Origin, trafficking, and intraepithelial fate of gut-tropic T cells

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The small intestine epithelium (SI-Ep) harbors millions of unconventional (γδ and CD4−CD8− NK1.1− TCRαβ) and conventional (CD8αβ and CD4) T cells, designated intraepithelial lymphocytes (IELs). Here, we identified the circulating pool of SI-Ep–tropic T cells and studied their capacity to colonize the SI-Ep under steady-state conditions in SPF mice. Developmentally regulated levels of α4β7 endowed recent thymic emigrants (RTEs) of unconventional types with higher SI-Ep tropism than their conventional homologues. SI-Ep–tropic RTEs, which in all lineages emerged naive, homed to the SI-Ep, but this environment was inadequate to stimulate them to cycle. In contrast, conventional and, unexpectedly, unconventional T cells, particularly Vy7+ (hallmark of γδ IELs), previously stimulated to cycle in the gut–associated lymphoid tissue (GALT), proliferated in the SI-Ep. Cycling unconventional SI-Ep immigrants divided far more efficiently than their conventional homologues, thereby becoming predominant. This difference impacted on acquisition of high Granzyme B content, which required extensive proliferation. In conclusion, SI-Ep–tropic T cells follow a thymus–SI-Ep or a GALT–SI-Ep pathway, the latter generating highly cytotoxic IELs.
In the SI-Ep, T cell populations are characterized by the pre-in the SI-Ep and in the hemolymphatic circuit Quantitative differences between T cells

RESULTS

home to the SI-Ep was challenged by evidence that CD8

Grand and Vassalli, 1986). The view that naive cells do not

SI-Ep via the blood stream (Guy-Grand et al., 1978; Guy-

and Hayday 2013), although some gut-tropic

molecules in TDLs according to their age and activation status.

Thymic development confers higher gut tropism to γδ and

uncTCRαβ T cells than to their conventional homologues

Using RAG2p-GFP transgenic mice, we determined the ex-

pression levels of αβ7 and CCR9 in newly generated T cells

at the stage of RTEs, identified by the expression of GFP,

which persists for ~3 wk after down-regulation of RAG-2 gene

transcription (Guy-Grand et al., 2003; Boursalian et al., 2004).

In the lymph of 6-wk-old mice, TDLs contained a high

frequency of GFP+ cells (Fig. 1 A), hereafter referred to as

RTEs, which in all T cell types were CD62L+ CD44low/int

i.e., naive (not depicted). The proportion of γδ T cells was

higher than in global TDLs (Table 1) Unconventional RTEs

expressed the highest levels of CCR9, which was undetectable in CD4+

RTEs and in most uncTCRαβ RTEs (Fig. 1 A).

The differential expression of gut-tropic molecules among

lineages was developmentally related, as it was already ap-

parent (albeit less markedly so) among the respective newly

generated mature thymocytes (Fig. 2), defined as TCRαβ+

CD69+ GFP+, which in all lineages were CD44low/int. In

contrast, TCRαβ+ CD69+ GFP+ thymocytes in all lineages

Table 1. T-cell subset distribution in IELs and TDLs

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<th>Frequency</th>
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<tr>
<td></td>
<td>CD3+ γδ</td>
</tr>
<tr>
<td>IELs</td>
<td>%</td>
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<tr>
<td></td>
<td>46.5 ± 11.5 (49)</td>
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<tr>
<td>TDLs</td>
<td>%</td>
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<tr>
<td></td>
<td>1.44 ± 0.5 (52)</td>
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<tr>
<td>RTEs</td>
<td>%</td>
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<td>2.65 ± 1 (8)</td>
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Values in parentheses show the number of mice individually analyzed.

1Percent CD3+ cells: TDLs, 76 ± 10; IELs, 84 ± 6.9.

2NK-T cells were excluded with an anti-NK1.1 mAb. Similar results were obtained in CD1+ T-cells.

3Frequency of unconventional T cells in RTEs was independent of the age of the mice.

