hTRP2 or Ad-β-gal. Synthetic poly:C and CpG were injected peritumorally on days 7, 11, and 15 to enhance the vaccine efficacy. Vaccination was repeated on day 18 followed by injections with TLR ligands on days 21, 25, and 29. Tumor growth was assessed twice weekly by multiplying the largest perpendicular tumor diameters, indicating the tumor area in mm$^2$. Routinely, mice were sacrificed when the tumor area exceeded 100 mm$^2$. Kaplan-Meier graph representing cumulative survival of mice in the indicated treatment groups from four independent experiments with five mice per group. **B,** size of cutaneous B16 melanoma in individual mice of the indicated treatment groups over time expressed as tumor area in mm$^2$. Results of two representative experiments with five mice per group. **C,** groups of five C57BL/6 mice were engrafted i.v. with $4 \times 10^5$ B16 melanoma cells. Four days later, mice were therapeutically vaccinated with Ad-hTRP2 or Ad-β-gal. Synthetic poly:C and CpG were injected intracutaneously on days 7, 11, and 15 to enhance the vaccine efficacy. Mice were sacrificed on day 17, and the number of B16 metastases on the lung surfaces were counted. **Points,** average number of lung metastases in the different treatment groups in three independent experiments with five mice per group; bars, SE.
Ad-hTRP2 and TLR ligands was able to promote rejection of established B16 melanoma in the skin of HGF × CDK4R24C mice. However, the percentage of tumor-free mice on day 50 was lower in HGF × CDK4R24C mice compared with WT mice. Alternatively, groups of HGF × CDK4R24C mice were challenged i.v. with B16 melanoma cells, vaccinated with Ad-hTRP2 or Ad-β-gal, and treated with TLR ligands according to the schedule depicted in Fig. 1C. Growth of B16 melanoma metastases in the lungs was significantly reduced in all mice receiving TLR ligands. Again, therapy was less effective in HGF × CDK4R24C mice compared with WT mice (Fig. 2D).

Carcinogen treatment induces autochthonous primary melanomas in the skin of HGF × CDK4R24C mice, which spontaneously metastasize in the lymph nodes and lungs. Previously, we observed that neonatal application of 200 μg DMBA on the skin of HGF × CDK4R24C mice followed by TPA resulted in rapid growth of ~50 autochthonous cutaneous melanomas in every single mouse within the first 3 months of life. To reduce the number of tumors, we compared carcinogen treatment with 200 and 20 μg DMBA followed by TPA. Cohorts of HGF × CDK4R24C mice were treated according to the schedule depicted in Fig. 3A. All mice in both treatment groups developed melanocytic tumors in the skin within the first weeks of life while still under TPA treatment. Primary cutaneous melanomas grew progressively, and all mice had to be sacrificed when the size of the largest tumor exceeded 100 mm² in tumor area. As shown in Fig. 3A, mice treated with 200 μg DMBA survived up to >100 days, whereas mice treated with only 20 μg DMBA survived up to ≥50 days. Representative pictures of mice are shown in Fig. 3B. On average, melanomas grew slightly slower in the 20 μg DMBA cohort (Fig. 3B). Treatment with 200 μg DMBA induced between 40 and 50 melanomas at the time of sacrifice, whereas mice treated with only 20 μg DMBA developed between 10 and 20 melanomas (Fig. 3C). Skin papillomas were not observed in HGF × CDK4R24C mice treated with 20 μg DMBA and only very rarely in mice treated with 200 μg DMBA. All mice developed spontaneous metastases in the draining lymph nodes and lungs. The number of lung metastases was similar in both groups (Fig. 3D). The homogeneous development of rapidly growing primary melanomas in all HGF × CDK4R24C mice and the spontaneous metastatic spread to lymph nodes and lungs provide an ideal experimental system for the evaluation of novel therapeutic strategies.

