PD-1<sup>+</sup>Tim-3<sup>+</sup> CD8<sup>+</sup> T Lymphocytes Display Varied Degrees of Functional Exhaustion in Patients with Regionally Metastatic Differentiated Thyroid Cancer

Jill J. Severson<sup>1</sup>, Hilary S. Serracino<sup>2</sup>, Valerica Mateescu<sup>2</sup>, Christopher D. Raeburn<sup>3,4</sup>, Robert C. McIntyre Jr<sup>3,4</sup>, Sharon B. Sams<sup>2,4</sup>, Bryan R. Haugen<sup>1,2,4</sup>, and Jena D. French<sup>1,4</sup>

Abstract

Regional metastatic differentiated thyroid cancer (mDTC) provides a unique model in which to study the tumor-immune interface. These lymph node metastases persist for years, generally without progression to distant metastases. Although the immune system likely impedes disease progression, it is unsuccessful in eliminating disease. Our previous studies revealed that programmed death-1 (PD-1)<sup>+</sup> T cells were enriched in tumor-involved lymph nodes (TILN). Tumor-associated leukocytes and tumor cells were collected from grossly involved lymph nodes from 12 patients to further characterize the phenotype and functional potential of mDTC-associated PD-1<sup>+</sup> T cells. PD-1<sup>+</sup>CD4<sup>+</sup> and PD-1<sup>+</sup>CD8<sup>+</sup> T cells were enriched in 8 of 12 TILN samples. PD-1<sup>+</sup> T cells coexpressed Tim-3 and CD69 and failed to downregulate CD27. CD8<sup>+</sup> T cells, but not CD4<sup>+</sup> T cells, from these samples were variably deficient in their ability to produce effector cytokines when compared with control TILNs that lacked resident PD-1<sup>+</sup> T cells. PD-1<sup>+</sup>CD8<sup>+</sup> T cells were capable of exocytosis but lacked intracellular perforin. Surprisingly, T-cell proliferative capacity was largely maintained in all samples. Thus, although PD-1 expression by mDTC-associated CD8<sup>+</sup> T cells was associated with dysfunction, exhaustion was not complete. Notably, molecular markers of exhaustion did not translate to dysfunction in all samples or in CD4<sup>+</sup> T cells. Regulatory T cells (Treg), PD-L1, and galectin-9 were commonly found in mDTC and likely contributed to the initiation of T-cell exhaustion and disease progression. Therapies that release the effects of PD-1 and Tim-3 and reduce the suppressive effects of Tregs may encourage tumor elimination in patients with mDTC. Cancer Immunol Res; 3(6); 620–30. ©2015 AACR.

Introduction

More than 500,000 people in the United States have a diagnosis of thyroid cancer, and the incidence is steadily growing, with an estimated 62,000 new cases in 2014 (1). Although localized differentiated thyroid cancer (DTC) is generally managed by surgery and radioactive iodine therapy, approximately 10% of patients develop progressive invasive primary disease and 5% develop distant metastases (1). Twenty percent to 30% of patients with DTC develop persistent or recurrent disease, most commonly in locoregional lymph nodes, requiring additional surgical intervention with increased morbidity and expense (2). Patients with aggressive DTC that are resistant to standard treatments may be excellent candidates for innovative adjuvant therapies, including immunomodulating approaches.

DTC provides a unique model in which to study the interplay between the immune response and the metastatic tumor. Lymph node metastases are common in patients with DTC (>60%; ref. 3). These regional metastases are thought to persist for years, generally without progression to distant metastasis. The 5-year survival rate for these patients is 97.4%, only slightly reduced compared with the 99.9% survival rate observed in patients with localized disease. In contrast, regional lymph node involvement in patients with lung, melanoma, or breast cancer indicates a significantly reduced rate of survival compared with localized disease (53.5% to 26.1%, 98.3% to 62.4%, and 98.6% to 84.4%, respectively; ref. 1). Despite their presumed indolent nature, DTC metastases are not eliminated by the immune system, suggesting that the immune response may be compromised. In support of this theory, our previous studies revealed that regulatory T cells (Treg) and programmed death-1 (PD-1)<sup>+</sup> T cells are elevated in tumor-involved lymph nodes (TILN) and may contribute to disease severity and recurrence (4).

T-cell exhaustion, which was originally described in models of chronic viral infections, is now established as an important mechanism of immune evasion in cancer. Exhausted T cells are characterized by the sustained expression of one or more inhibitory molecule [e.g., PD-1, cytotoxic T-lymphocyte antigen-4 (CTLA-4), and programmed death-1 (PD-1)]. However, the role of the PD-1<sup>+</sup> T cells in the persistence of DTC is not clear.
PD-1 and T-cell Exhaustion in Metastatic Thyroid Cancer