4Percent Vγ7+ in γδ T-cells.
were in majority CD44high and expressed neither α4β7 nor CCR9 (Fig. 2). Thus, the contribution of the thymus to the circulating pool of gut-tropic T cells appears restricted to cells with a naive phenotype, whose levels of α4β7 are highest at the stage of RTE.

To assess whether levels of α4β7 and CCR9 in RTE correlated with SI-Ep homing efficiency, TDLs of RAG2p-GFP B6 mice (CD45.2) were transferred to nonirradiated B6-CD45.1 recipients. At 18 h after transfer, the frequency of donor CD3+ TDLs in MLN and SI-Ep, Histograms show the frequency of GFP+ cells and respective T cell subset distribution (bar graphs) in donor TDLs (eight mice individually studied in seven independent canulation experiments) and in the indicated recipient’s organs (five mice in five independent transfer experiments). *, P < 0.02; †, P = 0.056. (C, left) Absolute number of donor RTEs in the indicated organs of the recipients described in B. Values are based on the total number of CD3+ cells per organ, calculated as described in Materials and methods. Arithmetic means are indicated. (C, right) Ratio of the number of donor cells in LN versus SI-Ep for each T cell subset. For CD4 T cells, the average ratio (see asterisk) did not take into account the outlier value. ****, P < 0.0001 (pooled unconventional versus conventional LN/IEL ratios). (D) Expression of α4β7 in Vγ7+ and Vγ7− GFP+ (RTEs) TDLs (two mice studied in two independent experiments). (E) RAG2p-GFP TDLs were transferred to wild-type (CD45.1) B6 recipients and analyzed 18 h later. The histograms show the frequency of Vγ7+ and Vγ4+ cells in GFP+ (RTEs) cells in the indicated organs. A second recipient, in another transfer experiment, gave similar results; the average frequency, as percentage of γδ RTEs, of all pooled organs was as follows: Vγ7+, 11.2 ± 2.5; Vγ4+, 23.2 ± 4.1. In detail, for IELs 13.7% (Vγ7+) and 23.9% (Vγ4+), for MLN 9.8% (Vγ7+) and 20.4% (Vγ4+), for the spleen 10.2% (Vγ7+) and 20.3% (Vγ4+).
Experiments are representative of four mice individually studied in three independent experiments.

MFI of DP thymocytes were 250 for CD8<sup>+</sup>, and 318 versus 252 (CD4). For comparison, the MFI of GFP<sup>+</sup> versus GFP<sup>-</sup> 616 versus 285 (CD8<sup>+</sup>), and 524 versus 173 (CD4). CCR9 MFI of GFP<sup>+</sup> cells in the SI-Ep, as at all other sites (Fig. 1 E).

In conclusion, SI-Ep tropism is a general property of newly generated γδ RTEs in the adult, implying that the predominance of Vγ7<sup>+</sup> T cells in IELs is not developmentally determined.

**SI-Ep tropism is a general property of γδ RTEs**

The fact that the overwhelming majority of newly generated γδ T cells expressed gut-tropic molecules suggested that the paradigm that cells bearing particular TCRγ families are programmed in the thymus to home to specific peripheral sites might not apply to the SI-Ep.

In the thymus, the expression of gut-tropic molecules in cells expressing Vγ7, which is the dominant TCRγ family in IELs, was almost exclusively confined to GFP<sup>+</sup> cells, which were CD62L<sup>high</sup> CD44<sup>low</sup> (unpublished data). Vγ7<sup>+</sup> cells represented 12% of γδ RTE TDLs (Table 1), and their αβ<sub>7</sub> or CCR9 expression profiles were perfectly superimposable on those of Vγ7<sup>-</sup> RTEs (Fig. 1 D and not depicted). This suggested that RTEs expressing Vγ family poorly represented in the SI-Ep, i.e., Vγ4 (25–30% in circulating γδ RTEs versus <10% in γδ IELs), should have a SI-Ep homing potential equivalent to that of Vγ7<sup>-</sup> RTEs. Indeed, at 18 h after transfer, the frequency of both γδ subsets in all organs was similar to that in transferred TDLs, Vγ4<sup>+</sup> cells outnumbering Vγ7<sup>+</sup> cells in the SI-Ep, as at all other sites (Fig. 1 E).

