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Matthew P. Rausch,*‡ Kari R. Irvine,‡ Paul A. Antony,§,† Nicholas P. Restifo,‡ Peter Cresswell,§,* and K. Taraszka Hastings*‡,‖

Melanocyte differentiation Ags, including tyrosinase-related protein (TRP) 1, are relevant to both autoimmune skin depigmentation (vitiligo) and tumor immunity, because they are expressed by both benign melanocytes and many malignant melanomas. Melanoma patients generate CD4+ T cells that specifically recognize these proteins. TRP1 contains internal disulfide bonds and is presented by MHC class II molecules. γ-IFN–inducible lysosomal thiol reductase (GILT) facilitates the generation of class II-binding peptides by the endocytic reduction of protein disulfide bonds. We show in this study that GILT is required for efficient MHC class II-restricted processing of a TRP1 epitope in vitro and accelerates the onset of vitiligo in TRP1-specific TCR transgenic mice. The presence of GILT confers a small increase in the percentage of autoreactive T cells with an effector memory phenotype that may contribute to earlier disease onset. The onset of vitiligo is associated with a greater increase in the percentage of autoreactive T cells with an effector memory phenotype. Given that many self and tumor Ags have disulfide bonds and are presented on MHC class II, GILT is likely to be important in the pathogenesis of other CD4+ T cell-mediated autoimmune diseases and for the development of effective cancer immunotherapy. The Journal of Immunology, 2010, 185: 2828–2835.

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In this study, we identify TRP1 as a new disease-relevant Ag that requires GILT for efficient class II-restricted processing, demonstrate that GILT accelerates CD4\(^+\) T cell-mediated vitiligo, and evaluate GILT’s role in vivo in the development and function of TRP1-specific CD4\(^+\) T cells. Induction of autoimmunity is used as a surrogate for an antitumor response as autoimmunity to melanocyte differentiation Ags and other self Ags improves antimaleno-ma immune responses in animal models (18, 22) and in patients undergoing immunotherapy (23).

Materials and Methods

Cell lines

The 95−10, a subclone of 7A6 (18), is an I-Ab\(^{-}\)-restricted T cell hybridoma recognizing murine TRP1. The minimal epitope is murine TRP1\(_{113-126}\) CRPGWRGACNQKI (18). Two murine H-2\(^{d}\)-derived tumor cell lines were used as follows: B16.F10 melanoma line (American Type Culture Collection, Manassas, VA) and PDV (24), a keratinocyte-derived squamous cell carcinoma (SCC) line provided by M. Girardi (Yale University, New Haven, CT).

Mice and onset of vitiligo analysis

C57BL/6 (wild-type) mice were obtained from The Jackson Laboratory (Bar Harbor, ME). GILT\(^{-/-}\), TRP1tg, and TRP1\(^{Bw}\)-RAG\(^{-/-}\)/TRP1tg mice have been described (5, 18, 21). TRP1tg mice were backcrossed on the C57BL/6 background. Thymi, spleens, and skin-draining lymph node (inguinal, axillary, and cervical) were harvested. Thymocytes, splenocytes, and lymph node cells were liberated by mechanical dissociation; splenocytes were additionally depleted of RBCs using 0.15 M NH\(_4\)Cl, 1 M KHCO\(_3\), and 0.1 mM Na\(_2\)EDTA. Mice bearing the TRP1tg were visually inspected each week for the development of depigmented fur and eye changes.

Statistical analyses

Comparisons between two groups were performed using independent sample \(t\) tests. Comparisons among three groups were performed with ANOVA. Pairwise analysis of the time to onset curves between three groups was performed by the log rank test. In each case, \(p \leq 0.05\) was considered to be significant. Adjustment for multiple comparisons was made using the Bonferroni correction.