Materials and Methods

Antibodies

- Anti–CD3-AlexaFluor700 (UCHT1), anti–CD4-APC-eFluor480 (RPA-T4), anti–CD69-biotin (FN50), anti–CD127-PerCP-Cy5.5 (eBioRDRS), anti–CD27-APC-eFluor780 (1G7F9), anti–CD4–FITC (RPA-T4), anti–CD27–PE-Cy7 (G7.7F9), anti–CD45-APC-Cy7 (2D1), and anti–EpCam-PE (IB7), anti–FoxP3-PE-Cy7 (PCH110), anti–IL-27-PE-Cy7 (MQ1-17H12), anti–IFN-γ-APC-eFluor780 (4S.B13), anti–TNFR-PerCP-Cy5.5 (Mab11), anti–PD-1–APC (M1H4), anti–PD-L1–PE-Cy7 (MH1), mlgG1–PE-Cy7 (P3.K6.2.8.1), anti–CD45RA–FITC (HI100), anti–CD45RO-iotin (UCHL1), CD62L–PE-Cy7 (DREG-56), CCR7–APC-eFluor780 (3D12), anti–CD3–PE (CD28.2), and anti–CD28–PE (CD28.2) were purchased from eBioscience. Anti–CD8–BV510 (RPA-T8) was purchased from BioLegend. Anti–CTLA-4–Biotin and anti–Ki67–PerCP-Cy5.5 (B56) were purchased from BD Biosciences. Anti–TIM-3–PE (344823) was purchased from R&D Systems. Anti–IAG–3–FITC (17B4) was purchased from Enzo Life Sciences International, Inc. Anti–CD107a–PE–Cy7 (1H4A3) and anti–perforin–PerCP-Cy5.5 (6C9) were purchased from BD Biosciences. Anti–galectin-9 (ab69630) was purchased from Abcam. Control rabbit IgG (BA-1000) was purchased from Vector Labs. Goat–anti–Rabbit IgG-HRP was purchased from Dako. All antibodies were used per the manufacturer’s recommendations.

Ex vivo phenotyping by flow cytometry

Nonadherent cells were stained with Fixable Viability Dye eFluor450 (1:1,000 in DPBS; eBioScience) for 30 minutes at 4°C. Cells were incubated 10 minutes in FcRy Block (eBioScience). For each case was retrospectively assessed for lymph node involvement, size of metastases, and extranodal extension. Three normal lymph nodes from trauma patients were acquired from the National Disease Research Interchange. An archived normal lymph node from a patient with no history of cancer or autoimmune disease was used as a control for immunohistochemistry.

Sample acquisition and processing

Lymph nodes ranged from 1.5 to 2.9 cm in greatest diameter and housed visible tumor parenchyma. Each TILN was bisected, and an interior tissue section was donated. Multiple nodes were sampled when available to increase yield. Samples were collected in Hanks balanced salt solution (HBSS) and digested with 2.5 mg/mL Liberase DL and 10,000 U/mL DNase I (Roche) at 37°C for 1 hour. Red blood cells were lysed [37°C for 5 minutes; 150 mmol/L ammonium chloride, 10 mmol/L potassium bicarbonate, and 0.1 mmol/L ethylenediaminetetraacetic acid disodium salt dehydrate (EDTA)], and the remaining cells were incubated overnight in media [RPMI1640 (Gibco), 10% heat-inactivated HI-FBS, 1:500 penicillin/streptomycin (Gibco)]. Nonadherent cells (enriched for lymphocytes) were harvested and adherent cells (enriched for tumor cells) were trypsinized (0.25% Trypsin-EDTA; Gibco). Cells were cryopreserved in freezing media [10% dimethyl sulfoxide (DMSO) in HI-FBS at 1–10 × 10^7 cells/mL]. Sample size and tumor/lymphoid composition varied; thus, a complete phenotypic and functional analysis was not attainable for all samples. Normal or patient-matched peripheral blood was donated for isolation of mononuclear cells (PBMC) using Lymphoprep gradient media (Axis-Shield PoC AS). Normal lymph nodes were manually disaggregated to obtain a single-cell suspension. Peripheral blood and normal lymph nodes were cryopreserved as described above. Cryopreserved cells were thawed within 6 months of freezing.

Materials and Methods

Patients and histopathologic parameters

Patients with thyroid cancer undergoing surgical neck dissection for primary or recurrent disease at the University of Colorado Hospital between 2012 and 2014 were offered enrollment in this Institutional Review Board–approved study. Twelve patients were enrolled for the study and were confirmed by histopathology or previous medical reports to have conventional papillary thyroid cancer (PTC; patients 2–9), follicular variants (patient 10), or diffuse sclerosing variants (patients 1, 11, and 12). Chronic lymphocytic thyroiditis was evident in patients 1, 2, and 12. Each
analysis of T-cell exhaustion, cells were split and stained with the following antibody combinations: (i) anti–CD3-Alex fluor700, anti–CD4-Fitc, anti–CD8, anti–PD-1, anti–TIM-3, anti–CD127, anti–CD27-APC-elfor780, and anti–CD69-biotin or (ii) anti–CD3-Alex fluor700, anti–CD4-APC-elfor780, anti–CD8, anti–PD-1, anti–TIM-3, and anti–LAG-3 for 25 minutes at 4°C. Anti–CD69-biotin was detected with Streptavidin-PE-TR (15 minutes at 4°C; eBioscience). Cells were resuspended in × 1 Fixation/with × 1 Permeabilization Buffer (eBioscience) and stained with either (i) anti–FoxP3 or (ii) anti–CTLA-4-biotin and anti–Ki67 (25 minutes at 4°C). Anti–CTLA-4-biotin was detected with Streptavidin-PE-TR (15 minutes at 4°C) for memory-cell marker analysis, cells were stained for CD3, CD8, PD-1, TIM-3, CD45RA, CD45RO, CD62L, CCR7, and intracellular perforin as described above. For PD-L1 expression analysis, adherent mDTC cells were stained with anti–EpCAM and anti–CD45 and either left unstained or stained with mlgG or anti–PD-L1 (25 minutes at 4°C). BCPAP, an adherent DTC cell line, was used as a positive control for both EpCAM and PD-L1. Stained cells were fixed in 2.5% paraformaldehyde (PFA; in PBS). Data were acquired using the Gallios 561 flow cytometer (Beckman Coulter). Ten-color compensation was achieved using mlgGx Compbeads (BD Bioscience). Data analysis was performed with FlowJo software (Tree Star, Inc.). Histogram overlays are displayed in unit area to compare populations containing a wide-range of events.

