T cell surveillance is often effective against virus-associated tumors because of their high immunogenicity. It is not clear why surveillance occasionally fails, particularly against hepatitis B virus– or hepatitis C virus–associated hepatocellular carcinoma (HCC). We established a transgenic murine model of virus-induced HCC by hepatocyte-specific adenovirus-induced activation of the oncogenic SV40 large T antigen (TAg). Adenovirus infection induced cytotoxic T lymphocytes (CTLs) targeted against the virus and TAg, leading to clearance of the infected cells. Despite the presence of functional, antigen-specific T cells, a few virus-infected cells escaped immune clearance and progressed to HCC. These cells expressed TAg at levels similar to HCC isolated from neonatal TAg-tolerant mice, suggesting that CTL clearance does not select for cells with low immunogenicity. Virus-infected mice revealed significantly greater T cell infiltration in early-stage HCC compared with that in late-stage HCC, demonstrating progressive local immune suppression through inefficient T cell infiltration. Programmed cell death protein-1 (PD-1) and its ligand PD-L1 were expressed in all TAg-specific CD8+ T cells and HCC, respectively, which contributed to local tumor-antigen-specific tolerance. Thus, we have developed a model of virus-induced HCC that may allow for a better understanding of human HCC.

Introduction

T cell surveillance is often effective against virus-induced tumors because of their high immunogenicity (1, 2). It remains unclear why surveillance occasionally fails, e.g., against hepatitis B virus–associated (HBV-associated) or hepatitis C virus–associated (HCV-associated) hepatocellular carcinoma (HCC). Possible reasons could be an initial failure to induce effective T cells (3–5), T cell exhaustion due to chronic antigen stimulation (6, 7), tumor-induced tolerance (8), immune escape by loss of immunogenicity (9), or tumor development in tolerogenic organs, e.g., the liver (10). In humans, T cell responses appear to be more efficient in those individuals who completely cleared the virus (11, 12); however, it is difficult to identify individuals in the acute infection phase (4, 12). HCC progresses in a great proportion of individuals with chronic HCV infection in the presence of virus-specific CD8+ T cells (13–15). On the other hand, impaired HCV-specific T cell responses have been observed in PBMCs or liver biopsies obtained from patients with chronic HCV infection (4, 16–18). Heterogeneity within individuals, difficulties in analyzing local T cell responses, and the need of in vitro manipulation and expansion for functional analysis of HCV-specific T cells make firm conclusions difficult. Likewise, in chimpanzees, no strict correlation between virus clearance and vigorous T cell responses was observed (19, 20).

Several HCV transgenic mouse lines with constitutive or inducible HCV expression and models that allow infection of hepatocytes by HCV have been generated (21–28). While these models have yielded important information about viral pathogenesis, the mice were either tolerant for viral antigens or did not develop HCC with reliable, high frequency. Thus, the endogenous T cell response to virus-induced HCC throughout the course of the disease has not been analyzed. To overcome the problem of T cell tolerance to viral antigens, T cells from HBV-immunized wild-type mice were transferred into HBV transgenic mice. The data showed that CD8+ T cells were mainly responsible for hepatitis and that viral replication was abolished by cytolytic and noncytolytic mechanisms (29). The chronic necroinflammatory T cell response was suggested to contribute to HCC development (30). On the other hand, HCC developed in some HCV transgenic mice independent of inflammation (25), and it is not clear whether the fate of adoptively transferred CD8+ T cells recapitulates that of the endogenous T cell pool following viral infection. Here, we established a model of virus-induced HCC, in which a viral oncogene, SV40 large T antigen (TAg), was activated in hepatocytes through viral infection of a host, LoxP-TAg mice, that can efficiently respond to TAg. In LoxP-TAg mice, Cre recombinase–encoding adenoviruses (Ad.Cre) with high tropism for the liver deleted a stop cassette, which prevented TAg expression. Previously, we have shown that these mice have retained CD8+ T cells against peptide IV (pIV), the dominant epitope of TAg, which could be induced by prophylactic immunization for protection from sporadic tumors that occur late in life (8, 31). In contrast to mice with virus-induced HCC reported here, mice with sporadic lesions readily developed TAg-specific CD8+ T cell tolerance.

