Regulatory T Cells in an Endogenous Mouse Lymphoma Recognize Specific Antigen Peptides and Contribute to Immune Escape

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Abstract

Foxp3+ regulatory T cells (Tregs) sustain immune homeostasis and may contribute to immune escape in malignant disease. As a prerequisite for developing immunologic approaches in cancer therapy, it is necessary to understand the ontogeny and the antigenic specificities of tumor-infiltrating Tregs. We addressed this question by using a λ-MYC transgenic mouse model of endogenously arising B-cell lymphoma, which mirrors key features of human Burkitt lymphoma. We show that Foxp3+ Tregs suppress antitumor responses in endogenous lymphoma. Ablation of Foxp3+ Tregs significantly delayed tumor development. The ratio of Treg to effector T cells was elevated in growing tumors, which could be ascribed to differential proliferation. The Tregs detected were mainly natural Tregs that apparently recognized self-antigens. We identified MHC class II–restricted nonmutated self-epitopes, which were more prevalent in lymphoma than in normal B cells and could be recognized by Tregs. These epitopes were derived from proteins that are associated with cellular processes related to malignancy and may be overexpressed in the tumor.

Introduction

The immune system is capable of distinguishing harmful pathogens from self-tissues or innocuous environmental factors. CD4+ regulatory T cells (Tregs), which are characterized by the expression of surface CD25 and the transcription factor forkhead box p3 (Foxp3), are thought to contribute to immune tolerance, thereby limiting proinflammatory responses in infectious disease and preventing autoaggressive disorders (1–3). Deficiency of Foxp3+ Tregs results in T-cell–mediated tissue damage, inflammatory bowel disease, and allergies (4, 5). The suppressive functions exerted by Tregs are mediated by cytokines such as interleukin-10 (IL10) or transforming growth factor–β (TGFβ) or by cellular contacts.

The Treg lineage can be subdivided into two subsets: natural Treg cells (nTregs), also known as thymic Treg cells (iTregs), differentiate from potentially self-reactive T-effector cells (Teffs) upon high-affinity recognition of major histocompatibility complex (MHC) class II–peptide complexes in the thymus, whereas induced Tregs (iTregs) derive from Teffs in the periphery (therefore also known as pTregs) when exposed to antigen (Ag) under tolerogenic conditions (4, 6–8). It was suggested (9) that nTregs can be defined by their expression of Helios, a member of the Ikaros transcription factor family, although this was reported not to be sufficient in subsequent studies (10–12). In the mouse, nTregs express the surface molecule neuropilin-1 (Nrp-1; refs. 13, 14).

Tregs also seem to induce immune tolerance against tumors. The presence of Foxp3+ Tregs is associated with suppression of antitumor responses in patients with, e.g., ovarian or colorectal cancer (15, 16). In breast cancer, high Foxp3 expression correlated with poor prognosis (17). The tumor-promoting function of Tregs was demonstrated in mouse models where selective Treg depletion gave rise to enhanced responses against mammary carcinoma or melanoma (18, 19).

Previous studies suggested that the generation of the Treg repertoire is dependent on Ag recognition by T-cell receptors (TCR) and that Tregs differentiated in the thymus receive activating antigenic signals in the periphery (20–23). Little is known, however, of the origin and the Ag specificity of Tregs that are coopted by growing tumors. This knowledge is indispensable for better understanding Treg-associated pathways of tumor immune escape and eventually developing strategies to break immune tolerance.

Because malignant B-cell neoplasia has still a poor prognosis in the clinic, therapeutic regimens that include approaches to overcome immune escape are needed. Therefore, we set out to understand the identity of potentially immunosuppressive Tregs in lymphoma and how they affect tumor growth. As endogenous tumor models more closely reflect the clinical situation and show
more pronounced immune alterations than transplanted cancer models (24), we investigated mice that develop endogenous lymphomas due to the presence of a λ-MYC transgene specifically expressed in B cells (25). Using MYC transgenic animals whose Foxp3+ Tregs can be selectively depleted by diphtheria toxin (DT; refs. 5, 26), we show that Tregs contribute to tumor immune escape. In this model, we could identify specific self-peptides that are recognized by Tregs.

Materials and Methods

Animal experiments

All mice were kept in our animal facility under specific pathogen-free conditions. Experiments were performed in accordance with and with the approval of Regierung von Oberbayern. Mice were sacrificed when they had visible tumors. Spleens of treated animals were dissected for analyzing tumor-infiltrating immune cells and results were compared with untreated age-matched control mice.