In conclusion, SI-Ep tropism is a general property of newly generated γδ T cells in the adult, implying that the predominance of Vγ7<sup>+</sup> T cells in IELs is not developmentally determined.

**TDLs with the highest levels of αβ<sub>7</sub> and CCR9 are GALT-related conventional and unconventional cycling blasts, highly enriched in Vγ7<sup>+</sup> cells**

Next, we assessed the expression of gut-tropic molecules in TDLs defined according to the activation status. In each TDL T cell subset, a minor fraction of cells expressed 10–20-fold higher levels of αβ<sub>7</sub> and CCR9 than the respective GFP<sup>+</sup> RTEs (Fig. 3 A), but low levels of CD62L (not depicted). These cells were CD44<sup>high</sup> (Fig. 3 A), large sized (not depicted), and expressed high levels of the cell cycle marker Ki-67 (Fig. 3 B). The presence in the thoracic duct lymph of conventional cells with these properties was expected, as they correspond to the classical description of circulating cycling blasts generated upon immune responses in the GALT (Cheroutre et al., 2011). The unexpected finding here was the identification of cycling blasts of the unconventional type (Fig. 3, A and B), highly enriched in αβ<sub>7</sub><sup>high</sup> CCR9<sup>high</sup> CD44<sup>high</sup> TDLs, as compared with total TDLs (Fig. 3 C). Remarkably, Vγ7<sup>+</sup> cells accounted for <50% of αβ<sub>7</sub><sup>high</sup> Ki-67<sup>high</sup> γδ TDLs, against 6% in naive γδ TDLs (Fig. 3 D). Of note, whereas most CD44<sup>high</sup> γδ TDLs had lost αβ<sub>7</sub>, most corresponding Vγ7<sup>+</sup> TDLs had up-regulated this molecule (Fig. 3 A, blue gates), indicating that they were preferentially activated under conditions that reinforce gut tropism.

We then searched for cells with similar features in lymphoid structures drained by the thoracic duct. Both conventional and unconventional αβ<sub>7</sub><sup>high</sup> CD44<sup>high</sup> blasts, highly enriched in Vγ7<sup>+</sup> cells, were found in MLN but not in PLN (Fig. 3 E), indicating that the GALT was the source of those blasts. In MLN, a fraction of conventional and uncTCRαβ αβ<sub>7</sub><sup>high</sup> CD44<sup>high</sup> blasts expressed CD69 (not depicted), a molecule attesting activation but also retention in the tissue.
since it counteracts S1PR1 required for exit to efferent lymphatics (Shiow et al., 2006; Bankovich et al., 2010). In contrast, corresponding γδ blasts, in particular Vγ7+, lacked CD69 (Fig. 3F). This “mobile” mode suggested that they might have been generated upstream. PPs, whose efferent lymphatics converge to MLN, contained α4β7+ CD44high γδ blasts, in
particular Vγ7+ (Fig. 3 E), most of which expressed CD69 (Fig. 3 F). Thus, PPs might be one site where cycling γδ blasts are generated, but further dynamic studies are required to prove this point.

In conclusion, as in conventional T cells, recirculation through the GALT leads to selective priming of unconventional T cell subsets that reinforced SI-Ep tropism and diminished recirculation potential through LN.

Cycling TDL blasts home selectively to the SI-Ep, but they constitute a minor fraction of the immigrant population

Our results indicate that the pool of gut-tropic TDLs is essentially composed of naive cells and of few GALT-related cycling blasts, both enriched in unconventional cells. To assess whether these are the circulating cells that might continuously enter the SI-Ep, we analyzed the phenotype of TDL-derived immigrants in recipients sacrificed 18 h after transfer.