Treatment of carcinogen-induced autochthonous primary melanoma in HGF × CDK4R24C mice with genetic vaccination and synthetic TLR ligands delays tumor growth but does not lead to tumor regression. One of the most important aims of our study was to evaluate the therapeutic efficacy of adenoviral vaccination in combination with TLR ligands against autochthonous primary melanomas in the skin. Litters of newborn HGF × CDK4R24C mice were treated with 20 μL DMBA followed by TPA. Melanocytic lesions appeared under TPA treatment during the first 5 weeks of life. Their number and sizes were recorded from day 56 on. Cohorts of 15 melanoma-bearing mice were randomly assigned to two treatment groups at ages 4 to 6 weeks when they were separated to avoid any bias by the selection of mice. One group was therapeutically vaccinated starting at around day 74 of life with Ad-hTRP2 followed by peritumoral injections with TLR ligands according to the schedule shown in Fig. 4A. The second group received two injections of Ad-β-gal only. Treatment with Ad-hTRP2 and TLR ligands delayed growth of autochthonous melanomas in the skin and prolonged survival up to 50 days compared with the control group (Fig. 4A and B). We did not observe tumor regression or vitiligo-like fur depigmentation in any of the mice. At the time of sacrifice, the total number of primary cutaneous melanomas did not differ between the two treatment groups (Fig. 4C). However, the number of lung metastases in mice receiving Ad-hTRP2 and TLR ligands was significantly lower (Fig. 4D). ELISPOT assays done at the time of sacrifice confirmed the induction of TRP2180–188 peptide–reactive memory T cells in vivo (data not shown).
Histopathologic investigations revealed areas of lymphocytic infiltrations in and around heavily pigmented primary melanomas only in mice injected with TLR ligands. Tumors from both treatment groups consistently expressed the melanocytic antigen TRP2, excluding antigen loss as a potential tumor escape mechanism (data not shown). Taken together, these experimental results show that our candidate immunotherapeutic strategy shows therapeutic efficacy against autochthonous primary melanoma and spontaneous lung metastases but does not induce tumor regression.

Comparison of growth kinetics and histopathologic appearance between engrafted B16 melanoma and carcinogen-induced autochthonous primary melanoma in the skin. In direct comparison, engrafted B16 melanoma in the skin grew much more rapidly than carcinogen-induced autochthonous primary melanomas in HGF × CDK4R24C mice. Specifically, B16 melanomas reached a size of 100 mm² within a little more than 2 weeks after injection, whereas autochthonous melanomas took >2 months to develop the same size (Fig. 5A). B16 melanoma cells predominantly established in the deep dermis and subcutis with little or no contact to the upper dermis or epidermis, whereas carcinogen-induced primary melanomas in HGF × CDK4R24C mice involved the dermo-epidermal junction and grew horizontally in the epidermis and vertically into the dermis and subcutis. The architecture of primary melanoma in HGF × CDK4R24C mice was reminiscent of the histomorphology of human melanoma (Fig. 5B, 1). B16 melanoma showed a rather uniform cellular phenotype with prominent cellular atypia as well as many mitoses, whereas primary melanomas in HGF × CDK4R24C mice were composed of a mixture of epitheloid and spindle-shaped cells arranged in strands and nests with only occasional cellular atypia (Fig. 5B, 2). B16 melanoma was always surrounded by a fibrotic capsule and an inflammatory infiltrate similar to a foreign body reaction, whereas primary melanomas in HGF × CDK4R24C mice did not show an inflammatory infiltration or a mesenchymal tissue reaction (Fig. 5B, 3). Both transplanted as well as autochthonous melanoma grew invasively in underlying s.c. fat and muscle and induced neoangiogenesis (Fig. 5B, 4). As expected, B16 melanoma and primary melanomas in HGF × CDK4R24C mice both expressed the melanocytic antigen TRP2, which represents our candidate vaccine target (Fig. 5B, 5). In agreement with the macroscopically visible growth kinetic and mitotic index, B16 melanoma cells were highly positive for the proliferation marker Ki67. In contrast, primary melanomas in HGF × CDK4R24C mice only showed occasional spindle-shaped cell staining positive for Ki67 (Fig. 5B, 6). These observations documented the profound differences of the two experimental models.
Evidence for tumor immunotolerance in carcinogen-treated HGF × CDK4R24C mice bearing autochthonous primary melanomas in the skin. Finally, we investigated the ability of carcinogen-treated HGF × CDK4R24C mice bearing autochthonous primary melanoma to reject transplanted B16 melanoma. Cohorts of HGF × CDK4R24C mice were treated neonatally with DMBA followed by application of TPA as described in Fig. 3A. Starting at around day 74, mice bearing autochthonous primary melanoma were therapeutically vaccinated with Ad-hTRP2 in combination with synthetic TLR ligands as described in Fig. 1A. A control cohort of carcinogen-treated HGF × CDK4R24C mice received Ad-β-gal only. Kaplan-Meier graph representing survival of carcinogen-treated HGF × CDK4R24C mice in the two treatment cohorts. Routinely, mice were sacrificed when melanomas grew progressively and tumor area exceeded 100 mm².