Wild-type (WT) C57BL/6 mice were purchased from Taconic, λ-MYC C57BL/6 mice (25) were bred in our animal facility, DEREG mice were obtained from Technische Universität München and from The Jackson Laboratory. λ-MYC/DEREG mice were established by crossing DEREG mice with λ-MYC animals. Offspring carrying both the λ-MYC and the DEREG allele were identified using polymerase chain reaction (26). For specific depletion of Foxp3+ Tregs, λ-MYC/DEREG mice were treated intraperitoneally (i.p.) with 0.5 μg DT (EMD Chemicals) per injection. Each depletion step required injections on two consecutive days (days 55/56, 69/70, and 83/84). The extent of depletion was confirmed on days 57, 71, and 85, respectively, by analyzing peripheral blood by flow cytometry using fluorochrome-labeled monoclonal antibodies (mAb) against Foxp3. A complete depletion was only seen after the first two treatment cycles, exactly as described earlier (26).

Flow cytometry

Mouse splenocytes were characterized by staining with fluorochrome-labeled mAbs against CD4 (RM4-5; eBioscence), CD69 (H1.2.F3; eBioscence), CD62L (MEL-14; eBioscence), CTLA-4 (UC10-4B9; BioLegend), Neuropilin-1 (3E12; BioLegend), and CD137 (17B8; eBioscence) for 30 minutes at 4°C in FACS buffer. Occasionally, cells were also stained with LIVE/DEAD Fixable Blue Dead Cell Stain Kit (Thermo Fisher Scientific). Intracellular detection of Foxp3, Ki-67, and Helios was performed using the Foxp3 Staining Kit with mAb against Foxp3 (FJK-16s), Ki-67 (SolA15), and Helios (22F6, all eBioscience). For intracellular detection of Foxp3, Ki-67, and Helios was performed using the Foxp3 Staining Kit with mAb against Foxp3 (FJK-16s), Ki-67 (SolA15), and Helios (22F6, all eBioscience). For intracellular detection of Foxp3, Ki-67, and Helios was performed using the Foxp3 Staining Kit with mAb against Foxp3 (FJK-16s), Ki-67 (SolA15), and Helios (22F6, all eBioscience). For intracellular detection of Foxp3, Ki-67, and Helios was performed using the Foxp3 Staining Kit with mAb against Foxp3 (FJK-16s), Ki-67 (SolA15), and Helios (22F6, all eBioscience). For intracellular detection of Foxp3, Ki-67, and Helios was performed using the Foxp3 Staining Kit with mAb against Foxp3 (FJK-16s), Ki-67 (SolA15), and Helios (22F6, all eBioscience). For intracellular detection of Foxp3, Ki-67, and Helios was performed using the Foxp3 Staining Kit with mAb against Foxp3 (FJK-16s), Ki-67 (SolA15), and Helios (22F6, all eBioscience).

Identification of Treg epitopes

MHC class II ligands of λ-MYC lymphoma cells as well as WT cells were isolated by immunofinity chromatography. Cells were lysed in buffer containing PBS, 0.6% CHAPS, and complete protease inhibitor (Roche), shaken for 1 hour and subsequently sonicated for 1 minute. Following centrifugation for 1.5 hours, the supernatant was applied on a precolumn (100 μm × 2 cm, C18, 5 μm, 100 Å) and separated on Acclaim Pepmap100 columns (75 μm × 50 cm, C18, 3 μm, 100 Å; Dionex) using an Ultimate 3000 RSLCnano uHPLC system (Dionex). A gradient

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Published OnlineFirst March 20, 2019; DOI: 10.1158/2326-6066.CIR-18-0419

www.aacrjournals.org Cancer Immunol Res; 7(4) April 2019 601

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ranging from 2.4% to 32% of AcN/H2O with 0.1% formic acid was used to elute the peptides from the columns over 125 minutes at a flow rate of 300 nL/min. Online electrospray ionization (ESI) was followed by tandem mass spectrometry (MS) analysis (30) in an LTQ Orbitrap XL instrument (Thermo Fisher Scientific). Survey scans were acquired in the Orbitrap mass analyzer with a resolution of 60,000 and a mass range of 300 to 1500 m/z. Fragment mass spectra of the 5 most intense ions of each scan cycle were recorded in the linear ion trap (top5 CID). Normalized collision energy of 35%, activation time of 30 ms and isolation width of