Results

Virus-induced oncogene activation and HCC development. LoxP-TAg mice allow activation of the dormant TAg oncogene by Cre/loxP recombinase–mediated stop cassette deletion (Figure 1A). Based on Ad.Cre infection of the liver we established a model for virus-induced HCC. LoxP-TAg mice were injected i.v. with Ad.Cre and monitored for tumor development by MRI, palpation, and determination of liver enzymes alanine aminotransferase (ALT) and aspartate transaminase (AST). By MRI, palpation, and determination of liver enzymes alanine aminotransferase (AST) and aspartate transaminase (ALT)
detected in the liver 8–16 weeks after virus infection (Figure 1B). Elevated ALT and AST levels were detected 1 week after virus infection, indicating liver damage (Supplemental Figure 1; supplemental material available online with this article; doi:10.1172/JCI64742DS1). After 4 to 6 weeks, ALT/AST values returned to slightly elevated levels, when compared with those of control mice, and subsequently increased proportionally to HCC development. The virus-induced TAg activation induced multinodular HCC of classical type, resembling hepatocytes with a predominantly trabecular (plate-like) architectural pattern within 8 to 24 weeks (in some

Figure 1
LoxP-TAg transgenic mice develop HCC after i.v. injection of Ad.Cre. (A) Cre recombinase–mediated TAg activation. (B) For induction of HCC, 8- to 12-week-old LoxP-TAg mice were injected i.v. with $1 \times 10^9$ PFUs of Ad.Cre, and HCC development was detected by MRI and palpation. Representative MR images (left) and macroscopically visible tumors of livers 10 (middle) and 20 weeks (right) after Ad.Cre injection are shown. MR image and liver photograph (middle) are from the same mouse. Arrows indicate tumor nodules. (C) LoxP-TAg mice that received Ad.Cre (red line, $n = 14$) and double-transgenic LoxP-TAg × Alb-Cre (DTg) mice (blue line, $n = 15$) were monitored for HCC development. Nontreated LoxP-TAg mice (black line; $n = 10$) served as control. Time after adenovirus injection is given for Ad.Cre-injected mice, and age is given for double-transgenic LoxP-TAg × Alb-Cre mice. (D) Immunohistology of liver tissue sections of LoxP-TAg mice at different time points after Ad.Cre injection as indicated. Tissues were stained with antibodies specific for TAg and Ki-67 and counterstained with hematoxylin. Scale bar: 100 μm. At least 3 mice were analyzed for each time point, and a representative staining is shown. Schematic drawings show an overview of the cumulative data of the average tumor number and progression not considering inter-mouse variability.
mice 35 weeks) (Figure 1, C and D, and Supplemental Figure 2). In comparison, neonatal TAg-tolerant LoxP-TAg × albumin-Cre (Alb-Cre) mice that express the Cre recombinase by the albumin promoter and activate TAg in the liver early in life developed HCC within 7 to 14 weeks of age (Figure 1C). Upon liver tumor development, LoxP-TAg × Alb-Cre mice showed an increase of ALT/AST values that stayed elevated until mice succumbed to HCC and cholangiolar carcinoma (Supplemental Figure 3). Nontreated LoxP-TAg mice did not develop HCC or pathological abnormalities in the liver during the more than 12-month observation time, as assessed by MRI, histology (data not shown), and determination of liver enzymes ALT and AST (Supplemental Figure 4). TAg expression was abundantly detected throughout the liver 1 week after viral infection (Figure 1D). Ki-67 expression often mirrored TAg expression, indicating abundant cell proliferation in TAg-expressing hepatocytes. Within the next 3 weeks, TAg⁺ cells were almost completely eliminated, leaving behind few microscopically small TAg⁺ lesions, which then progressed to HCC (Figure 1D).

TAg recognition during viral infection induces T cell immunity. Our model is based on the assumption that the stop cassette is deleted and TAg is activated in virus-infected liver cells and that TAg is recognized by the adaptive immune system concomitant with a strong antiadenoviral immune response. Within 3 weeks after Ad.Cre infection, LoxP-TAg mice developed high anti-TAg IgG antibody titers, demonstrating that TAg was rapidly recognized by the adaptive immune system and suggesting functional CD4⁺ T cell activation (Figure 2A). Neither Ad.Cre infection of C57BL/6 (B6) mice nor luciferase-encoding adenovirus (Ad.Luc) infection of LoxP-TAg mice induced anti-TAg antibodies. Bioluminescence (BL) imaging of Ad.Luc-infected LoxP-TAg mice confirmed the high tropism for the liver (Supplemental Figure 5). The TAg-specific IgG antibodies were of IgG1, IgG2a, and IgG2b isotypes (Figure 2B). Because
the IgG1 isotype was not observed in LoxP-TAg mice with sporadic tumors, TAg recognition in the viral context apparently induced functionally different CD4+ T cells. During subsequent HCC progression, anti-TAg IgG serum titers increased to dramatically high levels (Figure 2A). In order to directly assess the role of T cells during HCC development, CD4+ and CD8+ T cell–deficient LoxP-TAg mice were infected with Ad.Cre. The absence of both CD4+ T cells and CD8+ T cells substantially reduced the latency of virus-induced HCC in comparison with that in T cell competent–LoxP-TAg littermates (Figure 2C). Similarly, strongly accelerated HCC development was observed in combined Rag-2/IL-2 receptor γ chain–deficient LoxP-TAg mice, which lack T cells, B cells, and NK cells (Figure 2D). Because the immune deficiency also might have abolished antiaidenoviral T cell responses and clearance of virus-infected cells, HCCs were induced by viral infection in villin-Cre (Vil-Cre) × LoxP-TAg double-transgenic mice. Due to constitutive stop cassette deletion and TAg activation in epithelial cells of the gastrointestinal tract, these mice had developed neonatal cytotoxic T lymphocyte (CTL) tolerance for TAg but were otherwise immune competent (32). Virus-induced HCC developed with similar reduced latency in Vil-Cre × LoxP-TAg mice as in T cell–deficient mice (Figure 2E). Collectively, the data indicate that virus-induced TAg activation in hepatocytes led to T cell immunity, which inhibited but did not prevent HCC development long term. Furthermore, TAg-specific T cells were mainly responsible for impairing HCC progression.