Results

GILT is required for efficient MHC class II-restricted processing of TRP1

As a source of properly folded TRP1 protein potentially susceptible to GILT-mediated reduction, we used freeze-thaw lysates of melanoma cell line B16. Immunoblot analysis confirmed that TRP1 was expressed in lysates of B16 cells, but not the PDV keratinocyte-derived SCC line (Fig. 1A). Initially, resting B cells from wild-type and GILT\(^{-/-}\) mice were used as APCs. Their purity was 96% based on CD45R (B220) staining, and I-Ab\(^{a}\) surface expression was equivalent on wild-type and GILT\(^{-/-}\) B cells (Fig. 1B). Ag processing was evaluated by coculturing I-Ab\(^{a}\)-restricted TRP1-specific T cells with APCs and melanoma lysate and measuring IL-2 production by ELISA (Fig. 1C). SCC lysate served as a negative control, and 10 \(\mu\)g/ml TRP1 peptide served as a positive control (Fig. 1C). Wild-type B cells were able to process and present TRP1 in the melanoma lysate, inducing T cell hybridoma 95-10 to produce IL-2 in the range of 600–840 pg/ml (Fig. 1C). In contrast, GILT\(^{-/-}\) B cells were entirely unable to process TRP1 over the 8-fold range of tumor cell equivalents used (6.125 \(\times\) 10\(^3\) to 5 \(\times\) 10\(^5\)) (Fig. 1C). Comparison of the averages across all melanoma lysate doses using an independent sample \(t\) test showed a statistically significant difference between the ability of wild-type and GILT\(^{-/-}\) B cells to present the TRP1 epitope (\(p < 0.0001\)). Coculture of wild-type and GILT\(^{-/-}\) B cells with TRP1 peptide resulted in equivalent IL-2 production (\(p = 0.061\); Fig. 1C).

Next, we went on to evaluate the ability of wild-type and GILT\(^{-/-}\) DCs to process the TRP1 epitope and stimulate primary CD4\(^+\) TRP1-specific T cells. The DC preparations were 73% pure based on CD11c staining and had equivalent I-Ab\(^{a}\) and CD80 surface expression (Fig. 2A). Primary CD4\(^+\) TRP1-specific T cells isolated from TRP1\(^{Bw}\)-RAG\(^{-/-}\)/TRP1tg mice showed 95% purity (Fig. 2B). T cells from TRP1tg mice on the TRP1\(^{Bw}\) and RAG1\(^{-/-}\) background were used to ensure the absence of tolerance mechanisms and the specificity of the TCR, respectively. Wild-type DCs efficiently processed and presented TRP1 from the melanoma lysate to stimulate primary CD4\(^+\) TRP1-specific T cells generating a maximal IL-2 concentration of 5680 pg/ml with 10\(^5\) melanoma cell equivalents (Fig. 2C). GILT\(^{-/-}\) DCs required \(\approx\)100-fold more Ag than wild-type DCs to detect TRP1 processing (Fig. 2C). At the

peptide: NCGTCRPGWRGACNQKI (18). Two murine H-2\(^{d}\)-derived tumor cell lines were used as follows: B16.F10 melanoma line (American Type Culture Collection, Manassas, VA) and PDV (24), a keratinocyte-derived squamous cell carcinoma (SCC) line provided by M. Girardi (Yale University, New Haven, CT).

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Immunoblotting

Cells were lysed with 1% Triton X-100 in TBS for 30 min on ice. A total of 2 \(\times\) 10\(^5\) cell equivalents of postnuclear supernatants was resolved by SDS-PAGE (8% w/v acrylamide) and electrophoretically transferred to Immobilon-P membrane (Millipore, Bedford, MA). The membrane was blocked in PBS with 0.2% Tween 20 and 5% dehydrated milk, and then incubated with primary Ab. TRP1 was immunoblotted with mouse anti-TRP1 mAb supernatant (clone TA-99; American Type Culture Collection under nonreducing conditions. Rat anti-GRP94 mAb (1:5000; StressGen Biotech- nologies, Victoria, Canada) was used as a loading control. The membranes were then washed, incubated with HRP-conjugated goat anti-mouse or rat IgG (1:5000; Jackson Immunoresearch Laboratories) and enhanced chemiluminescent substrate (SuperSignal West Pico; Pierce, Rockford, IL), and exposed to film.