Figure 1.
Enhanced activation of CD4⁺ Foxp3⁺ Tregs in spleens of tumor-bearing λ-MYC mice. A, Absolute numbers of Foxp3⁺ Tregs in spleens of diseased λ-MYC mice (n = 20) and WT mice (n = 42; left) and fraction of Foxp3⁺ Tregs within the CD4⁺ T-cell compartments (right). All animals had identical tumor burdens, because analyses had to be done when clinical symptoms became visible. At earlier time points, tumor loads cannot be quantitated (see Results section). The animals analyzed had an age of 80 to 120 days. B, Enhanced activation of intratumoral Foxp3⁺ Tregs (left), shown by an increase of the early activation marker CD69 (n = 10) and a decrease of CD62L (n = 5) compared with WT splenocytes (n = 20 and n = 4). For comparison, the activation markers of Foxp3⁻ cells are also shown (right). C, Left, proliferation indices of Foxp3⁺ Treg and Foxp3⁻ Teff cells from λ-MYC spleens (n = 12) in comparison with WT mice (n = 20). Proliferation was measured after stimulation with anti-CD3/anti-CD28 in vitro and normalized to unstimulated control splenocytes from WT mice. Right, ratio of the mean Treg to Teff proliferation indices in λ-MYC animals compared with WT mice (n = 13 and n = 12). For CTLA-4, surface expression is shown because this is relevant for potential suppressor activity mediated by cell contact. The expression patterns of Foxp3⁻ cells are included for comparison.
2 m/z was utilized for fragment mass analysis. Dynamic exclusion was set to 1 second. The RAW files were processed against the murine proteome as comprised in the Swiss-Prot database using Mascot server version 2.3.04 (Matrix Science) and Proteome Discoverer 1.4 (Thermo Fisher Scientific). A mass tolerance of 5 ppm or 0.5 Da was allowed for parent and fragment masses, respectively. Filtering parameters were set to a Mascot Score < 20, search engine rank = 1, peptide length of 15 to 25 AA, achieving a false discovery rate of 5% as determined by an inverse decoy database search.

**Quantitative reverse-transcription polymerase chain reaction (qRT-PCR)**

A total of \(10^6\) 291, B16F0, or immunomagnetically separated WT B cells were lysed in 200 µL TRIzol reagent (Invitrogen). Then, total RNA was extracted with 1-Bromo-3-chloro-propane (Sigma) followed by precipitation with isopropanol. cDNA was generated by reverse transcription using the First-Strand cDNA Synthesis kit (Roche Diagnostics) and quantified with isopropanol. cDNA was generated by reverse transcription using the First-Strand cDNA Synthesis kit (Roche Diagnostics) and quantified with isopropanol.

**Statistical analysis**

Data analysis was performed using Prism 5.0 software (GraphPad). All results were expressed as means ± SEM. A normal distribution was assumed for the experiments, and all data were subjected to the Grubbs test for statistical outliers. The unpaired Student t test was used to assess differences between two independent groups. Survival curves of λ-MYC/DEREG mice were compared using the log-rank (Mantel-Cox) test. Unless otherwise indicated, n refers to the number of mice or samples from different mice. The significance level is depicted as follows: *, \(P < 0.05\); **, \(P < 0.01\); and ***, \(P < 0.001\).

**Results**

**Lymphoma-infiltrated spleens harbor activated and proliferating Foxp3+ Tregs**

λ-MYC mice bear the MYC oncogene under the control of the B-cell-specific immunoglobulin λ enhancer and develop clinically apparent lymphomas at an age of about 80 to 120 days. Tumors grow in spleens and lymph nodes and reflect several biological features of human Burkitt lymphoma (25). The mice are euthanized as soon as clinical symptoms become visible; at these time points, the tumor loads are identical. In earlier disease phases, tumor burdens cannot be quantitated because normal and malignant B cells cannot be discriminated.

To address the role of Tregs in this endogenous lymphoma model, we initially examined the frequency of CD4+ Foxp3+ T cells in tumor-infiltrated spleens of diseased λ-MYC mice. In comparison with normal spleens, the absolute numbers of Foxp3+ cells were diminished, but their fraction within the CD4+ population, hence the ratio between Foxp3+ and Foxp3− cells, was significantly augmented in the lymphomas (Fig. 1A). Further analyses of the CD4+ Foxp3+ Treg population in tumors revealed an activated phenotype that was evident by the upregulation of the early activation marker CD69 and downregulation of L-selectin CD62L (Fig. 1B).