Virus-induced HCCs “sneak through” despite persistently functional CTLs. In LoxP-TAg mice with sporadic tumors, anti-TAg IgG antibodies predicted TAg-specific CTL tolerance (31). In contrast, in vivo CTL assays in Ad.Cre-infected LoxP-TAg mice revealed that functional CTLs directed against the immunodominant TAg pIV were induced as early as 2 weeks after virus infection (Figure 3, A and B). Remarkably, pIV-specific CTLs persisted in the presence of progressing TAg+ HCC (Figure 3B). The strongest pIV-specific CTL
activity was detected in mice with large tumor burdens, suggesting that the progressing HCC upregulated CTL activity in the spleen (Figure 3B, white circles). CTLs specific for the adenovirus protein DNA-binding protein 43 (dbp43) were also induced upon Ad.Cre infection and were detectable by in vivo kill analysis throughout the experiment (Figure 3C).

As a more rigorous test for functional pIV-specific CTLs, HCC-bearing LoxP-TAg and − as controls − Rag2−/− mice, young LoxP-TAg mice, and old LoxP-TAg mice with sporadic tumors were challenged s.c. with the TAg-expressing tumor cell line 16.113 (Table 1). Whereas in Rag2−/− mice tumors grew, most LoxP-TAg mice infected with viruses 4, 8, and 24 weeks before (22 out of 24 mice) rejected the transplanted tumor cells, while the primary TAg+ HCC progressed. In accordance with previous observations, LoxP-TAg mice with sporadic tumors did not reject 16.113 cells, whereas young LoxP-TAg mice rejected the transplanted tumors cells. Thus, TAg-specific CTLs, functionally activated upon virus-mediated TAg expression, were not systemically tolerized by tumor cells. Therefore, no selection for low immunogenicity occurred in TAg-expressing HCC, despite the persistent presence of functional pIV-specific CTLs.

Virus-induced HCCs induce antigen-specific local tolerance. The previous experiments raised the question of how the HCCs, regressors upon transplantation, could progress in the presence of functional pIV-specific T cells. Histopathological examination of livers from nontreated and Ad.Cre-infected LoxP-TAg mice at different time points thereafter revealed moderate infiltration of the tumor nodules by CD3+ T cells (Figure 5A). Quantitative analysis of CD3+ T cell infiltration revealed significantly higher infiltration of small tumor nodules that developed 6–10 weeks after Ad.Cre infection in comparison with that of end-stage HCCs in mice 12–35 weeks after Ad.Cre infection. Peritumoral CD3+ T cell infiltration in end-stage tumors was only slightly higher (statistically not significant) than intratumoral infiltration (Supplemental Figure 6). Whereas FoxP3+ cells were not detected (Figure 5A), F4/80+ cells, comprising macrophages and Kupffer cells, were equally distributed in the livers of naive and virus-infected mice (Figure 5A, weeks 0–4) but were decreased in cancerous tissue (Figure 5A, weeks 6–10 and 12–35). Solid tumors are supposed to create an immune-suppressive environment. We detected CD163+ M2 macrophages, FAP+ stromal cells, and CD11b+/Gr-1− immature myeloid cells in end-stage HCC (Supplemental Figure 7). Therefore, these components potentially could contribute to local immune suppression. To analyze local T cell function in HCC, 16.113 cells, transduced to express luciferase (Fluc) and EGFP (16113gl), were injected into the livers of virus-induced HCC-bearing LoxP-TAg mice, and mice were observed until they had to be sacrificed due to primary HCC burden. Histological analysis of liver sections revealed the growth of 16.113gl tumors with the typical ductal appearance of this (gastrointestinal-derived) tumor, TAg-specific staining, and absence of the liver/HCC-specific marker HepPar1 in both HCC-bearing LoxP-TAg and Rag2−/− mice (Figure 5B). Age-matched tumor-free LoxP-TAg mice rejected 16.113gl cells injected into the liver (data not shown). Because 16.113 cells were rejected in HCC-bearing mice at a s.c. injection site (Table 1), the data demonstrate local tolerance in HCC-bearing LoxP-TAg mice.