Flow cytometry

FcγRII/II was blocked by preincubating cells with rat anti-mouse CD16/ CD32 mAb (1 \(\mu\)g per million cells, mouse BD Fc block; BD Biosciences, San Jose, CA) in PBS with 1% BSA and 0.05% sodium azide. Cells were stained with FITC-, PE-, PerCP-, or allophycocyanin-conjugated mAbs against murine CD45R (B220; clone RA3-6B2), I-Ab\(^{a}\) (AF6-120.1), CD11c (N418), CD80 (16-10A1), CD4 (RM4-5), CD8 (53-6.7), V\(_{\beta}\) (14-2), V\(_{\beta}\) (20.1), V\(_{\beta}\) (3.2) (RR-3-16), V\(_{\beta}\) (B21.14), V\(_{\beta}\) (11.1/1.12) (RR-8-1), CD44 (IM7), CD62L (Mel-14), CD25 (PC6.15), Fox3 (FJK-16s), and corre-sponding isotype controls (eBioscience; eBioscience, San Diego, CA); the TCR V\(_{\beta}\) screening panel was purchased from BD Biosciences. For intracellular staining of Fox3, cells were fixed and permeabilized using the Foxp3 staining buffer set (eBioscience). Cell-associated fluorescence was measured using an LSRII flow cytometer (BD Biosciences), and analysis was performed using FlowJo software (Tree Star, Ashland, OR).

Class II Ag-processing assay

A total of 1 \(\times\) 10\(^5\) TRP1-specific T cells was cocultured with 5 \(\times\) 10\(^5\) wild-type or GILT\(^{-/-}\) APCs and B16 melanoma lysate, murine TRP1\(_{109-130}\)
highest levels of melanoma cell equivalents (10^5–10^6), GILT−/− DCs exhibited modest processing of the TRP1 epitope with a maximal IL-2 concentration of 1430 pg/ml (25% of the maximum with wild-type DCs; Fig. 2C). Comparison of the averages across all melanoma lysates using an independent sample t test demonstrated a statistically significant difference between the ability of wild-type and GILT−/− DCs to present the TRP1 epitope (p ≤ 0.05). Taken together, the data show that GILT is necessary for efficient class II-restricted processing of this TRP1 epitope in vitro.

**GILT accelerates the onset of vitiligo mediated by TRP1-specific CD4+ T cells**

Because GILT strongly influenced the class II-restricted presentation of this TRP1 epitope in vitro, we sought to determine whether GILT would impact the development of a TRP1-specific autoimmune response in vivo. TRP1tg mice on the C57BL/6 background developed patches of hair graying, which progressed to involve greater portions of the coat over time (Fig. 3A). We refer to this depigmentation as vitiligo (22). Similar to the clinical presentation of vitiligo in humans, TRP1tg mice commonly developed disease around the eyes and at sites of trauma (e.g., venipuncture; data not shown). Because GILT is required for efficient processing of the TRP1 epitope in vitro, we predicted that vitiligo would develop more slowly or with less severity in GILT−/− TRP1tg mice. TRP1tg mice on the wild-type (n = 127), GILT+/− (n = 56), and GILT−/− (n = 76) backgrounds were visually inspected each week for the appearance of patches of depigmentation (Fig. 3B). Vitiligo spontaneously developed over a range of 6–31 wk of age (Fig. 3B). Wild-type and GILT+/− TRP1tg mice spontaneously developed vitiligo with a median onset of 12 wk, whereas on the GILT−/− background the median onset was delayed to 19 wk (Fig. 3B). This delay in onset was highly significant (p < 0.0001). Although the development of spontaneous vitiligo in GILT-deficient TRP1tg mice was delayed, GILT-deficient TRP1tg mice eventually developed vitiligo with the same pattern and severity (number, size, and distribution of lesions) as GILT-expressing TRP1tg mice (data not shown). The data show that GILT plays a significant role in the onset of this TRP1-specific autoimmune response.

To demonstrate that GILT in APCs is necessary for the accelerated onset of vitiligo, we adoptively transferred CD4+ TRP1-specific T cells into RAG−/− and GILT−/− RAG−/− hosts. As above, TRP1-specific T cells from TRP1-deficient and RAG-deficient TRP1tg mice were used to ensure that the T cells were not subject to tolerance mechanisms, that the T cells were uniformly naive, and that all T cells were specific for TRP1. Adoptive transfer of TRP1-specific CD4+ T cells into RAG−/− hosts produced large patches of depigmented fur and ocular damage with a median onset of 4 wk (Fig. 4A, top), consistent with prior studies and the expression of TRP1 in melanocytes located in hair follicles and in the retinal pigment epithelium (18). In contrast, the severity of the vitiligo was dramatically reduced with adoptive transfer of the same T cells into GILT-expressing TRP1tg mice (data not shown). The data show that GILT increases the severity and accelerates the onset of vitiligo.