The increased ratio of Treg to Teff cells in spleens of tumor-bearing mice might be ascribed to differential proliferation of the two T-cell subtypes. Therefore, we determined the numbers of cycling cells after CD3 and CD28 stimulation in vitro. Both CD4+ Foxp3+ Teff and CD4+ Foxp3+ Tregs showed decreased expansion in vitro as compared with healthy WT mice, which might indicate a state of exhaustion following chronic stimulation in vivo. However, this impairment was significant in the Teff cell compartment only (Fig. 1C). The differential suppression of proliferation may explain the increased fraction of Tregs within the CD4+ compartment of λ-MYC spleens.

We then examined the expression of molecules that may impart immunosuppressive functions of the Tregs. Compared with its WT counterpart, the Foxp3− Treg compartment of tumor mice showed higher fractions of cells expressing IL10 and CTLA-4, respectively (Fig. 1D). As expected, no expression of interferon-γ (IFNγ) was detected in the Tregs.

**Lymphoma growth is suppressed in the absence of Foxp3+ Tregs**

To elucidate the functional relevance of the Tregs found in endogenous lymphoma, we crossed λ-MYC animals with DEREG mice, which are engineered to express a fusion gene encoding the DT receptor and the green fluorescent protein under the control of the Foxp3 locus. DT treatment of DEREG animals resulted in a selective ablation of the Foxp3+ Treg compartment (Fig. 2A), as described earlier (5, 26).

If untreated, the λ-MYC/DEREG strain developed lymphomas with the same kinetics as the parental λ-MYC mice. However, when these λ-MYC/DEREG animals were depleted of Foxp3+ Tregs by injecting DT between days 55 and 84 after birth (26), a significant delay of tumor growth was observed (Fig. 2B). When spleens of DT-injected λ-MYC/DEREG mice were isolated, an elevated fraction of CD8+ T cells, but not other immune cells,

![Figure 2](image-url)

**Figure 2.** Treg depletion in λ-MYC/DEREG mice induces prolonged survival. A, Effect of DT injection on CD4+ Foxp3+ T-cell counts in peripheral blood (n = 4). B, Kaplan-Meier diagram showing the survival times of λ-MYC/DEREG mice treated with DT (n = 14) compared with untreated controls (n = 8).
was found in comparison with untreated \(\lambda\)-MYC/DEREG animals (Supplementary Fig. S1). Thus, the effector cells that benefit from Treg depletion may mainly be CD8\(^+\) T cells, as described earlier (19). Taken together, our results strongly suggest that Foxp3\(^+\) Tregs suppress immune responses against endogenous lymphoma.

**Tregs in \(\lambda\)-MYC lymphoma are predominantly nTregs**

To shed light on the origin of the Treg fraction in \(\lambda\)-MYC tumors, we analyzed the expression of the transcription factor Helios, a member of the Ikaros family, and the surface protein Nrp-1. Most intratumoral Foxp3\(^+\) Tregs were Helios\(^+\) and Nrp-1\(^+\) (Fig. 3A and B). This phenotype indicates that the majority of the Foxp3\(^+\) Tregs in tumor spleens are nTregs. Because the proportion of Foxp3 positivity within the CD4\(^+\) population rose by a factor of 2.3 after tumor development (Fig. 1A) and the percentage of Helios\(^+\) cells within the Foxp3\(^+\) compartment increased only 1.3-fold (Fig. 3A), a slight increment of Helios\(^+\) Tregs within the total CD4\(^+\) population has also occurred (Fig. 3C). Helios\(^+\) cells showed a significantly higher amount of the proliferation marker Ki-67 compared with the Helios\(^-\) population (Fig. 3D) and expressed significantly more CD137 than their Helios\(^-\) counterparts (Fig. 3E). This molecule, which is a marker of effector T cells with known and unknown antigen reactivity, was mostly confined to the Helios\(^+\) subpopulation (Fig. 3F). Taken together, the data suggest that immunosuppressive Foxp3\(^+\) Tregs in \(\lambda\)-MYC lymphomas are predominantly derived from the nTreg compartment.