16.113 cells were transduced to express luciferase and EGFP (16113gl) not only to visualize tumor growth but also to express foreign antigens in the tumor cells. This allowed us to ask whether tolerance in the tumor microenvironment was specific for TAg, the dominant transplantation rejection antigen in TAg-transformed tumors (8), or whether CTLs were suppressed independent of their specificity. First, 16113gl cells were injected s.c. to analyze whether variants that lost the marker proteins (or the coexpressed selectable markers neomycin and hygromycin) could be selected in suitable hosts. In Rag2−/− mice, tumors grew and retained Fluc expression, as detected by BL imaging (Figure 5C). In LoxP-TAg × Alb-Cre mice, which are TAg tolerant but generate normal CTL responses to other antigens (31), Fluc (and EGFP; data not shown) signals became undetectable within 2 to 3 weeks (Figure 5, C and D), while TAg+ tumors progressed after a short selection phase (Figure 5D). In young LoxP-TAg mice, 16113gl tumors were rejected. Compatible with previous experiments, in old LoxP-TAg mice with sporadic tumors, which had developed TAg tolerance and CTL hyporesponsiveness to unrelated antigens (31), 16113gl

<table>
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<td>Rag2−/−</td>
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<td>–</td>
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1 × 105 TAg+ 16.113 cells were injected s.c. into untreated 8- to 12-week-old Rag2−/− mice. LoxP-TAg mice (Young Tg), LoxP-TAg mice bearing large sporadic tumors (Tg, sporadic), and LoxP-TAg mice that had been injected with Ad.Cre when they were 8–12 weeks old (Tg). Tumor growth was followed using caliper measurement. aThe number of mice with challenge tumor per mice in experiment is shown. Mice were observed until they had to be sacrificed because of primary HCC or challenge tumor grew to an average size of at least 6 mm in diameter (for these mice, time to growth of transplanted tumor cells is given in brackets). bYoung LoxP-TAg mice observed for the indicated time were tumor free.
transiently, while retaining the Fluc signal, albeit at reduced level (Figure 5, C and D). These data show that antigen loss variants progressed (Figure 5B). These signals were lost within 2 to 3 weeks (Figure 5E and Supplemental Figure 14). Probably, the few TAg+ cells from nontreated age-matched LoxP-TAg mice (Figure 6A). The frequency of Kb/IV-tetramer+ cells of the CD8+ T cells but not in nonvirus-induced sporadic cancer, leading to impaired CTL responses against unre- and lack of local inflammation prevented T cells from inducing autoimmunity and liver damage (33). If such a mechanism would be operative in our model, blockade of PD-1 should not be effective. To test this possibility, we blocked PD-1/PD-L1 interactions. LoxP-TAg mice with HCC 12 weeks after virus infection were treated with anti-PD-1 antibodies for 2 weeks, revealing a significant delay in HCC progression when compared with mice that received isotype control antibodies (Figure 6D). The data are in agreement with data in HBV transgenic mice showing functional suppression of virus-specific CD8+ T cells by PD-1/PD-L1 interaction (34). However, this study left open whether other mechanisms contributed to CD8+ T cell suppression and whether PD-1+CD8+ T cells could suppress primary PD-L1+ HCC in a permissive host. We also analyzed pIV-specific CD8+ T cells in the liver for the presence of other inhibitory receptors involved in T cell exhaustion, namely Lag3, Tim-3, and CD160. We found that a high proportion of intrahepatic pIV-specific CD8+ T cells expressed Lag3, Tim-3, and CD160. This result is in agreement with previous studies suggesting that accessibility of T cells to the liver microenvironment is mediated by PD-1/PD-L1 independent and independent mechanisms. pIV-specific CD8+ T cells in livers and spleens of LoxP-TAg mice with virus-induced HCC were analyzed with Kb/IV-tetramers. A high frequency of the CD8+ T cells in the livers of HCC-bearing LoxP-TAg mice were pIV specific (14%–31% Kb/IV-tetramer+ cells of the CD8+ T cells) but not in age-matched nontreated LoxP-TAg mice (Figure 6A). The frequency of Kb/IV-tetramer+ CD8+ T cells in the spleens of HCC-bearing LoxP-TAg mice was 5%–6%, whereas it was undetectable in the control mice. Importantly, programmed cell death protein-1 (PD-1) receptor was expressed on almost all Kb/IV-tetramer+ CD8+ T cells in the liver (Figure 6B). PD-1 expression was higher on liver compared with that on spleen pIV-specific CD8+ T cells (Supplemental Figure 9). All virus-induced HCC cell lines investigated expressed the ligand PD-L1, whereas hepatocytes from noninfected LoxP-TAg mice did not (Figure 6C). In addition, immunohistochemical analysis of livers from HCC-bearing LoxP-TAg mice showed PD-L1 expression on TAg-positive carcinoma cells and TAg-negative stromal cells (Supplemental Figure 10). Notably, intrahepatic CD11c+, CD68+, and Gr-1+ cells showed upregulation of PD-L1 when HCC-bearing LoxP-TAg mice 10–20 weeks after Ad.Cre infection were compared with untreated age-matched LoxP-TAg mice (Supplemental Figure 11). The sporadic tumor cell line 16.113 that grew in livers of HCC-bearing mice also expressed PD-L1 (Figure 6C).