Donor SI-Ep immigrants were ~0.5% of CD3+ IELs (~10% in LN, spleen or blood), and the bulk of them lack CD69 (not depicted). They contained a high proportion of unconventional cells (Fig. 4 A) compared to donor TDLs (Table 1). In each T cell subset, ~90% of the immigrants were CD44low/int (Fig. 4 B). CD44high CD3+ immigrants were Ki-67high and large sized (Fig. 4 C and not depicted). The resemblance of these cells with α4β7high CCR9high cycling TDLs was further documented by the similar T cell subset distribution, and the high frequency of Vγ7+ cells (Fig. 4 B; compare with Fig. 3, C and D).

Donor CD44high Ki-67high blasts were <1% of the immigrants in MLN and virtually undetectable in PLN (unpublished data), in line with their low levels of CD62L. They were also undetectable in the recipient’s lymph collected between 24 and 44 h after transfer (not depicted). Together, these results suggest that most GALT-related blasts circulate for a short period before being selectively arrested in the SI wall.

In conclusion, the pool of SI-Ep immigrants resembles the set of cells in circulation previously identified on the basis of expression levels of gut-tropic molecules.

SI-Ep homing is highly dependent on α4β7

Levels of α4β7 were significantly lower in cycling SI-Ep immigrants than in the corresponding cells in circulation. This is compatible with down-regulation upon interaction with MadCAM, expressed by the venules of the SI-LP. The implication of this integrin in homing to the SI wall was confirmed by the strong reduction (85%) of the number of donor T cells in IELs (Fig. 4 C) and LP lymphocytes (LPLs; not depicted) in recipients under continuous treatment with a nondepleting anti-α4β7 mAb (Hamann et al., 1994; Staton...
et al., 2006). CD44^{high} Ki-67^{high} cells were hardly detectable (Fig. 4 C), and the number of unconventional and conventional naive immigrants was 3–5% and 10–20% of the corresponding subsets in untreated controls (Fig. 4 C). In contrast, the frequency of donor cells in spleen, MLNs, and PLNs was not significantly changed (unpublished data), in agreement with previous studies. Similar results were obtained in treated recipients sacrificed 44 h after transfer (unpublished data).

These results confirm, and extend to all T cell types, the major role of α4β7 in SI-Ep homing, although some conventional naive cells might home in a α4β7–independent manner.

**RTEs arrested in the SI-Ep do not proliferate in situ**

To study the potential of RTEs to colonize the SI-Ep, we assessed their capacity to react to local cues and to proliferate in situ. In a preliminary experiment, sorted GFP+ (RTEs) TDLs of RAG2p-GFP mice were labeled with violet cell division tracer and transferred to nonirradiated animals. A control group received GFP– TDLs. At day 4 after transfer, no decay of the Violet tracer was observed in SI-Ep immigrants of recipients of GFP+ TDLs, whereas significant decay was observed in the control group (unpublished data). In LN, few GFP+ TDLs had proliferated, and decay of the violet tracer, indicative of up to five rounds of division, correlated with decay of GFP, which was still detected in most cells in the 3rd generation (unpublished data). The failure of RTEs to proliferate in the SI-Ep could not be explained by the lack of reactivity to local cues, as 40–50% of γδ RTEs, including Vγ7+, had up-regulated CD69, as compared with 6–7% of CD4 and CD8αβ RTEs (unpublished data).

Because RTEs that went through at least 3 rounds of division in LN could still be identified by the GFP, to obtain better yields of transferred RTEs, we repeated the aforementioned experiment with total TDLs. In general agreement with previous transfers, <3% of the RTEs in the SI-Ep had divided, and essentially only once, as compared with other immigrants that in 4 d generated progenies accounting for close to 40% of the GFP– SI-Ep donor population (Fig. 5 A). As also shown, many undivided unconventional RTEs, in particular Vγ7+, had up-regulated CD69, as compared with a minor fraction of conventional RTEs. The higher reactivity of unconventional RTEs to local signals was confirmed by the average frequency of CD69+ RTEs at an earlier time point (44 h after transfer): ~20% in γδ, 30–40% in Vγ7+, and ~13% in uncTCRαβ, as compared with ~3% in CD8αβ and ~5% in CD4+ RTEs (unpublished data).