**Figure 3.**

Foxp3\(^+\) nTregs play a role in \(\lambda\)-MYC tumors. **A,** Increased fraction of Helios\(^+\) cells in the CD4\(^+\) Foxp3\(^+\) compartment of tumor-bearing \(\lambda\)-MYC mice \((n = 23)\) compared with WT mice \((n = 18)\). **B,** Representative diagram showing the coexpression of Helios and Nrp-1 in CD4\(^+\) Foxp3\(^+\) Tregs from a diseased \(\lambda\)-MYC mouse. **C,** Distribution of Helios\(^+\) and Helios\(^-\) cells within the total CD4\(^+\) population of WT \((n = 18)\) and \(\lambda\)-MYC mice \((n = 23)\). **D,** Enhanced proliferation of intratumoral Foxp3\(^+\) Helios\(^+\) compared with Foxp3\(^+\) Helios\(^-\) Tregs from \(\lambda\)-MYC mice \((n = 6)\) compared with WT mice \((n = 5)\). **E,** Expression of CD137 on Helios\(^+\) and Helios\(^-\) Tregs from \(\lambda\)-MYC mice \((n = 6)\) compared with WT spleens \((n = 5)\). **F,** Coexpression of Helios and CD137 in Foxp3\(^+\) Tregs. Representative dot plot from six and five experiments, respectively.
Foxp3\(^+\) Tregs in lymphoma recognize specific peptides

In light of these results, we speculated that the Foxp3\(^+\) Tregs identified in \(\lambda\)-MYC mice recognize specific tumor-associated self-peptides via their TCR. To test this hypothesis, we cocultivated total purified CD4\(^+\) T cells from tumor-bearing \(\lambda\)-MYC mice with irradiated tumor cells. As specific stimulators, we used 291 cells, which were derived from a \(\lambda\)-MYC tumor (27). The B16F0 melanoma served as an irrelevant control tumor.

When Ki-67 was analyzed in the gate of the CD4\(^+\) Foxp3\(^+\) population after 7 days, an augmented activation status of the Tregs was found after their stimulation in the presence of the MYC lymphoma but not in the presence of the control cells. The same results were obtained when the T cells were derived from healthy WT mice (Fig. 4A). We therefore hypothesized that the peptides interacting with Tregs of \(\lambda\)-MYC as well as WT mice represent normal self-antigens, which may be overexpressed in the lymphoma cells.

To define these self-peptides, we first asked whether lymphoma recognition by Foxp3\(^+\) Tregs is MHC class II restricted. Indeed, the lymphoma-dependent Treg stimulation observed could be abrogated by mAb-mediated blockade of MHC class II during cocultivation (Fig. 4B). This prompted us to isolate MHC class II–peptide complexes from \(\lambda\)-MYC as well as from normal WT cells by affinity chromatography using anti-MHC II. Peptides were eluted and subsequently subjected to MS, as outlined in Materials and Methods. Sixty-eight sequences were identified after elution from the \(\lambda\)-MYC cells, which were prevalent in the lymphoma as compared with normal B cells and which could be assigned to a total of 44 proteins (Supplementary Table S1). From those proteins, 10 were selected on the basis of their potential involvement in processes such as cell-cycle control, apoptosis, or malignant transformation. Based on the core sequences revealed by MS, 10 synthetic peptides were then generated representing each of the proteins (Table 1).

These synthetic peptides were examined with respect to their capability of stimulating the proliferation of Foxp3\(^+\) Tregs. To this end, normal splenocytes were pulsed with the synthetic peptides and cultivated together with CD4\(^+\) T cells from \(\lambda\)-MYC mice. Then, proliferation was measured in the Foxp3\(^+\) fraction. Four of the 10 peptides were able to induce proliferative responses of the Foxp3\(^+\) Tregs that were significantly different from the control responses that were seen after incubation with normal B cells and antigen-presenting cells in the absence of peptides (Fig. 5A). This peptide reactivity was evident mainly in the Helios\(^+\) Tregs but not in the Helios\(^-\) Treg population (Supplementary Fig. S2A). As expected, the T-cell responses that were significantly different from the control could be abolished by blocking MHC II (Supplementary Fig. S2B). The identified peptide sequences originated from gene loci that are related to silencing of tumor suppressor genes, regulating cell growth and promoting metastasis. A similar stimulation pattern was detected in the Foxp3\(^+\) Teff fraction (Fig. 5B), indicating that potentially protective Teff cells may be suppressed by Tregs directed against the same epitopes.