**Increased percentage of TRP1-specific transgenic T cells in GILT-deficient mice**

We hypothesized that GILT could accelerate autoimmunity to TRP1 through altered T cell development or increased peripheral activation...
of TRP1-specific T cells. First, we investigated T cell development. Total cell numbers isolated from thymi, spleens, and lymph nodes of the GILT-positive and -negative strains were identical (Fig. 5A). Both CD4+ and CD8+ T cell strains developed (Fig. 5B). No statistically significant differences in the CD4+CD8+ T cell ratio were observed in the thymus, spleen, or lymph node between TRP1tg and GILT−/−TRP1tg mice (Fig. 5B). The transgenic TCR is composed of Vα3.3 and Vβ14 (18). Because a specific tetramer, clonotypic Ab, or Vα3.3 Ab is not available, transgenic T cells were identified by Vβ14 and CD4 staining. CD4+Vβ14+ T cells were present in the spleen and lymph node cells of TRP1tg and GILT−/−TRP1tg mice (Fig. 5C). A diverse array of endogenous TCR Vβ-chains was expressed in TRP1tg mice, suggested by the presence of Vβ14+ T cells (Fig. 5C). No significant TCR down-modulation was observed, as measured by binding with the anti-Vβ14 mAb (data not shown). There were Vβ14+ CD4+ cells (Fig. 5C) that were CD8− (Supplemental Fig. 1), suggesting that the transgenic TCR or a TCR composed of the transgenic β-chain and an endogenous α-chain may also be able to select CD8− T cells. Comparison of the percentage of CD4+CD8− Vβ14+ cells in the thymus and CD4+Vβ14+ cells in the spleen and lymph nodes of TRP1tg and GILT−/−TRP1tg mice revealed an increased percentage of transgenic T cells in the thymus, spleen, and lymph nodes in the GILT−/− background (Fig. 5D). The increased percentage of peripheral autoreactive T cells in GILT−/−TRP1tg mice suggested possible defects in tolerance when TRP1 is not efficiently presented.

Barjaktarevic and colleagues (26) have described increased proliferation of GILT−/− T cells. To exclude the absence of GILT in T cells as the cause of increased T cells, we evaluated the percentage of nontransgenic T cells. If the absence of GILT in T cells was responsible for the increased percentage of T cells, one would expect an increase in all T cell specificities. However, GILT did not alter the percentage of nontransgenic CD4+Vβ14+ T cells (Fig. 5E). To further investigate GILT’s impact on T cell development and evaluate the expression of endogenous TCR chains in RAG-expressing TRP1tg mice, suggested by the presence of Vβ14+ peripheral T cells (Fig. 5C), lymph node cells from TRP1tg and GILT−/−TRP1tg mice were analyzed for Vα and Vβ expression. A diverse array of endogenous TCR Vα- and Vβ-chains was expressed (Fig. 5F), which is not surprising given that αβ TCR transgenic mice commonly express endogenous TCR chains (27–29). No differences in TCR usage were detected between TRP1tg and GILT−/−TRP1tg mice, other than the increased percentage of CD4+Vβ14+ T cells in the GILT−/− background identified above (Fig. 5D). Taken together, the data show that the expansion of T cells is limited to the TRP1-specific CD4+Vβ14+ T cells.

T regulatory (Treg) cells play an established role in containing autoimmunity and have been shown to delay vitiligo in this model (21). To reconcile the apparent contradiction of increased TRP1-specific T cells in GILT-deficient animals that have diminished TRP1-mediated autoimmunity, we next evaluated whether there were increased Treg cells in GILT-deficient TRP1tg mice. No differences in the percentage of CD4+CD25+FoxP3+ T cells in the lymph node cells of TRP1tg and GILT−/−TRP1tg mice were observed (Fig. 5G). In addition, no differences in the mean fluorescence intensity of FoxP3 expression in CD4+CD25+FoxP3+
T cells were seen; the mean fluorescence intensities ± SEM in TRP1tg and GILT−/−TRP1tg mice were 430 ± 61 and 360 ± 11, respectively. The data show an increased percentage of peripheral autoreactive T cells, but no change in the percentage of Treg cells, in TRP1tg mice on the GILT−/− background, prompting us to evaluate T cell activation in disease development.