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Sneaking through has been described previously in tumor models. However, in our study, most TAg+ hepatocytes survived, while neighboring infected TAg– cells were eliminated. We observed that the tumor-unrelated T cell responses were also suppressed within the suppressive tumor microenvironment. Remarkably, transplanted tumor cells were selected against expression of foreign antigen but not TAg in the livers of HCC-bearing mice, demonstrating local tolerance specifically for the rejection antigen of HCC. Tolerance required the presence of HCC, because young untreated LoxP-TAg mice rejected TAg+ tumor cells injected into the liver. Our data contrast those obtained in a tumor transplantation model, suggesting that tumors are a privileged site for bacterial growth (48). Because the rapid growth of the transplanted tumor, bacterial accumulation could be observed for only 6 days after intratumoral injection. Therefore, it is not clear whether an innate or adaptive immune response was impaired and whether the bacteria would have been eliminated at a later time point. This model is also difficult to compare to ours, because the bacteria, Listeria monocytogenes, reside inside macrophages and CD4+ T cells are mainly responsible for protection.

The virus-induced HCC used at least 2 independent mechanisms of local tolerance, each of which was necessary for unimpaired progression. PD-1, expressed by almost all TAg-specific CD8+ T cells in HCC-bearing mice, and PD-L1, expressed by the HCC, together with the observation that a brief treatment with anti-PD-L1 blocking antibodies substantially delayed HCC progression, reveal the first immune escape mechanism. We cannot exclude a contribution of PD-L1 expression by tumor stroma cells for T cell inhibition. This appears even likely, because various tumor stroma cell types expressed PD-L1 (49–52). PD-1 expression by CD8+ T cells has been associated with cellular exhaustion in models of persistent viral infection (6, 53). Even though we cannot rule out some functional impairment of the TAg-specific PD-1+ CD8+ T cells (5), they exhibited undiminished CTL activity in vivo, rejected TAg+ tumor cells injected at a s.c. site and, importantly, inhibited autochthonous HCC progression upon transfer into sublethally irradiated mice. In fact, CTL activity was upregulated as HCC progressed and antigen amount was increased. Thus, while PD-1/PD-L1 interaction was clearly involved in local immune suppression, it was not sufficient to constrain HCC progression. We found additional inhibitory receptors, Lag3, CD160, and CD226, which are recognized by several tumor associated antigens (54). In contrast to PD-1/PD-L1, Lag3 and CD226 do not influence antibody production and T cell activation. Therefore, it is possible that CD226 and Lag3 are involved in immune tolerance.}

7 weeks after viral infection (Supplemental Figure 4B) was similarly effective as that after 12 weeks (Figure 6, E and F). Together, both PD-1/PD-L1-dependent and –independent mechanisms appear to contribute to local tolerance. Furthermore, PD-1+CD8+ T cells have the potential to eliminate HCC in conditioned hosts.

**Discussion**

We established a model that recapitulates several features of virus-induced HCC in humans. A strong viral antigen, for which the mice were not tolerant at young age, was activated and recognized by T cells during viral infection of hepatocytes. The virus infection induced an antiviral response concomitant with a rapid and strong response against TAg, the cancer-driving oncogene, due to stop cas- sette deletion in the infected hepatocytes. T cell recognition resulted in hepatitis and clearance of the infected TAg+ cells, at least the vast majority. Because adenoviruses do not replicate in mice, we ensured that the very few remaining TAg+ hepatocytes escaped elimination and were not induced by viral spread. It remains enigmatic why these few TAg+ hepatocytes survived, while neighboring infected TAg– cells were eliminated. They could have expressed less TAg during the effector CTL response (35), deleted the stop cassette when effector CTLs already went through the contraction phase (36), or reflected a subtype of hepatocytes that are resistant to elimination (37, 38). Strikingly, the few TAg+ hepatocytes that sneaked through, despite functionally activated TAg-specific CTLs, were recognized at some point and upregulated systemic tumor immunity, at least at sites distant from the primary tumor, while progressing to lethal HCC. Sneaking through has been described previously in tumor transplantation models, in which low numbers of injected tumor cells remained unrecognized for too long by T cells (39). Sneaking through had not been demonstrated before in a primary tumor model in the presence of functionally activated CTLs.