To determine whether these peptides may be overexpressed in lymphoma cells, we examined the expression of peptides, which

| Table 1. Peptides selected for T-cell stimulation in vitro |
|------------------|-------------------|-----------------|
| Peptide sequence | Gene              | Protein         |
| GSPVIAANSGIPvPAAGAQQ | Csnk2a1           | Casein kinase II subunit alpha |
| DLDAPDDVDFV       | Snt               | Serrate RNA effector molecule homolog |
| LERLDLDISTSAGPVVF | Trim28            | Transcription intermediary factor 1-beta |
| DSWIVPDLNTDKDDDEEHTL | Podxl           | Podocalyxin |
| APIDRVGQTE        | Hnrcpm            | Heterogeneous nuclear ribonucleoprotein M |
| EALEGQILP         | Cdk7              | Cyclin-dependent kinase 7 |
| VRPPVPLASSHPITNEPVLED | Mtsa2           | Metastasis-associated protein MTA2 |
| EAVLGLVEA         | Tel2              | Telomere length regulation protein TEL2 homolog |
| SIAAFIQRL        | Bag6              | Large proline-rich protein BAG6 |
| RIEPLSPKIN       | Fxyd5             | FXYD domain-containing ion transport regulator 5 |

NOTE: Based on the core sequences identified by MS (see text), 10 synthetic peptides were synthesized and used for in vitro T-cell stimulation assays.
cytokine milieu (24, 27, 31) promoting microenvironment is created, which, e.g., involves the become impaired during lymphoma growth, and a tumor-overridden. Thus, natural killer cells, T cells, and dendritic cells endogenous tumor model, numerous alterations have been iden-
clinics demands further improvement. In the lymphoma model because therapy of this disorder in the stand the pathways of tumor immune escape. We investigated a
Discussion
For developing approaches to cancer treatment, we must understand the pathways of tumor immune escape. We investigated a lymphoma model because therapy of this disorder in the clinics demands further improvement. In the λ-MYC transgenic endogenous tumor model, numerous alterations have been identified that allow protective antitumor immune responses to be overcome. Thus, natural killer cells, T cells, and dendritic cells become impaired during lymphoma growth, and a tumor-promoting microenvironment is created, which, e.g., involves the cytokine milieu (24, 27, 31–33).

Here, we show that Foxp3+ Tregs mediate immune escape in endogenous B-cell lymphoma, because tumor development was delayed after DT-mediated ablation of Foxp3+ Tregs in λ-MYC/DEREG mice. Tregs recover about 2 weeks following initial depletion in DEREG mice (26, 34). In our model, depletion started at day 55 after birth, a time point when malignant cells were presumably already present, albeit clinically still unapparent (27). The second depletion cycle at days 69 and 70 was as successful as the first one. A third DT treatment cycle at days 83/84 was no longer effective; perhaps due to loss of the transgene and/or induction of a humoral anti-DT response (26, 34). Therefore, the antitumor effect induced by depletion of Foxp3+ Tregs in the λ-MYC model may even be underestimated. At the time points when mice were sacrificed, the tumor loads were identical irrespective of whether or not Tregs had been depleted. Thus, the survival benefit effected by Treg depletion is only the result of a delay of tumor growth in early disease phases, which, however, cannot be monitored in the λ-MYC model because normal and malignant B cells cannot be discriminated. A tumor-promoting role of Tregs was also described in other lymphoma models (35–37), but these studies were only done using transplanted tumors, which do not reflect the tumor-induced immune alterations as closely as our clinically relevant endogenous lymphoma model (24, 27).

The Treg-to-Teff ratio was elevated in tumor-infiltrated spleens of λ-MYC mice, which could be explained by a differential suppression of the proliferation of the two T-cell subsets. Of course, an unequal recruitment into the growing tumor as an additional mechanism cannot be precluded. The upregulation of CD69 on intratumoral Tregs indicates immunosuppressive activity (38) but might also reflect retention of the cells (39). Activation of Tregs associated with CD69 upregulation was also observed in a model of carcinogen-induced fibrosarcoma where thymus-derived Helios-expressing Tregs accumulated in the tumor tissue and showed increased proliferation as indicated by their expression of Ki-67 (40).