Effector memory cells are increased in the presence of GILT following development of vitiligo

Because a direct consequence of Ag presentation is T cell activation, we anticipated diminished activation of TRP1-specific T cells in GILT-deficient animals. We examined markers of naive and Ag-experienced T cells in TRP1tg and GILT−/−TRP1tg mice. Within the CD4+Vβ14+ population, the percentages of CD62L+CD44+ (effector memory), CD62L−CD44− (central memory), and CD62L+CD44− (naive) populations were determined in the skin-draining lymph nodes. Initially, we evaluated 10- to 20-wk-old TRP1tg mice with and without GILT, because we would have anticipated the greatest difference in T cell phenotype in this age range based on the onset to vitiligo analysis (Fig. 3). However, the results in this age range were highly variable (data not shown), most likely due to the extremely variable onset of spontaneous disease. When we restricted the analysis to mice ≥10 wk old for a more uniform population, we observed a decrease in effector memory T cells in GILT-deficient mice and an increase in effector memory T cells correlating with vitiligo onset (Fig. 6). The majority of the TRP1-specific T cells in GILT−/−TRP1tg mice and TRP1tg mice (with or without vitiligo) were naive (Fig. 6). Comparison of GILT−/−TRP1tg with all TRP1tg mice showed an increase in effector memory cells from 8.0 to 18% and a corresponding decrease in naive cells from 81 to 52%.
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FIGURE 6. Effector memory cells are increased in the presence of GILT and following development of vitiligo. Cervical, axillary, and inguinal lymph node cells from age-matched, 4- to 9-wk-old TRP1tg and GILT/

A

TRP1tg mice were analyzed. Staining with CD44 and CD62L was evaluated in the CD4+V14 population. A, Representative dot plots demonstrating CD44 and CD62L staining in CD4+V14 cells in GILT/

B

BL4 mice without vitiligo, TRP1tg mice without vitiligo, and TRP1tg mice with vitiligo. B, Bar graphs summarizing the mean percentage of TRP1-specific transgenic T cells with a CD62L/CD4+ naive and CD62L/CD44 effector memory phenotype ± SEM for seven pooled experiments comparing GILT/

TRP1tg mice without vitiligo, TRP1tg mice without vitiligo, and TRP1tg mice with vitiligo. There were significant differences between GILT/

TRP1tg mice and TRP1tg mice by independent sample t tests showed a statistically significant decrease in the percentage of naive cells (**p < 0.01) and increase in the percentage of effector memory cells (**p < 0.01) in the presence of GILT. A secondary analysis was performed dividing the TRP1tg mice into mice with and without vitiligo. A one-way ANOVA was performed separately for the percentage of naive and the percentage of TRP1tg mice into mice with or without vitiligo. A one-way ANOVA was performed separately for the percentage of naive and the percentage of effector memory T cells in the three groups of mice (GILT/

TRP1tg mice without vitiligo, TRP1tg mice without vitiligo, and TRP1tg mice with vitiligo). There was an increase in the percentage of TRP1-specific effector memory T cells (**p = 0.001) and a corresponding decrease in naive cells (**p < 0.001) in TRP1tg mice with vitiligo compared with TRP1tg mice without vitiligo. There were significant differences between GILT/

TRP1tg mice and TRP1tg mice with vitiligo in both naive cells (**p < 0.001) and effector memory cells (**p < 0.001). No significant differences were observed between TRP1tg mice without disease and GILT/

TRP1tg mice for either naive (p = 0.20) or effector memory cells (p = 0.54).

Discussion

TRP1 is a melanocyte differentiation Ag that is relevant to both autoimmune skin depigmentation (vitiligo) and melanoma, because it is expressed by both benign melanocytes and many malignant melanomas. TRP1 contains disulfide bonds (11, 12), is presented on MHC class II (10, 18, 22, 30, 31), and, thus, could be subject to GILT-mediated reduction in the late endosomes and lysosomes prior to class II-restricted presentation. The data presented in this study show that GILT is necessary for efficient generation of an I-A* restricted TRP1 epitope in vitro, identifying a new GILT-dependent epitope in a disease-relevant Ag (Figs. 1, 2). GILT is required for detection of class II-restricted presentation of this epitope in B cells (Fig. 1C). However, in the presence of a large amount of Ag, a small amount of GILT-independent processing is observed in DCs (Fig. 2C). The differential abilities of GILT/-/ DCs and B cells to process large amounts of TRP1 might be anticipated given the superior Ag presentation capability of DCs (32). Given that other melanocyte differentiation Ags, including tyrosinase, TRP2, and gp100/Pmel17, contain disulfide bonds (11, 12, 33) and are presented on MHC class II (30, 34–37), and that prior studies demonstrated that an epitope of human tyrosinase is partially GILT dependent in vitro (6), GILT will most likely be of general importance in the MHC class II-restricted presentation of this group of melanoma and melanocyte Ags.