Stimulated cytokine production
Nonadherent cells were resuspended in media plus Golgi Plug (1:1,000; BD Biosciences) and plated at 2.0 × 10⁶ cells per well in a 96-well round-bottom plate. Cells were left unstimulated, stimulated with PMA (50 ng/mL; Sigma) plus ionomycin (0.5 µg/mL; Sigma), or stimulated with plate-bound anti–CD3 (5 µg/mL) plus soluble anti–CD28 (2 µg/mL) and incubated for 6 hours (37°C/5.0% CO₂). Cells were harvested, incubated with Fixable Viability Dye, pretreated with FcR block, and stained for CD3, CD4, CD8, PD-1, and TIM-3. Following fixation and permeabilization, cells were stained for intracellular IL2, IFNγ, and TNFα (25 minutes at 4°C). Samples were fixed with 2.5% PFA and analyzed by flow cytometry.

Stimulated proliferation studies
Nonadherent cells were resuspended at 5 × 10⁶ cells/mL and loaded with 10 nmol/L 5-(and 6)-Carboxyfluorescin diacetate succinimidyl ester (CFSE; eBioscience) and were plated in media at 2.0 × 10⁶ cells/well in a 96-well round-bottom plate. Samples were stimulated with immobilized anti–CD3 (0.2 or 5 µg/mL) alone or in combination with soluble anti–CD28 (2 µg/mL) or with anti–CD3/anti–CD28 Dynabeads CTS (Life Technologies) at a 1:1 bead to cell ratio. Recombinant human IL2 was added to each well at 30 U/mL (eBioscience), and cells were incubated for 72 hours. Staining was performed for surface CD3, CD4, and CD8. Cells were fixed in 2.5% PFA and analyzed by flow cytometry.

Cytotoxic potential studies
Nonadherent cells were plated in media plus Golgi Plug (1:1,000) at 2.0 × 10⁶ cells/well in a 96-well round-bottom plate and left unstimulated or stimulated with PMA (50 ng/mL) plus ionomycin (0.5 µg/mL) for 4 hours. Anti–CD107a was added at the start of the incubation to detect CD107α within the extracellular membrane throughout the stimulation. Cells were harvested, incubated with Fixable Viability Dye, pretreated with FcR block, and stained for CD3, CD4, CD8, PD-1, and TIM-3. Following fixation and permeabilization, cells were stained for intracellular perforin and IFNγ (25 minutes at 4°C). Fixed with 2.5% PFA, and analyzed by flow cytometry.

Galectin-9 expression analysis by immunohistochemistry
TILN specimens were chosen from each patient’s archived tissues based on the presence of both overt metastases and tumor-associated lymphocytes. Tissue sections (4 µm) were deparaffinized and rehydrated. Antigen retrieval was performed in citrate buffer [10 mmol/L trisodium citrate (Sigma), 0.05% Tween-20 (Sigma), pH 6; 15 minutes, 110°C] in a Decloaking Chamber (Biocare Medical). Tissues were incubated with H2O2 (3%; 30 minutes) followed by serum block (5% goat serum plus 1% BSA in DPBS; 1 hour) and stained with control rabbit IgG or anti–galectin-9 (4 µg/mL) overnight at 4°C. Anti–galectin-9 was detected with goat anti–rabbit-HRP and ImmPact Diaminobenzidine (DAB; Vector Labs). Tissues were counterstained with Mayer’s hematoxylin (Sigma-Aldrich) and mounted with Cytoseal-XYL (Thermo Scientific). Staining intensity was scored on a 1+ to 3+ scale, and the percentage of positive cells was recorded. Allred scores were generated for comparison between samples (24).

Statistical analysis
To determine the statistical significance of interval data, we used the Mann–Whitney nonparametric, two-tailed t test. The level of statistical significance, with 95% confidence, was calculated and noted where P ≤ 0.05 (*) or P ≤ 0.01. To ensure statistical significance in our flow cytometry analyses (based on Poisson statistics), a minimum of 100 events were collected in the populations of interest.

Results
mDTC-associated PD-1+CD8+ and CD4+ T cells display a molecular profile indicative of exhaustion
Clinical details of the 12 patients with mDTC are summarized in Table 1. As shown in Fig. 1A, CD8+ or CD4+ T cells isolated from TILNs were assessed for expression of PD-1. PD-1+ T-cell levels were absent or low in frequency in peripheral blood (CD8+: 0.8 ± 0.8; CD4+: 0.6 ± 0.6), normal lymph nodes (nLN; CD8+: 0.2 ± 0.2; CD4+: 1.7 ± 0.4), and patients 4, 6, 7, and 8 (CD8+: 2.9 ± 2.0; CD4+: 3.6 ± 2.1). In the remaining patients, PD-1+ T-cell frequencies were elevated and ranged from 5% to 38% and from 4% to 33% of the CD8+ (18.0 ± 14.0; P = 0.03) and CD4+ (16.1 ± 11.0; P = 0.02) subsets, respectively. PD-1+ and PD-1− T cells were compared for expression of Tim-3, CD69, CD127, and CD27 (Fig. 1A and B). Where PD-1+ cells were too low in frequency to be characterized, the expression of these molecules was assessed in total CD8+ or CD4+ subsets. Tim-3 was not expressed by T cells in the PD-1− group but was coexpressed at uniformly high levels by PD-1+ CD8+ T cells in patients 1, 2, 3, and 11 and at varied levels in patients 5, 9, 10, and 12. In patients 2 and 3, PD-1+ CD8+ T cells also expressed Tim-3. As expected, T cells in the PD-1+/Tim-3− group contained a mixed profile of activated (CD69hi, CD25hi) and naïve or resting (CD69lo, CD25lo) cells in this setting to that in normal lymph nodes, although CD69hi T cells were more frequent in TILNs. In contrast, CD8+ T cells from the PD-1−Tim-3+ group...
Table 1. Clinical summary and CD8<sup>+</sup> T-cell phenotype