Our data illustrate the fundamentally different immune response to sporadic and virus-induced tumors, directed against the same antigen in the same mouse model. If left untreated, LoxP-TAg mice develop in a stochastic manner sporadic tumors late in life after a long premalignant phase (8, 31). TAg recognition in mice with premalignant lesions, as detected by the generation of anti-TAg IgG antibodies, induced CTL tolerance, and no transient phase of functional activation was detected (31). In sharp contrast, if TAg was recognized by T cells during viral infection, anti-TAg antibodies were of partially different IgG subtype, indicating already the qualitatively different adaptive immune response. More importantly, in the viral context, CD4+ and CD8+ T cells were functionally activated and substantially delayed HCC progression. The response was primarily directed against TAg, because TAg-tolerant mice rapidly succumbed to HCC. In contrast to (non)virus-induced sporadic tumors, the virus-induced HCC needed to escape immune control. Immune escape did not involve systemic CTL tolerization or the apparent selection of low immunogenic variants. However, the observation that HCCs, progressors in the primary host with systemic tumor immunity, were regressors in transplantation experiments raises doubts about the ability of this assay to measure immune selective processes in the primary host.
research article
Local tolerance is mediated by PD-1/PD-L1–dependent and –independent mechanisms. (A) Spleen and liver cells from nontreated and HCC-bearing LoxP-TAg mice 27 weeks after Ad.Cre infection were analyzed for CD8 expression and Kb/IV tetramer binding. Representative plots (n = 5; range from 14%–31% double-positive cells) are shown. (B) CD8+ T cells as in A were analyzed for PD-1 expression and Kb/IV tetramer binding. Representative plots (n = 4; 7%–23% of Kb/IV tetramer– CD8+ T cells expressed PD-1) are shown. (C) Hepatocytes from nontreated LoxP-TAg mice (liver), HCC line Ad.Cre, and 16.113 cells were stained with isotype control or anti–PD-L1 antibodies. Representative plots (n = 4) are shown. (D) HCC-bearing LoxP-TAg mice 12 weeks after Ad.Cre infection received anti–PD-L1 (red line, n = 5) or isotype control antibody (black line, n = 5) for 2 weeks, and survival was monitored. One of two experiments with comparable results is shown. (E) HCC-bearing LoxP-TAg mice 14 weeks after Ad.Cre injection (red line, n = 6) received irradiation (5 Gy) and 5 × 106 spleen cells from Ad.Cre-treated HCC-bearing LoxP-TAg mice (16 weeks after Ad.Cre injection) or were left untreated (black line, n = 5), and survival was monitored (see also Supplemental Figure 14B). (F) Irradiated HCC-bearing LoxP-TAg mice 16 weeks after Ad.Cre injection (red line, n = 11) were treated with 1 × 106 CD8+ T cells obtained from mice as in E or left untreated (black line, n = 4), and survival was monitored.

One could have expected that tumor development in the liver, as a supposedly tolerogenic organ, rather than in the lung would have induced systemic tolerance, yet the opposite was the case. The high immunogenicity and the high infection rate of the adenovirus compared with that of the lentivirus may explain the different results. Thus, the adenovirus may act as stronger adjuvant to activate TAg-specific T cells compared with the lentivirus that helps the activation of the chosen model antigens SIY and ovalbumin (59, 60). Two reasons may explain the different mechanisms of immune escape in the HCC model (retention of the target antigen/high immunogenicity and local tolerance) versus the sarcoma model (loss of target antigen and selection for low immunogenicity). Sequences introduced into cells by viral infection may be silenced easier by epigenetic mechanisms than sequences introduced into the germline. More importantly, in the HCC model, the T cell response was directed against the cancer-driving oncogene, which cannot be easily selected against (61), while, in the sarcoma model, the T cell response was directed against surrogate antigens, which better reflect passenger mutations and can be easily selected against (60).

Because HCC progresses in a great proportion of patients with chronic HCV infection, despite the presence of HCV-specific CD8+ T cells (15–17, 62), and the liver-infiltrating CD8+ T cells in these patients expressed PD-1 (63), we think that our model encompassing both initial anti-virus immune response and HCC development bears high similarity to the human disease.

**Methods**

*Mice.* LoxP-TAg, Alb-Cre × LoxP-TAg, and Vil-Cre × LoxP-TAg transgenic mice were described previously (8, 31, 32). Rag2−/− mice (B6.129S6-Rag2tm1Flv5/J) and Rag2−/− C57BL/6J mice (C57BL/6J) were purchased from Taconics Farms; Cd4+−/− mice (B6.129S2-Cd4tm1Mak/J) and Cd8+−/− mice (B6.129S2-Cd8tm1Mak/J) were purchased from The Jackson Laboratory; B6 mice were obtained from Charles River; and CD45.1 congenic mice were bred in our animal facilities.