A central question pertains to the identity and Ag specificity of Tregs. In infectious disease of the central nervous system, for example, virus-specific Tregs seem to arise from the nTreg compartment and suppress Teffs upon interaction with cognate virus epitopes (41). Immunosuppressive nTregs recognizing specific peptides may also play a role in limiting proinflammatory responses against cancer. MHC class II–restricted self-peptides that are recognized by a Treg clone are prevalent in mouse prostate carcinoma, thus indicating that these Tregs are thymus-derived nTregs (42).
In line with these results, we mainly found thymus-differentiated nTregs in the B-cell lymphomas. A slight—albeit not statistically significant—increase of iTregs, which, in contrast to nTregs, arise from T cells converted in the periphery to express Foxp3, was also observed. Given the role of TCR-dependent recognition of self-peptide-MHC class II complexes for driving nTreg development in the thymus (20, 43) and for subsequent induction of immune tolerance in the periphery, it was of interest to define the peptides recognized by Tregs in B-cell lymphoma. The pattern of recognition of tumor cells by Tregs suggested that the specificities involved are not only present in tumor-bearing but also in healthy WT mice. The sequences that stimulated Tregs were indeed nonmutated self-epitopes, which also occurred in WT cells. Thus, the responses observed were not dependent on the origin of the Tregs but presumably just on altered presentation of the (normal) peptides by the tumor. The epitopes originated from proteins whose functions are, among others, related to malignant transformation. These proteins were overexpressed in the lymphoma cells but not in the control tumor. However, genes were also identified that are overexpressed in 291 cells, even though their products are not recognized by Tregs. Indeed, high gene expression does not necessarily give rise to efficient peptide presentation.

The mode of action of Tregs in λ-MYC tumor mice has not yet been elucidated in detail. In previous studies, suppression of T cells mediated by IL10 or TGFβ was also identified (44–46). In particular, it is not yet clear by which mechanisms the peptide-specific Treg activation leads to T cell suppression in the λ-MYC model. Experiments suggest that Tregs from MYC mice exert suppressor activity, which is partly dependent on IL10, and that peptide recognition by Tregs correlates with their IL10 expression. However, cellular contacts may also play a role. Of course, the increased ratio of Tregs-to-Teffs in tumor spleens should be relevant for Treg-induced diminution of antitumor responses.

The pattern of peptide recognition was similar when Treg and Teffs were compared. With the exception of peptide 8, all epitopes recognized by Tregs were also able to induce statistically significant proliferation of Teffs. This suggests that Tregs may be recruited selectively against tumor antigens that could serve as targets for potentially protective Teffs. Even more Treg specificities may exist in λ-MYC tumors in addition to the four epitopes described in this paper, because only 10 antigens were selected for detailed analysis of their potential to stimulate Tregs. Nonetheless, the data presented here demonstrate the principle that lymphomas may use Tregs to counteract the attack of immune effector cells.

**Disclosure of Potential Conflicts of Interest**

M. Röcken discloses professional relationships with Deutsche Dermatologische Gesellschaft, Deutsche Forschungsgemeinschaft, Deutsche Krebshilfe, European Academy of Dermatology and Venereology, Institut für medizinische und pharmazeutische Prüfungsfragen, and Wilhelm Sander-Stiftung; is responsible for study recruitment for AB Science, Abbott Laboratories, Abbott Pharmaceuticals, Abbvie Deutschland, Almirall Hermal, Astra Zeneca, Bayer, Biogen, Bristol-Myers Squibb, Celgene, Calderma, and CSC, and is a shareholder or patent holder for Merck & Company, MSD Sharp & Dohme, and EP-Patent 13826995.1. No potential conflicts of interest were disclosed by the other authors.

**Authors’ Contributions**

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**Acknowledgments**

The work was supported by grants from Deutsche Krebshilfe (70112332, 70112337, 110662, and 110664), Wilhelm-Sander-Stiftung (2012.056.3), and Deutsche Forschungsgemeinschaft (SFB-TR 156). We are grateful to Michael Hagemann, Franziska Lieb, and Jasmin Teutsch for taking care of animal husbandry and Angela Hoffmann for help in preparing the manuscript. The study includes parts of the doctoral theses of F.A. and T.R. at the Ludwig-Maximilians-Universität München.

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Received June 21, 2018; revised November 13, 2018; accepted January 29, 2019, published first March 20, 2019.

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_Cancer Immunol Res_ 2019;7:600-608. Published OnlineFirst March 20, 2019.

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