Figure 4. Treatment of carcinogen-induced HGF × CDK4R24C mice with recombinant adenovirus and TLR ligands delays growth of autochthonous primary melanomas in the skin and spontaneous metastases in the lungs. A, cohorts of HGF × CDK4R24C mice were treated with 20 μg DMBA at day 4 after birth followed by twice weekly application of 5 μg TPA from week 3 to 8. Starting at around day 74, mice bearing autochthonous primary melanoma were therapeutically vaccinated with Ad-hTRP2 in combination with synthetic TLR ligands as described in Fig. 1A. A control cohort of carcinogen-treated HGF × CDK4R24C mice received Ad-β-gal only. Kaplan-Meier graph representing survival of carcinogen-treated HGF × CDK4R24C mice in the two treatment cohorts. Routinely, mice were sacrificed when melanomas grew progressively and tumor area exceeded 100 mm². B, size of the largest primary cutaneous melanoma in representative groups of five individual mice over time expressed as tumor area in mm². C, points, number of primary cutaneous melanomas at the time of sacrifice; bars, SE. D, points, number of spontaneous lung metastases at the time of sacrifice; bars, SE.

Figure 5. Growth kinetics and histopathologic appearance of engrafted B16 melanoma and carcinogen-induced autochthonous primary melanoma in the skin differ considerably. A, growth kinetics of 10⁵ B16 melanoma cells engrafted in the skin of WT mice versus autochthonous primary melanoma in the skin of HGF × CDK4R24C mice treated neonatally with 20 μg DMBA and TPA as described above. Sizes of B16 melanomas or the largest primary melanoma in a representative group of individual mice over time expressed in mm². B, histologic and immunohistologic comparison of engrafted cutaneous B16 melanoma and primary autochthonous melanoma in the skin of carcinogen-treated HGF × CDK4R24C mice. 1, representative H&E-stained skin sections at low-power magnification (×25). 2, cellular morphology at high-power magnification (×200). 3, inflammatory infiltrate and mesenchymal reaction at the tumor border at high-power magnification (×200). 4, angiogenesis and invasion at the deep tumor front at high-power magnification (×200). 5, immunohistochemical staining for TRP2 confirming the melanocytic origin of the tumor cells and expression of the antigenic target at high-power magnification (×200). 6, immunohistochemical staining for the proliferation marker Ki67 at high-power magnification (×200).
rapidly in the skin and lungs of both groups. To rule out that carcinogen treatment could have caused general immunosuppression, we engrafted groups of five WT mice, which were also treated neonatally with DMBA and TPA either intracutaneously or i.v. with B16 melanoma cells and therapeutically vaccinated with Ad-hTRP2 in combination with synthetic TLR ligands as described in Fig. 1A. Control cohorts of mice received Ad-β-gal only. Kaplan-Meier graphs representing survival of therapeutically vaccinated carcinogen-treated WT, CDK4R24C, or HGF/C2CDK4R24C mice. Routinely, mice were sacrificed when melanomas grew progressively and tumor area exceeded 100 mm². C, size of cutaneous B16 melanoma in representative groups of five individual mice over time expressed as tumor area in mm². D, points, average number of B16 melanoma lung metastases in the different treatment groups from two independent experiments with five mice per group; bars, SE.