**Immunization/tumor cell transplantation.** For TAg-specific immunization, mice were injected i.p. with 5 × 106 to 10 × 106 TAg+ 16.113 tumor cells. Adenovirus-specific immunization was performed by i.v. injection of 1 × 109 PFUs of Ad.Cre. For tumor challenge experiments and analysis of TAg-specific CTL response, mice were injected s.c. with 1 × 106 cells of the indicated cell lines: 16.113 is a tumor cell line that developed spontaneously in the gastrointestinal tract of a LoxP-TAg mouse (8), HCC cell lines Ad.56/Ad.451/Ad.434 were obtained from LoxP-TAg mice 5–6 months after Ad.Cre administration, and HCC cell lines Alb.7/Alb.14/Alb.346 were isolated from 3-month-old LoxP-TAg × Alb-Cre mice (31). For analysis of local tolerance in the liver, 16.113 cells were retrovirally transduced with pLGSN and subsequently transfected with pCAG-Fluc generating cell line 16.113Fluc. For selection of transduced and transfected clones neomycin and hygromycin resistance markers were used, respectively. 1 × 106 16.113Fluc cells (bulk culture) expressing EGFP and Fluc were injected into the liver parenchyma, and growth of 16.113Fluc cells was determined by histology of liver tissue sections. Tumor volume in mice injected s.c. with 1 × 106 16.113Fluc cells into the flank was determined by caliper measurement of the tumor parameters (x,y,z) according to the formula (x2y2z2)/2. Animals that rejected the challenge tumors were monitored for at least 60 days.

**In vivo kill assays.** CTL activity against the TAg-specific pIV (VVYD-FLKL; ref. 8) was analyzed in vivo separately or simultaneously with the adenovirus dbp43 (FALSNAEDL; ref. 64). Single pIV-specific in vivo kill assay was performed as previously described (8). For simultaneous detection of CTL activity against pIV and dbp43, nonloaded (Ø) and pIV- and dbp43 peptide–loaded (1 μM each) CD45.1+ congenic spleen cells (1 × 106...
each) were labeled with CFSE in a final concentration of 0.75 μM (CFSElo), 0.075 μM (CFSEint), or 0.0075 μM (CFSEhi), respectively. A total of 3 x 10⁶ mixed cells at a 1:1:1 ratio were injected i.v. into the indicated mice. 18 hours later, spleens of recipient mice were stained with APC-labeled anti-CD45.1 antibodies (A20, BD Pharmingen) to separate CFSE-labeled cells. The ratios among the 3 populations were determined by flow cytometry, and the specific cytolytic activity was calculated as follows: percentage of specific killing = [1 – (ratio of control mice/ratio of immunized)] or 1 – [ratio of control mice/(Ad.Cre-injected mice) x 100], where the ratio is the percentage of CFSElo/CFSEint or CFSElo/CFSEhi.

ELISA. Serum samples from individual mice were collected. For detection of anti-TAg antibody, ELISA plates, coated with TAg protein, were used as described previously (8). Mouse TAg antibody (PAb 10B; BD Pharmingen) was used as standard. TAg-specific IgG1, IgG2α, IgG2b, and IgG3 were determined in serum samples, obtained from individual mice. The mouse immunoglobulin screening/isotyping kit (Zymed Laboratories) was used according to the manufacturer’s instructions.

Histology and immunohistochemistry. During autopsies of LoxP-TAg mice, whole organs or macroscopically detectable tumor tissues were embedded in paraffin. Serial sections (2–4 μm) were mounted on slides and stained with hematoxylin and eosin. For immunostaining, consecutive slides were subjected to a heat-induced epitope retrieval step before incubation with the following antibodies: mouse anti-SV40 large T, small t antigen (PAb 10B; BD Pharmingen), Ki-67 (TEC-3, Dako), CD3 (N1580, Dako), FoxP3 (FJK-16s, eBioscience), F4/80 (BM8, eBioscience), CD163 (M-96, Santa Cruz Biotechnology), fibroblast activation protein (FAP; Abcam), and HepPar1 (OCH1E5.2.10, Dako). For detection, the Streptavidin-AP Kit (K 4010, Dako) or Alexa Fluor phosphate (AP) and peroxidase were developed by Fast Red as chromogen or diaminobenzidine (DAB) (Vector Laboratories), respectively. For double immunofluorescence staining, secondary antibodies were used followed by the Streptavidin-AP Kit or the EnVision Peroxidase Kit (K 4010, Dako). Alkaline phosphatase (AP) and peroxidase were developed by Fast Red as chromogen or diaminobenzidine (DAB) (Vector Laboratories), respectively. For double immunofluorescence staining, secondary antibodies were used followed by the Streptavidin-AP Kit or the EnVision Peroxidase Kit (K 4010, Dako). Alkaline phosphatase (AP) and peroxidase were developed by Fast Red as chromogen or diaminobenzidine (DAB) (Vector Laboratories), respectively.