The TRP1tg mouse strain generated by Muranski et al. (18) allowed us to evaluate the role of GILT in the in vivo autoimmune response. Because this strain expresses a TCR specific for a naturally occurring epitope of an endogenously expressed Ag, it represents an ideal model to study the development and function of T cells relevant to the pathogenesis of autoimmune disease and antitumor responses to differentiation Ags. Remarkably, GILT expression accelerated the development of an in vivo TRP1-mediated immune response, resulting in spontaneous vitiligo (Fig. 3B), which is the first demonstration that GILT can exacerbate an autoimmune disease. Consistent with severely diminished Ag processing of the TRP1 epitope observed in GILT/-/ APCs in vitro (Figs. 1, 2), GILT/-/ TRP1tg mice have a significant delay in the onset of spontaneous vitiligo (Fig. 3B). Interestingly, GILT-deficient TRP1tg mice eventually develop spontaneous vitiligo with the same severity as those expressing GILT, suggesting that the low level of epitope presentation in the absence of GILT is sufficient to produce disease over time. Because GILT is also expressed in T cells (26), we performed adoptive transfer experiments to determine whether GILT expression in APCs was necessary for the exacerbated autoimmune response. Transfer of TRP1-specific T cells into GILT-deficient RAG2/2 mice developed vitiligo by 9 wk of age. In GILT-expressing TRP1tg mice with vitiligo, a mean of 51% of the transgenic T cells were naive and a mean of 34% were effector memory cells, whereas in mice without vitiligo 73% were naive and 13% were effector memory cells (Fig. 6B, right). Thus, effector memory cells were increased, whereas naive cells were reduced in mice with vitiligo. The differences between the TRP1tg mice with and without vitiligo in both the percentage of naive (p ≤ 0.001) and effector memory TRP1-specific transgenic T cells (p ≤ 0.001) were statistically significant. Therefore, increased T cell activation as measured by an increased percentage of effector memory cells correlates with the development of vitiligo. In summary, these data support the idea that GILT facilitates class II-restricted processing of TRP1, thereby enhancing T cell activation and accelerating vitiligo.

68%, respectively (Fig. 6B, left). These differences are both statistically significant (p < 0.01 for each). Therefore, although there is a greater percentage of TRP1-specific T cells in GILT-deficient mice, a smaller percentage of these cells have an effector memory phenotype. The reduction in effector memory cells in GILT-deficient mice suggests that the delay in vitiligo onset in the absence of GILT may reflect delayed activation of TRP1-specific T cells.

A secondary analysis was performed dividing the TRP1tg group into mice with and without vitiligo (Fig. 6B, right). GILT/-/ TRP1tg mice with vitiligo were not included in the analysis because during the time course of this experiment, no GILT/-/ TRP1tg mice developed vitiligo by 9 wk of age. In GILT-expressing TRP1tg mice with vitiligo, a mean of 51% of the transgenic T cells were naive and a mean of 34% were effector memory cells, whereas in mice without vitiligo 73% were naive and 13% were effector memory cells (Fig. 6B, right). Thus, effector memory cells were increased, whereas naive cells were reduced in mice with vitiligo. The differences...
GILT expression in T cells could, in theory, affect the development of the autoimmune phenotype in the TRP1tg system. The absence of GILT in T cells results in increased T cell proliferation and cytotoxic function (26), which may be due to decreased superoxide dismutase 2 activity and increased levels of reactive oxygen species (38). GILT expression increases with T cell maturation from double-positive to single-positive thymocytes to peripheral T cells (39) and may raise the threshold for T cell sensitivity to self Ags. Indeed, GILT+/- T cells induce more severe hyperglycemia following streptozotocin injection, a CD8+ T cell-mediated model of diabetes that excludes GILT’s role in class II-restricted Ag processing (39). In contrast, we observe diminished severity and delayed onset of vitiligo in GILT-deficient hosts in our model, which most likely reflects GILT’s role in Ag processing of TRP1 and decreased peripheral epitope generation.