<table>
<thead>
<tr>
<th>Patient</th>
<th>Lymph node source</th>
<th>Age</th>
<th>Gender</th>
<th>T-cell phenotype</th>
<th>Primary (P) or recurrent (R)</th>
<th>TILN/total lymph node (%)</th>
<th>Extraneural extension</th>
<th>Largest met (cm)</th>
<th>Phenotype</th>
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<tbody>
<tr>
<td>1</td>
<td>CND</td>
<td>33</td>
<td>F</td>
<td>pT3 pT1b M0</td>
<td>P</td>
<td>36/83 (43)</td>
<td>Y</td>
<td>2</td>
<td>PD-1/Tim-3</td>
</tr>
<tr>
<td>2</td>
<td>RLND</td>
<td>25</td>
<td>F</td>
<td>pT3 pT1b M0</td>
<td>P</td>
<td>14/58 (24)</td>
<td>Y</td>
<td>2.2</td>
<td>PD-1/Tim-3</td>
</tr>
<tr>
<td>3</td>
<td>CND, RLND</td>
<td>51</td>
<td>F</td>
<td>pT4a pT1b MX</td>
<td>P</td>
<td>4/65* (6)</td>
<td>Y</td>
<td>2.1</td>
<td>PD-1/Tim-3</td>
</tr>
<tr>
<td>4</td>
<td>CND, RLND</td>
<td>59</td>
<td>M</td>
<td>pT3 pT1b M0</td>
<td>P</td>
<td>34/65 (57)</td>
<td>Y</td>
<td>2.2</td>
<td>PD-1/Tim-3</td>
</tr>
<tr>
<td>5</td>
<td>CND</td>
<td>48</td>
<td>M</td>
<td>pT1 pT1a M0</td>
<td>R (7 months)</td>
<td>7/7 (7); 36/86 (43)</td>
<td>N</td>
<td>1.3</td>
<td>PD-1/Tim-3</td>
</tr>
<tr>
<td>6</td>
<td>CND</td>
<td>37</td>
<td>F</td>
<td>pT3 pT1b M0</td>
<td>R (7 months)</td>
<td>2/12 (P); 7/10 (R) (41)</td>
<td>Y</td>
<td>1.1</td>
<td>PD-1/Tim-3</td>
</tr>
<tr>
<td>7</td>
<td>CND, LLND</td>
<td>24</td>
<td>M</td>
<td>pT3 pT1b M0</td>
<td>P</td>
<td>28/73 (38)</td>
<td>Y</td>
<td>2.5</td>
<td>PD-1/Tim-3</td>
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<td>8</td>
<td>CND, LLND</td>
<td>79</td>
<td>M</td>
<td>pT3 pT1b M0</td>
<td>R (10 months)</td>
<td>2/12 (P); 2/9 (R) (11)</td>
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<td>PD-1/Tim-3</td>
</tr>
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<td>9</td>
<td>CND, LLND</td>
<td>48</td>
<td>F</td>
<td>pT3 pT1b M0</td>
<td>P</td>
<td>8/72 (11)</td>
<td>N</td>
<td>0.4</td>
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<td>LLND</td>
<td>53</td>
<td>M</td>
<td>pT3 pT1b M0</td>
<td>P</td>
<td>3/45 (7)</td>
<td>ND</td>
<td>0.4</td>
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</tr>
<tr>
<td>11</td>
<td>LLND</td>
<td>53</td>
<td>M</td>
<td>pT3 pT1b M0</td>
<td>P</td>
<td>77/141 (55)</td>
<td>Y</td>
<td>2.5</td>
<td>PD-1/Tim-3</td>
</tr>
<tr>
<td>12</td>
<td>CND, LLND</td>
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<td>F</td>
<td>pT2 pT1b M0</td>
<td>P</td>
<td>28/708 (26)</td>
<td>N</td>
<td>0.4</td>
<td>PD-1/Tim-3</td>
</tr>
</tbody>
</table>

NOTE: For recurrent patients, the time from initial treatment to surgery for recurrence is noted in parentheses.}

Abbreviations: CND, central neck dissection; LLND, left lateral neck dissection; met, metastasis; RLND, right lateral neck dissection.

Denotes samples where lymph nodes were matted due to tumor metastasis and determination of lymph node number was compromised. Patients categorized as PD-1/Tim-3 are shaded gray.

showed signs of exhaustion. Specifically, CD69 was expressed at uniformly high levels by PD-1<sup>+</sup> T cells. A significant portion of PD-1<sup>+</sup> CD4<sup>+</sup> and CD8<sup>+</sup> T cells from patients 2 and 3 upregulated CD69, suggesting that these lymph nodes were highly reactive despite the presence of advanced metastases. CD27 remained highly expressed by both PD-1<sup>+</sup>- and PD-1<sup>-</sup>-CD8<sup>+</sup> T cells from the PD-1<sup>+</sup>/Tim-3<sup>-</sup> group. A statistically significant reduction in CD127 expression was evident in PD-1<sup>+</sup>-CD8<sup>+</sup> T cells from PD-1<sup>-</sup>/Tim-3<sup>-</sup> TILNs compared with that in normal lymph nodes (Fig. 1B). Intracellular CTLA-4 was expressed at low levels by PD-1<sup>-</sup>-CD8<sup>+</sup> T cells from patients 1, 2, 3, 5, 11, and 12. CTLA-4 expression was also observed on a subset of PD-1<sup>-</sup>-CD8<sup>+</sup> T cells from patients 2 and 3 and by a subset of CD8<sup>+</sup> T cells from patient 7. Analysis of the CD4<sup>+</sup>-T-cell population revealed CD69, CD127, and CD27 expression profiles that were similar to patient-matched CD8<sup>+</sup> T cells. However, Tim-3 and PD-1 were clearly coexpressed only in patients 2, 3, 11, and 12. CTLA-4 expression was more robust in the CD4<sup>+</sup>-T-cell subset of both groups, likely due to the inclusion of CD4<sup>+</sup>-Tregs in this analysis. PD-1<sup>-</sup>-CD4<sup>+</sup> T cells were uniformly CTA4<sup>-</sup>- in patients 1, 2, 3, 5, 11, and 12 and also evident in a subset of CD4<sup>+</sup>-T cells in patients 4, 7, and 8. Collectively, these data suggest that PD-1 expression is a sign of T-cell exhaustion in mDTC.