We conclude that RTEs reacting to signals in the SI-Ep environment do not acquire competence to expand. Moreover, unconventional RTEs, in particular Vγ7+, are preferentially retained, whereas the overwhelming majority of conventional RTEs remain mobile.

**Unconventional cycling SI-Ep immigrants have a higher proliferation potential than conventional homologues**

To assess whether immigrants that proliferated extensively in the SI-Ep were progenies of cycling TDLs, a kinetic analysis of the proliferation pattern was performed at distinct time points after transfer of CFSE-labeled TDLs, with the expectation that cycling immigrants would rapidly engage in proliferation.

At 18 h after transfer, no loss of CFSE was apparent (Fig. 5 B). However, whereas CD44^{low/m} immigrants were CD69–, 30–50% of the CD44^{high} cells already expressed CD69 (unpublished data). At 44 h, decays indicative of 2–4 rounds of division were already observed in a significant fraction of immigrants (Fig. 5 B), especially Vγ7+ (Fig. 5 C). This burst of proliferation in such short time interval, involving many Vγ7+ cells, highly represented in the 18 h pool of cycling immigrants (Fig. 4 B), strongly suggested that rapidly dividing cells are the progenies of TDL-derived cycling immigrants.

The frequency of dividing cells and the number of divisions were highest in γδ immigrants, and lowest in CD4+ immigrants (Fig. 5, B and C). These differences were amplified in the following days (Fig. 5 B), with unconventional cells predominating in late cell division generations (Fig. 5 D). By day 6 after transfer, the γδ/CD4 ratio was 4:1 in the pool of immigrants that divided in situ and resident IELs, as compared with 1:4 in the pool of cycling immigrant at 18 h after transfer (Fig. 5 E).

In summary, the predominance of unconventional over conventional IELs is established in situ due to the higher proliferative potential of the respective cycling TDL precursors.

**SI-Ep immigrants acquire high Granzyme B content upon extensive cell division**

A large fraction of normal IELs are characterized by cytoplasmic granules containing high amounts of Granzyme B (Guy-Grand et al., 1978, 1991), a feature particular to lymphoid cells displaying strong cytotoxic activity (Tschopp and Nabholz, 1990). In contrast to TDLs or LN cells, essentially all IELs (T and non–T cells, including B cells), expressed detectable levels of Granzyme B (Fig. 6 A), but clusters of these molecules were only observed in CD3+ IELs identified as Granzyme B^{high} in flow cytometry (Fig. 6 B).

We then determined whether TDLs that colonized the SI-Ep had acquired Granzyme B, and whether this process required cell division. As illustrated in Fig. 6 C for γδ and CD8αβ cells, the bulk of SI-Ep immigrants expressed Granzyme B at variable levels. Low content of this molecule was already apparent at 18 h after transfer, and it appeared a specific signature of cells that entered the SI-Ep, since immigrants in the SI-LP scored negative (unpublished data). In contrast, high content of Granzyme B correlated with cell division, but only by the fourth generation did the frequency of these cells approach that of host IELs (Fig. 6 C). Granzyme B^{high} cells were 3–4-fold less frequent in CD4 T cell immigrants, in line with their lower proliferative potential (unpublished data).

In conclusion, only cycling immigrants contribute to the pool of highly cytotoxic IELs.

**Identification of SI–Ep immigrants and respective progenies in normal IELs at steady state**

To validate our transfer system as representative of SI-Ep homing and colonization in physiological conditions, we...
CD4/CD8 ratio was reversed, and the frequency of Vγ7+ cells were 3–4 fold higher (Fig. 7 B). Many CD69+ RTEs were CD44high and displayed typical IELs features, such as CD8αβ (Fig. 7 C) and high levels of CD103 (not depicted), but were not cycling (Fig. 7 D). Thus, as in transfers, unconventional RTEs, as well as Vδ cells of the Vγ7 family, are preferentially retained and activated in the SI-Ep, but do not proliferate in situ.