GILT could exacerbate autoimmunity by altering T cell development or enhancing peripheral activation of autoreactive T cells. Unexpectedly, GILT+/−TRP1tg mice generated increased percentages of TRP1-specific T cells (Fig. 5C, SD). Although we cannot entirely exclude a minor role for GILT in T cells that leads to increased T cell numbers, GILT’s expression in T cells is unlikely to account for our findings. Enhanced proliferation of all T cells lacking GILT would be expected to lead to global T cell expansion. However, we demonstrated that the expansion was restricted to the TRP1-specific Vβ14+ T cells (Fig. SD–F). These findings suggest that the absence of GILT influenced the development of T cells specific for a GILT-dependent epitope in a manner similar to Ag deficiency (i.e., because TRP1 cannot be efficiently presented as a self Ag in the absence of GILT, more TRP1-specific T cells develop). For example, in class I-restricted, tyrosinase-specific TCR transgenic mice and in dual transgenic mice expressing a class II-restricted, HEL-specific TCR and a membrane-bound form of HEL under the TRP2 promoter to create a melanocyte-specific neoantigen, autoreactive T cells are increased in Ag-deficient mice (40, 41).

Possible explanations for the apparent contradiction of increased autoreactive T cells in GILT-deficient animals with delayed autoimmunity are increased Treg cells or diminished T cell activation in GILT-deficient animals. Treg cells have been shown to control autoimmunity in this and related models. For example, FoxP3-deficient TRP1tg mice develop spontaneous vitiligo earlier than FoxP3-expressing TRP1tg mice (21). Likewise, development of vitiligo in chimeric class I-restricted, tyrosinase-specific TCR transgenic mice is accelerated with anti-CD25 mAb treatment (42). In another mouse model with vitiligo, mice expressing a HEL-specific, class II-restricted TCR have an increased percentage of clonotype-specific T cells that are CD4+CD25+ in HEL-expressing mice compared with HEL-deficient mice (40). Although Treg cells are important in controlling autoimmunity and vitiligo in particular, there were no differences in the percentages of CD4+CD25+FoxP3+ Treg cells between TRP1tg and GILT+/−TRP1tg mice (Fig. 5G), suggesting that GILT did not affect the development of Treg cells, and a difference in the percentage of Treg cells did not contribute to the delayed onset of vitiligo in the absence of GILT.

We demonstrated that an increase in TRP1-specific cells with an effector memory phenotype correlates with vitiligo onset, and that there is a decrease in effector memory T cells in GILT-deficient mice (Fig. 6B). Thus, although more TRP1-specific T cells develop in the absence of GILT, a smaller percentage becomes activated. The changes observed in the absence of GILT are similar to those seen in the absence of Ag. A recent study observed T cells with an effector memory phenotype in Ag-expressing TRP1tg mice, but not in Ag-deficient TRP1PfRAG−/−TRP1tg mice (21). Similarly, in HEL-specific, class II-restricted TCR transgenic mice, CD4+CD44+ T cells are increased in the lymph node in the presence of melanocyte-restricted HEL expression (40). Presumably, inefficient class II-restricted processing of TRP1 in GILT-deficient mice diminishes T cell activation, and thus delays the onset of vitiligo.

Recent studies using adoptive transfer of TRP1PfRAG−/−TRP1tg T cells to treat established melanoma tumors have elucidated the mechanism of melanoma destruction (20, 21). Following adoptive transfer into Ag-expressing recipients, TRP1-specific T cells that developed in the absence of Ag and RAG secrete IFN-γ, express granzyme B and Fas ligand, and demonstrate cytotoxicity; furthermore, melanoma destruction is not dependent on NKT or NK cells (20, 21). A similar mechanism may be responsible for melanocyte destruction, resulting in spontaneous vitiligo in Ag-expressing, RAG-expressing TRP1tg mice. TRP1tg T cells that develop in the presence of Ag and RAG are also capable of producing IFN-γ (M. Rausch and K. Hastings, unpublished data). Similar to melanoma cells, melanocytes can upregulate class II expression in response to IFN-γ and present class II-restricted Ags (43–48), suggesting that they may become sensitized to class II-restricted cytotoxicity by IFN-γ–secreting, melanocyte-specific CD4+ T cells (20, 37, 49, 50).

The TRP1tg model has revealed a role for GILT in the development and function of T cells important in autoimmunity and anti-cancer immunity. Given that many melanocyte differentiation Ags have multiple disulfide bonds and are presented on MHC class II, additional Ags in this group are likely to be GILT dependent. Therefore, GILT is likely to have a more general role in the development of an effective anti-melanoma immune response.

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References