Discussion

In our investigations, we evaluated the efficacy of an immunotherapeutic strategy combining adenoviral vaccination with injections of CpG DNA and dsRNA against engrafted B16 melanoma and carcinogen-induced autochthonous primary melanoma. Our rationale was to induce tumor-reactive CD8⁺ T cells and support their effector function in the tumor tissue. We chose TRP2 as a clinically relevant, CTL-defined model self-antigen because it is naturally expressed by melanoma cells as well as melanocytes both in mouse and man. By using CpG DNA and polyI:C as ligands for TLR9 and TLR3, respectively, we sought to activate both MyD88- and TRIF-dependent signal transduction cascade and optimally stimulate the production of type I IFNs and other proinflammatory cytokines, which are able to enhance tumor immunity. In agreement with published data, we observed that injections of
TLR ligands alone were able to significantly inhibit growth of established B16 melanoma lung metastases (13). In contrast, combined stimulation of the innate and adaptive arm of the immune system was required to control growth of established B16 melanoma in the skin. Injections of CpG DNA alone only slowed the growth of cutaneous B16 melanoma as reported previously (12). Interestingly, vitiligo-like fur depigmentation was observed in mice, which rejected B16 melanoma following treatment with Ad-hTRP2 and TLR ligands, supporting the notion that effective immunity against melanoma is frequently associated with the induction of melanocyte-specific autoimmunity (1, 23). Future studies will have to show how the combined stimulation of the innate and adaptive immune system synergistically enhances antimelanoma immunity. An attractive hypothesis is the potential reciprocal interaction of activated natural killer (NK) and dendritic cells, which support the stimulation and the effector functions of antigen-specific CD8+ CTL.

The most important goal of our study was to evaluate the efficacy of our candidate immunotherapeutic strategy in a novel genetic mouse model against autochthonous primary melanoma, which more closely represents the expected clinical situation. We used HGF \times CDK4R24C mice, which rapidly develop primary cutaneous melanoma following neonatal treatment with DMBA and TPA. This model is very attractive because primary melanoma spontaneously metastasizes to lymph nodes and lungs in the absence of other tumor types. Our experiments showed that melanoma vaccination in combination with TLR ligand injections is able to delay growth of autochthonous primary melanomas and reduce the number of spontaneous lung metastases of genetically melanoma-prone HGF \times CDK4R24C mice. However, regression of primary melanoma and visible vitiligo-like fur depigmentation could not be achieved despite the induction of antigen-specific cellular immunity. This result reflects the experience in clinical trials for melanoma vaccines where the induction of tumor-specific T cells is occasionally associated with prolonged survival but only very rarely with complete tumor regression (24).