To formally show that newly generated T cells of all types reach the SI-Ep shortly after entering circulation, searched for the equivalents to immigrants, and respective progenies, in host IELs.

RTEs in the SI-Ep. In 10-wk-old RAG2p-GFP mice, 1–2% of CD3+ IELs were GFP+ (Fig. 7 A), and most (~60%) expressed CD69. In the CD69− GFP+ pool, the T cell subset distribution resembled that of RTE immigrants at 18 h after transfer, with a high enrichment of unconventional T cells, though still out-numbered by conventional T cells. In the CD69+ GFP+ pool, unconventional cells predominated, the CD4/CD8αβ ratio was reversed, and the frequency of Vγ7+ cells were 3–4 fold higher (Fig. 7 B). Many CD69+ RTEs were CD44high and displayed typical IELs features, such as CD8αβ (Fig. 7 C) and high levels of CD103 (not depicted), but were not cycling (Fig. 7 D). Thus, as in transfers, unconventional RTEs, as well as γδ cells of the Vγ7 family, are preferentially retained and activated in the SI-Ep, but do not proliferate in situ.

To formally show that newly generated T cells of all types reach the SI-Ep shortly after entering circulation,
determined levels of αβ7 among T cell lineages, as predicted from the transfers.

**Cycling SI-Ep immigrants and their progenies.** Next, we assessed whether mobile (CD69⁻) IELs contained cells that might correspond to GALT-related cycling immigrants identified in TDL transfers. CD69⁻ cells predominated in this pool (Fig. 8 A), which contained the bulk of naive (CD62Lhigh CD44low) IELs (not depicted). Among CD69⁻ RTEs immigrants in adults (Fig. 7 B), the T cell subset distribution and the frequency of unTCRαβ⁺, as compared, respectively to ~3% and ~0.2% in LN. Notably, the T cell subset distribution in avidin⁺ RTEs (Fig. 7 E) and in CD69⁻ RTEs immigrants in adults (Fig. 7 B) was comparable, suggesting that homing of RTEs operates similarly at distinct ages of IEL development.

Altogether, these results demonstrate that RTEs of all lineages continuously seed the SI-Ep at steady state, with efficiencies that respect the differences in developmentally determined levels of αβ7 among T cell lineages, as predicted from the transfers.

Figure 6. Cycling SI-Ep immigrants are the precursors of Granzyme B⁺ high cells. (A) Flow cytometric analysis of the expression levels of Granzyme B in normal IELs and MLNs (15 mice in 15 independent experiments). (B) Structural analysis of Granzyme B content with ImageStream system (Amnis) in the indicated subsets of CD3⁺ IELs, as defined in the accompanying dot plot (one experiment [preliminary]). (C) Dot plots correlating CD69 expression and levels of Granzyme B in the indicated CFSE generations of donor γδ or CD8αβ SI-Ep immigrants. Data are representative of seven recipients individually analyzed at days 4–8 after transfer, in seven independent experiments.
18-h pool of cycling immigrants in TDL transfers (compare bar graphs of Figs. 8 B and 4 B).

In transfers, cycling SI-Ep immigrants rapidly up-regulated CD69 and engaged in active proliferation (Fig. 5 B), a process that revealed selective advantage of unconventional immigrants, in particular γδ+ (Fig. 5, C and E). Resident (CD69+) CD3+ IELs also contained CD44hi cells coexpressing Ki-67 and α4β7 (Fig. 8, C and D), whose levels were positively correlated (Fig. 8 D). About one third of α4β7hi cells were large and had high DNA content (Fig. 8 D),
In conclusion, the heterogeneity of normal IELs reflected the main steps of SI-Ep colonization followed by transferred TDLs.

SI-Ep immigrants contribute significantly to the dynamics of IELs at steady state.

The SI-Ep is considered of low accessibility to newly coming immigrants because of the large number and long lifespan of resident IELs, hence the lack of available niches.