To further characterize mDTC-associated T cells, we assessed CD45RA, CD45RO, CCR7, and CD62L expression (Supplementary Fig. S1). CD4<sup>+</sup> and CD8<sup>+</sup> T cells from TILNs contained both naive CD45RA<sup>+</sup> and memory CD45RO<sup>+</sup> subsets, similar to that in normal lymph nodes. CCR7<sup>+</sup> memory cells were evident in patient 11, and CD62L<sup>+</sup> memory cells were found at a high frequency, more comparable with that observed in blood, in both TILNs. PD-1<sup>-</sup>-CD8<sup>+</sup> T cells from patients 11 and 12 were largely CD45RA<sup>+</sup>CD45RO<sup>+</sup> memory cells. The majority of these cells lacked CCR7<sup>-</sup> and expressed variable levels of CD62L. Thus, PD-1<sup>-</sup>- T cells from TILNs were primarily effector-memory T cells (T<sub>eff</sub>-CD45RA<sup>+</sup>/CCR7<sup>-</sup>/CD62L<sup>+</sup>) that had encountered antigens and differentiated within the TILNs or had migrated following activation (25).

CD8<sup>+</sup> T cells from PD-1<sup>-</sup>-Tim-3<sup>-</sup> samples were variably deficient in their ability to produce IL2, TNF<alpha>, and IFN<gamma>

To determine whether the presence of PD-1<sup>-</sup>- T cells was associated with compromised cytokine production, we compared production of IL2, TNF<alpha>, and IFN<gamma> by T cells from the PD-1<sup>-</sup>-Tim-3<sup>-</sup> and PD-1<sup>-</sup>-Tim-3<sup>+</sup> TILNs groups described above. PD-1<sup>-</sup>- and Tim-3<sup>-</sup>- T cells were upregulated following stimulation in vitro (Supplementary Fig. S2), comprising our ability to specifically analyze the inherent PD-1<sup>-</sup>-Tim-3<sup>-</sup> populations (Fig. 1). Despite short-term activation in culture, CD8<sup>+</sup>- T cells from PD-1<sup>-</sup>-Tim-3<sup>-</sup> TILNs were generally compromised in their ability to produce IL2 and TNF<alpha> compared with that in PD-1<sup>-</sup>-Tim-3<sup>-</sup> TILNs following PMA/ionomycin stimulation (Fig. 2A–C). This trend was evident when gating on total CD8<sup>+</sup> T cells and PD-1<sup>-</sup>- subsets, and most obvious when comparing PD-1<sup>-</sup>-Tim-3<sup>-</sup>- subsets. The frequencies of IL2<sup>+</sup> and TNF<alpha> CD8<sup>+</sup>- T cells were variable among PD-1<sup>-</sup>-Tim-3<sup>-</sup> TILNs. In contrast to the other PD-1<sup>-</sup>-Tim-3<sup>-</sup> TILNs, CD8<sup>+</sup>- T cells from patient 5 contained a frequency of IL2<sup>+</sup> and TNF<alpha> similar to that observed in PD-1<sup>-</sup>-Tim-3<sup>-</sup> TILNs when stimulated with PMA/ionomycin (Fig. 2C) or anti-CD3/anti-CD28 (Fig. 2D). IFN<gamma><sub>+</sub> T cells frequencies were not significantly reduced in PD-1<sup>-</sup>-Tim-3<sup>-</sup> TILNs following PMA/ionomycin stimulation (Fig. 2E); however, the IFN<gamma> response was significantly lower when cells were stimulated with anti-CD3/anti-CD28 (Fig. 2F). In line with our findings for IL2 and TNF<alpha>, IFN<gamma> production was maintained in patient 5 (Fig. 2F, arrows). Cytokine production by CD4<sup>+</sup>- T cells was comparable in PD-1<sup>-</sup>-Tim-3<sup>-</sup> and PD-1<sup>-</sup>-Tim-3<sup>+</sup> TILNs following PMA/ionomycin stimulation (Fig. 2G). Although a subset of PD-1<sup>-</sup>-Tim-3<sup>-</sup>- samples showed markedly reduced IL2 production following anti-CD3/anti-CD28 stimulation, a statistically significant difference was not observed (Fig. 2H). Of note, cytokine production by patient peripheral blood T cells was variable but comparable between the PD-1<sup>-</sup>-Tim-3<sup>-</sup>- and PD-1<sup>-</sup>-Tim-3<sup>+</sup>- groups (Supplementary Fig. S3). Cytokine levels were significantly lower in normal lymph nodes (Supplementary Fig. S3) likely due to the high percentage of naive T cells. Our comparison of PD-1<sup>-</sup>-Tim-3<sup>-</sup> and PD-1<sup>-</sup>-Tim-3<sup>+</sup>- TILNs suggests that expression of molecular markers of exhaustion was associated with impaired cytokine production by CD8<sup>+</sup>- T cells. However, the degree of dysfunction was variable and did not occur in all patients or in tumor-associated PD-1<sup>-</sup>-CD4<sup>+</sup>- T cells.