Flow cytometry. Single cell suspensions of spleen cells were stained with PE-labeled K0/pJv tetramers (Beckman Coulter), PerCP-labeled rat anti-mouse CD8α antibody (53-6.7; BD Pharmingen), APC-labeled hamster anti-mouse CD3α antibody (145-2C11; BD Pharmingen), APC-labeled hamster anti-mouse CD279 antibody (J43; BD Pharmingen), PerCP-eFluor 710-labeled anti-mouse CD223 (Lag3, C9B7W; eBioscience), Alexa Fluor 647-labeled anti-mouse Tim-3 (B8.2C12, BioLegend), and eFluor 660-labeled anti-mouse CD160 (CNX46-3; eBioscience). For analysis of hepatic lymphocytes and hepatocytes, livers were perfused with PBS, collagenase digested (1 mg/ml, 4 hours, 37°C), washed twice, and subsequently incubated with the antibody indicated above or PE-conjugated rabbit anti-mouse CD274 (MH5S; BD Pharmingen) and isotype-matched control antibody.

In vivo MRI. MRI experiments were performed with a 1.5-T clinical MRI instrument (Magnetom Symphony Maestro Class, Siemens), with either a CP-Breast Array or a Flex Loop Small surface coil (Siemens) as previously described (31).

Detection of liver enzymes. The transaminases ALT and AST were used as indicators for liver damage. Serum samples, mixed with Heparin, were analyzed (Laboklin).

**BL imaging.** Mice were injected i.p. with 3 mg t-luciferin (Biosynth) dissolved in PBS (30 mg/ml). 10 minutes later, mice were anesthetized with isoflurane, and BL image acquisition was performed using an exposure time of 180 seconds. BL imaging data were analyzed with the Living Image software (Caliper Life Science). For detection of adenovirus tropism, an adenovirus expressing the firefly luciferase under the control of the CMV promoter (Ad. Luc), provided by M. Zenke (Institute for Biomedical Engineering, Cell Biology, Aachen University Medical School, RWTH Aachen, Germany), was used.

**Western blot analysis.** Proteins were quantified with the Bio-Rad protein assay. 40 μg protein extract was loaded onto an NuPage Tris-acetate 3%–8% SDS-PAGE gel (Invitrogen) and blotted on a polyvinylidene fluoride membrane (Amersham Biosciences) using the XCell II blot module (Invitrogen). After blocking with 5% dried skim milk, the blot was incubated with anti-TAg IgG2a antibody (Ab-2, Calbiochem), washed with PBS containing 0.5% Tween, and subsequently incubated with HRP-labeled anti-mouse IgG2a antibody (BD Biosciences). Visualization was performed using the ECL Detection Kit (Amersham Biosciences) according to the manufacturer’s instructions and the LUMI-F1 Imaging Workstation (Roche). To confirm loading of equal amounts of protein, the blot was reprobed with anti-β-actin antibody (Abcam), followed by HRP-labeled goat anti-rabbit-IgG (BD Bioscience), and detected as described above.

**Primary tumor induction.** For HCC induction, LoxP-TAg mice (8) were injected with 1 x 10⁶ PFUs of Cre recombinase-expressing adenoviruses (Ad.Cre) by tail vein injection (i.v.).

**PD-L1 mAb treatment.** For in vivo antibody blockade, 200 μg rat anti-mouse PD-L1 (10F.9G2; Bio X Cell) and rat IgG2b isotype control (LTF-2; Bio X Cell) were injected i.p. into the indicated mice every third day for 2 weeks as described previously (7), and HCC development was monitored.

**Adoptive immune cell transfer.** For adoptive cell transfer, splenic CD8 T cells were purified by use of the CD8 + T cell isolation kit II (Miltenyi Biotech). 1 x 10⁶ purified CD8 + T cells (80%–95% purity) were injected i.v. into irradiated (5 Gy) HCC-bearing LoxP-TAg mice. For spleen cell transfer, single cell suspensions were prepared, and 5 x 10⁶ cells were transferred i.v. in vivo.

**Statistics.** Statistical analyses were performed using SPSS and Prism (GraphPad) Software. The overall significance of each graph was calculated with the Kruskal-Wallis test. Comparisons of 2 groups were done by Mann-Whitney U test. Survival curves were compared by Gehan-Breslow-Wilcoxon test. P values of less than 0.05 were regarded as statistically significant.

**Study approval.** Animal experiments were performed according to and with approval of Landesamt für Gesundheit und Soziales, Berlin, Germany.