The development of autochthonous primary melanoma in carcinogen-treated HGF \times CDK4R24C mice could, in principle, lead to spontaneous induction of melanocyte-specific immune responses associated with concomitant immunity to transplanted melanoma cells (25). This has been reported in the melanoma-prone MT/ret mice when crossed onto the C57BL/6 background (26). However, we found that carcinogen-treated HGF \times CDK4R24C mice bearing autochthonous primary melanomas were unable to reject B16 melanoma engrafted at an age of \( \sim 70 \) days even when treated with Ad-hTRP2 and TLR ligands. The apparent inefficacy of our immunotherapeutic strategy in melanoma-bearing HGF \times CDK4R24C mice was not due to the carcinogenic treatment with DMBA plus TPA because established B16 melanomas were rejected by a significant percentage of WT and CDK4R24C mice under the same experimental conditions. Furthermore, untreated HGF \times CDK4R24C mice were able to mount cellular immunity against TRP2 associated with therapeutic efficacy against established B16 melanoma metastases as well as vitiligo-like fur depigmentation. These results suggest that carcinogen-treated HGF \times CDK4R24C mice bearing autochthonous primary melanoma develop tumor tolerance. This agrees with a similar observation recently reported in another spontaneous mouse model (27). We hypothesize that injections of TLR ligands are able to partially overcome the intrinsic barrier to immune cell infiltration and effector function of the tumor in melanoma-bearing HGF \times CDK4R24C mice as has been shown in another autochthonous mouse tumor model (10). However, our experiments show that a vaccine combination that is effective against tumors engrafted in the skin of normal mice may not be as effective against autochthonous primary tumors. In our opinion, this observation is of great importance because the majority of concepts in tumor immunology stem from experiments based on tumors engrafted in syngeneic recipients. We compared the growth kinetics and the histopathologic appearance of engrafted B16 melanoma and autochthonous melanoma in HGF \times CDK4R24C mice in detail to show the fundamental difference. Autochthonous melanomas slowly develop for many weeks, which may allow for the establishment of a unique tumor microenvironment characterized by tolerogenic dendritic cells, high concentrations of immunosuppressive cytokines, such as interleukin-10 (IL-10) and tumor growth factor-\( \beta \) (TGF-\( \beta \)), ineffective T-cell cytotoxicity, and high frequency of regulatory T cells. In future experiments, the immunomodulation mechanisms preventing effective tumor immune defense in HGF \times CDK4R24C mice will have to be characterized to optimize our immunotherapeutic strategy. It is conceivable that mice develop tumor antigen-specific tolerance as a result of T-cell deletion, anergy, or regulation. However, nonspecific mechanisms impairing immunologic effector mechanisms, such as the cytotoxicity of T cells and NK cells in the tumor tissue, will also have to be considered. In our experimental model, transgenic overexpression of HGF may itself be involved in suppressing tumor immunity because HGF has recently been shown to inhibit the function of antigen-presenting dendritic cells and induce the expression of regulatory T cells. In future experiments, the immunosuppressive effect of HGF could also explain why treatment of established B16 melanoma with Ad-hTRP2 and TLR ligands was consistently less effective in HGF \times CDK4R24C mice compared with WT mice. Thus, HGF may represent a link between oncogenic transformation and suppression of antitumor immune responses, which have recently achieved increasing attention and may support the development of melanoma in our model (30, 31).

In addition to the stimulation of TLR, it might be helpful to attract more dendritic cells into tumor tissue and counteract immunoregulatory as well as immunosuppressive factors, such as IL-10 or TGF-\( \beta \) (28, 29). The potential immunosuppressive effect of HGF could also explain why treatment of established B16 melanoma with Ad-hTRP2 and TLR ligands was consistently less effective in HGF \times CDK4R24C mice compared with WT mice. Thus, HGF may represent a link between oncogenic transformation and suppression of antitumor immune responses, which have recently achieved increasing attention and may support the development of melanoma in our model (30, 31).

In our opinion, investigations in genetic mouse models, which are based on molecular changes observed in the pathogenesis of hereditary and sporadic human melanoma, in principle, represent the expected clinical situation much more adequately than models involving transplantation of tumor cell lines. We firmly believe that further investigations in genetic mouse models will improve our understanding of the role of the immune system in the pathogenesis of melanoma and will facilitate the optimization of treatment regimens, which might be effective in the future treatment of melanoma patients. The HGF \times CDK4R24C experimental mouse melanoma model provides unique possibilities for further studies because melanoma develops autochthonously in the skin and spontaneously metastasizes to lymph nodes and lungs in the absence of other tumor types.
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References


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