Proliferative potential is maintained in mDTC-associated CD8<sup>+</sup> and CD4<sup>+</sup>- T cells

To determine whether mDTC-associated T cells were compromised in their proliferative capacity, we assessed Ki67 by flow
Figure 1. Phenotype of T cells isolated from TILNs. T cells from peripheral blood (PB), normal lymph node (nLN), and TILN sections from 12 mDTC patients were analyzed by flow cytometry. A, viable CD8^+ T cells and FoxP3^+CD4^+ T cells were analyzed for PD-1 expression (%PD-1^+ is noted). Total CD8^+ or FoxP3^+CD4^+ populations were analyzed for the designated receptors in patients 4, 6, 7, and 8 whose PD-1^+ cells were too infrequent to assess (PD-1^loTim-3^+). In the remaining samples (PD-1^+Tim-3^+), PD-1^+ (black line) and PD-1^- (filled gray histogram) subpopulations were compared. FoxP3^+ Tregs were included in the analysis of intracellular CTLA-4 expression. Peripheral blood samples were used to determine the gating strategy. B, combined analysis of peripheral blood (thin hatched), nLN (thick hatched), PD-1^-Tim-3^- TILN (white), and PD-1^+Tim-3^- TILN (light gray) or PD-1^- (dark gray) and PD-1^+ (black) subsets in PD-1^-Tim-3^- TILN.

1, P ≤ 0.05; **, P ≤ 0.01.
In agreement with our previous studies in archived TILN tissues (4), a small percentage of T cells expressed Ki67. As shown in Fig. 3A, the percentages of Ki67$^+$ CD8$^+$ and CD4$^+$ T cells were similar in PD-1$^-$Tim-3$^-$ and PD-1$^+$Tim-3$^+$ TILNs. In PD-1$^+$Tim-3$^+$ TILNs, Ki67$^+$ cells were predominantly found in the PD-1$^+$ population of CD8$^+$ T cells (Fig. 3B) and CD4$^+$ T cells (data not shown). To determine their proliferative potential ex vivo, we stimulated CFSE-labeled nonadherent cells from TILNs for 3 days in the presence anti-CD3/anti-CD28–coated beads and IL2. CD8$^+$ T cells from patients 3, 5, 10, and 11 displayed a strong proliferative response that was only minimally reduced compared with peripheral blood–derived T cells (Fig. 3C). A similar trend was observed for CD4$^+$ T cells (data not shown).
observed in the CD4+ T cells from these patients. T cells from patient 9 showed an enhanced response compared with patient blood-derived T cells. The proliferative potential of T cells from patient 8, the only PD-1+/Tim-3- sample available for analysis, was comparable with that of control blood–derived T cells. Results were similar at lower bead:cell ratios (1:5 or 1:10) or in the absence of IL2 (data not shown). To interpret our results in the context of previous T-cell exhaustion studies in human cancers, we also assessed proliferation of mDTC-associated T cells from patient 11 in response to plate-bound anti-CD3 at low and high concentrations and anti-CD3 in combination with soluble anti-CD28 (Fig. 3C). The low concentration of anti-CD3 was a weak stimulant, driving only one division in normal peripheral blood T cells after 3 days. Only 26% of CD4+ T cells from patient 11 had divided. Of note, CD8+ T cells were significantly reduced in number in both blood and TILN samples when stimulated with 0.2 μg/mL of anti-CD3 (data not shown). Under stronger stimulatory conditions (5 μg/mL anti-CD3 and anti-CD3/anti-CD28), the proliferative response was slightly delayed in both CD8+ and CD4+ T cells from TILNs compared with those from control blood. Despite this delay, more than 96% of CD8+ T cells and 60% of CD4+ T cells had undergone at least one division by day 3. Thus, although mDTC-associated T cells were less responsive to suboptimal stimulation, proliferative capacity was largely preserved in response to moderate and strong stimuli ex vivo.

Cytotoxic potential may be compromised in CD8+ T cells from PD-1+ Tim-3- samples

We next assessed the ability of mDTC-associated PD-1+ Tim-3- CD8+ T cells to degranulate. Ex vivo cytotoxic potential is commonly measured by CD107a mobilization to the cell surface (26). As shown in Fig. 4A, 9.5% of peripheral blood CD8+ T cells had undergone degranulation following stimulation with PMA/ionomycin. In line with this finding, 9.1% of peripheral blood CD8+ T cells expressed intracellular perforin at baseline, and perforin expression was reduced to less than 1% following stimulation and exocytosis (Fig. 4B). Sixteen percent to 49% of CD8+ T cells from PD-1+ Tim-3- samples (patients 10, 11, and 12) mobilized CD107a to the cell surface (Fig. 4A). Of note, CD107a mobilization was most evident in the PD-1+ and PD-1+/Tim-3- CD8+ T-cell subsets in both peripheral blood and TILNs (Fig. 4A, column 3). Surprisingly, mDTC-associated CD8+ T cells showed no evidence of intracellular perforin (Fig. 4B). As expected, perforin expression in peripheral blood CD8+ T cells was confined to CD45RA+CCR7-TEMRA and, to a lesser extent, CD45RO+CCR7-TEm subsets (Fig. 4C; ref. 25). Perforin expression was absent in TEMRA (data not shown) and TEM (Fig. 4) in TILNs, regardless of PD-1 expression. These data suggest that although PD-1+ Tim-3- CD8+ T cells are capable of degranulation, their cytotoxic potential may be diminished.

PD-L1 and galectin-9 are expressed by metastatic DTC

PD-1 and Tim-3 inhibit T-cell function upon ligation of their requisite ligands, PD-L1 and galectin-9 (27–29). As shown in Fig. 5, we assessed PD-L1 expression by adherent cell populations derived from TILNs using flow cytometry. Tumor cells were identified by expression of epithelial-cell adhesion molecule (EpCAM; Fig. 5A). BCPAP, a DTC cell line, displayed uniformly low expression of EpCAM but high expression of PD-L1. Primary tumor cells were readily distinguished by their high EpCAM expression, and 9 of 10 tumors expressed PD-L1 to varying degrees (Fig. 5A and B). No correlation was observed between PD-L1 expression levels and the frequency of PD-1+CD4+ or PD-1+CD8+ T cells (data not shown). Although adherent cells from 2 PD-1+Tim-3- TILNs displayed relatively high levels of PD-L1, expression was not statistically different between PD-1+Tim-3- and PD-1+Tim-3+ groups (Fig. 5B; P = 0.2571). A subset of CD45+ tumor-associated leukocytes that remained in the adherent cell cultures displayed low levels of PD-L1 in 4 of 10 samples analyzed (Fig. 5A and C). In contrast, CD45+ leukocytes from normal lymph nodes lacked PD-L1 expression (Fig. 5A). As shown in Fig. 5D, galectin-9 was evident on both mDTC and tumor-associated leukocytes. Galectin-9 expression was similar between PD-1+/Tim-3- and PD-1+Tim-3- TILNs in both mDTC (6.1 ± 0.3 vs. 6.3 ± 0.5; P = 0.8101) and leukocytes (5.9 ± 0.6 vs. 4.9 ± 1.1; P = 0.1227; Supplementary Table S1). Leukocytes in normal lymph nodes stained at a similar intensity (Fig. 5D)
Thus, both PD-L1 and galectin-9 are commonly expressed in TILNs and may contribute to immune dysfunction.

Tregs are present at similar frequencies in both PD-1loTim-3⁻ and PD-1⁺Tim-3⁺ TILNs

Our previous studies using fine-needle aspirate biopsies revealed that FoxP3⁺CD25⁺CD127loCTLA-4⁺ Tregs were elevated on average in TILNs (15.4% ± 6.3%), compared with UILNs (10.3% ± 3.6%; ref. 4). To investigate the role of Tregs in this study, we assessed FoxP3 expression and other key phenotypic markers of Tregs by flow cytometry. As shown in Fig. 6, FoxP3⁺ Tregs were prominent in all TILN samples, ranging from 12.6% to 39.0% of the CD4⁺ T cells (29.5% ± 3.8%). These levels were significantly higher than that seen in patient-matched peripheral blood (Fig. 6B; 3.1% ± 0.5%) and normal lymph nodes (Fig. 6B; 5.0% ± 1.6%) and were elevated compared with our previous analysis of UILNs and TILNs. Tregs were present at similar frequencies in both PD-1loTim-3⁻ and PD-1⁺Tim-3⁺ TILNs (Fig. 6B; 29.5% ± 3.8% vs. 23.2% ± 3.5%; P = 0.26). CD127 expression was comparable in Tregs from blood, normal lymph nodes, and TILNs. Tregs expressed low levels of PD-1 in samples 2, 3, 7, 8, 9, and 10 and high levels of Tim-3 in 6 of 12 patients. Tim-3 was also expressed by a subset of Tregs in normal lymph nodes. Expression of PD-1 and Tim-3 has been associated with activated and highly suppressive Tregs (30, 31). These data suggest that Tregs may play a key role in the establishment of T-cell exhaustion (32) in PD-1⁺Tim-3⁺ TILNs and may create an additional barrier to tumor elimination by the immune system in mDTC.

Discussion

Although PD-1⁺ T cells have been found in association with many cancers, functional T-cell exhaustion has been characterized in only a subset of these studies (8–17). Here, we report variable defects in cytokine production by PD-1⁺CD8⁺ T cells isolated from TILNs in patients with mDTC. Although T cells from patient 5 displayed a molecular profile of exhaustion, their ability to produce cytokines was unimpaired. Of note, the PD-1⁺CD8⁺ T cells in this sample contained a definitive PD-1⁺Tim-3⁺ population. Although these data suggest that expression of multiple inhibitory receptors is necessary for reduced T-cell function, coexpression of PD-1 and Tim-3 by CD4⁺ T cells (patients 2 and 3) did not confer a dysfunctional phenotype. Our data lend further support to the theory that expression of molecular markers of exhaustion (PD-1, Tim-3, CD69hi, CD27hi) does not translate uniformly to impaired function (13, 33).

Figure 5.

PD-L1 and galectin-9 expression in TILNs. A, viable EpCAM⁺ tumor cells and CD45⁺ leukocytes that remained in the adherent cells from TILNs were gated and analyzed for PD-L1 expression by flow cytometry. Patient (Pt) 7 is shown as a representative sample. PD-L1 (black line) is compared with IgG (dotted line) or unstained (gray histogram) controls. Fold median fluorescence index (MFI) of anti–PD-L1/IgG is noted. B, relative PD-L1 expression is shown for each PD-1loTim-3⁻ and PD-1⁺Tim-3⁺ TILN. C, combined analysis of 4 experiments is shown. The dotted line denotes the threshold for PD-L1 expression. D, representative images of galectin-9 expression in TILNs (patient 1; ×40 magnification) and normal lymph node (nLN). mDTC, metastasis; TAL, mDTC-associated leukocytes.
Figure 6.
Treg frequency and phenotype in TILNs. A, the percentage of FoxP3+ cells in the total CD4+ T-cell population was determined by flow cytometry. FoxP3+ Tregs (black line) and FoxP3- (filled gray histogram) subsets were compared for expression of CD127, PD-1, and Tim-3. B, combined analysis of Treg frequency and activation markers in peripheral blood (PB; thin hatched), normal lymph node (thick hatched), PD-1loTim-3+ TILNs (white), and PD-1+Tim-3+ TILNs (light gray).
Viral and tumor models suggest that reduced cytotoxic potential occurs during the process of T-cell exhaustion. Specifically, reduced perforin expression was characteristic of exhausted CD8+ T cells in chronic lymphocytic choriomeningitis virus infection (7). Furthermore, perforin was absent in melanoma-specific CD8+ T cells from 6 of 9 TILNs (16). It is tempting to conclude that the lack of perforin expression in mDTC-associated CD8+ T cells is another sign of functional exhaustion. However, our analysis revealed no evidence of perforin expression in normal lymph node tissue and PD-1loTim-3 TILNs are required to determine whether the absence of perforin expression is due to tumor-induced T-cell exhaustion or inherent properties of lymph node tissue.

Studies in other types of cancer have shown that expression of PD-1 and Tim-3 by tumor-associated T cells results in reduced proliferative capacity (10, 13, 17). In follicular B-cell non-Hodgkin lymphoma, only 10% of Tim-3+CD8+ and 8% of Tim-3+CD4+ T cells had undergone at least one division after 72 hours compared with 45% of Tim-3CD8+ and 23% of Tim-3CD4+ T cells following stimulation with immobilized anti-CD3 (0.2 μg/ml). CLL-associated CD8+ T cells were defective in proliferation following stimulation with anti-CD3 (5 μg/ml) and anti-CD28 (13). In 7 of 20 CLL samples tested, the proportion of CD8+ T cells that had undergone division was less than 25%. CD8+ T-cell proliferation in the remaining 13 samples was similar to that observed in normal healthy controls. In our analyses using multiple stimulation regimens, we observed a subtle delay in T-cell proliferation in follicular B-cell patients. However, more than 86% had undergone at least one division following anti-CD3/ anti-CD28 stimulation. This is in sharp contrast to the markedly reduced CD8+ T-cell proliferative responses observed in CLL. These data suggest that proliferative capacity is largely maintained in mDTC-associated T cells, despite enrichment of PD-1+Tim-3+ cells. Taken together, our functional analyses lead us to conclude that CD8+ T-cell exhaustion is incomplete in patients with mDTC and may be readily reversible.

T cells from PD-1loTim-3 TILNs showed no evidence of phenotypic exhaustion or functional defect ex vivo. Surprisingly, the size and frequency of metastatic tumors were similar in PD-1loTim-3 and PD-1+Tim-3+ TILNs (Table 1). This paradox may be explained by the following hypotheses: (i) It is possible that, despite activation by professional antigen-presenting cells, tumors have escaped detection in these patients. High expression of CD69 by a significant portion of T cells in 3 of the 4 PD-1loTim-3+ TILNs suggests that these cells have undergone activation. Given the extent of tumor load in these lymph nodes, it is probable that these activated T cells are reactive to the tumor rather than to unrelated pathogens. However, the tumor cells may have downregulated their own antigen processing and presentation machinery necessary for immune recognition. (ii) T cells may be compromised (i.e., anergy and/or senescence) in vivo but not ex vivo. Functional defects may be reversed once the T cells are removed from the tumor microenvironment and exposed to nonphysiologic stimuli. In support of this hypothesis, Tregs, PD-L1, and galectin-9 were also evident in PD-1loTim-3+ TILNs and likely encourage immune dysfunction. (iii) It is conceivable that T-cell exhaustion is a common theme in all TILNs but that signs of exhaustion are not evident in all samples at the time of analysis. Specifically, our characterization of PD-1loTim-3 TILNs may have taken place at the early stages of exhaustion where function is largely maintained and inhibitory receptors are not yet upregulated. It is likely that ex vivo restimulation with physiologically relevant antigen would reveal an even broader continuum of dysfunction among mDTC patients. Additional studies are required to characterize alternative mechanisms of T-cell dysfunction and tumor escape in mDTC.

As described above, regional mDTC appears to be slow-growing and poorly metastatic, but persists without elimination by the host immune system. Our studies suggest that, in the majority of patients with grossly involved lymph nodes, tumor-reactive T cells are actively engaging the tumor. Although ineffective in elimination, this response likely impedes tumor growth and metastases. The degree of functional exhaustion was variable in patients with evident PD-1+Tim-3+ T-cell enrichment and may be reversible in the majority of cases. We suggest that immunomodulating therapies that inhibit PD-1/PD-L1 and/or Tim-3/galectin-9 are viable options for patients with persistent disease. These checkpoint therapies may also inhibit the suppressive activity of Tregs (34, 35). Current PD-1/PD-L1-targeted therapies display low toxicities, and if injected locally into TILNs via ultrasound guidance, may be even more tolerable (36–38).

Although these studies focus on regional mDTC, we expect that PD-1/PD-L1-targeted therapies may be effective in patients with aggressive localized DTC and distant metastatic disease that cannot be cured by standard therapies (i.e., surgery, radioactive iodine, or tyrosine kinase inhibitors [TKI]). The VEGFR2 inhibitor sorafenib was successful in slowing tumor growth, but did not achieve durable responses (39). Future studies are necessary to characterize the immune response in aggressive DTC and to investigate the potential for PD-1/PD-L1 blockade and TKI combination therapy.

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

Authors’ Contributions
Conception and design: R.C. McIntyre, B.R. Haugen, J.D. French
Development of methodology: J.D. French
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): J.J. Severson, H.S. Serracino, C.D. Raeburn, B.R. Haugen, J.D. French
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): J.J. Severson, S.B. Sams, B.R. Haugen, J.D. French
Writing, review, and/or revision of the manuscript: J.J. Severson, C.D. Raeburn, B.R. Haugen, J.D. French
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): R.C. McIntyre, B.R. Haugen, J.D. French
Study supervision: B.R. Haugen, J.D. French

Other (microscopic examination of the pathology slides for evaluation of the metastatic carcinoma): V. Mateescu

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