Based on the transfer experiments, we estimated the quantitative impact of the progenies of circulating cells, entering the SI-Ep every 18 h, on the respective IEL populations (Table 2, see legend for detailed information). The results are primarily built upon the estimation that the number of T cells

which is indicative of active proliferation. In the total pool of Ki-67+ α4β7+ CD69+ cells, the representation of γδ cells was significantly higher than in the corresponding CD69− pool, whereas that of CD4 T cells was lower (compare bar graphs of Fig. 8, B and C), as expected from the distinct proliferation potential of the respective cycling immigrants (Fig. 5 B,E). Of note, the frequency of CD4 T cells was lowest in Ki-67− α4β7+ CD44high cells in CD69− CD3+ IELs (6.9 ± 2.2%), and corresponding T cell subset distribution (bar graph). Frequency of Vγ7+ cells in α4β7+ CD44high Vγ8 IELs (right bar graph). Data correspond to the same experiments in (B). Shown is the statistical significance of CD69− versus CD69+ γδ IELs (right bar graph). Data correspond to the same experiments in (B). Shown is the statistical significance of CD69− versus CD69+ α4β7+ CD44high IELs for each T cell subset: *, P < 0.05 (γδ); **, P < 0.05 (CD4).

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entering the SI-Ep during that period is ~5% (2.5 million cells) of resident IELs. However, as detailed for each T cell subset in the following paragraphs, most immigrants will not establish interactions in situ, and hence, the number of circulating cells integrating the SI-Ep is low.

Because T cell subsets are distinctly distributed in SI-Ep immigrant and resident IEL populations, and naive and cycling immigrants have distinct reactivity to local cues and proliferation potential, the impact of the daily cohort of immigrants differed significantly between cell types.

For γδ T cells, 40–50% of IELs, the daily cohort of immigrants was ~1% of the respective resident population, but those with potential of integration only represented ~0.3%, of which one third were GALT-related cycling cells. In about 1 wk, the immigrant population accounted for ~3% of all γδ IELs, >90% of which were progenies of immigrants that expanded in situ. These results suggest that, if no other selective events operate (e.g., competition for survival), the progenies of cells continuously seeding the SI-Ep might generate in ~38 d a number equivalent to that of the resident IEL population. That is, the average life span of this pool could be ~38 d (Table 2). As also shown, similar estimations were obtained for unTCRαβ IELs.

For CD4 T cells, ~10% of IELs, daily immigrants were ~25% of the respective resident population, and those with potential of integration ~4%, of which two thirds were cycling. In ~4 d, these immigrants generated a population accounting for ~10% of CD4 IELs, 80% of which were the progenies of cycling immigrants. Thus, the CD4 IELs might be entirely renewed in ~14 d and CD8αβ IELs in ~20 d (Table 2).

In conclusion, despite their low number, circulating GALT-related cycling T cells have a high capacity of SI-Ep colonization, thereby contributing to the dynamics of normal IELs.

**DISCUSSION**

Based on a quantitative description of the natural history of SI-Ep tropic conventional and unconventional T cells, we show that all T cell subsets follow the same general rules of homing and colonization of the SI-Ep, and that in adult physiological conditions, circulating cells continuously colonize this tissue, contributing to the dynamics of resident IELs. This integrated view is schematized in Fig. S1.

The common homing pattern of T cell subsets reflected similarities in acquisition of gut-tropic molecules during development in the thymus, and in the reinforcement of the expression of these molecules upon immune responses in the GALT.

With respect to development, the key findings were that newly generated T cells of all lineages, identified by the recent expression of the RAG-2 gene, share two major general properties: they leave the thymus in a naïve state, and are endowed with the dual capacity of circulating through secondary lymphoid organs and the SI. However, whereas conventional RTEs, which express low levels of αβ and high levels of CD62L, circulate preferentially through lymphoid organs, unconventional RTEs, which express high levels of both molecules, have no preference between the secondary lymphoid organs and the SI.

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<th>Table 2. Dynamics of SI-Ep homing and colonization at steady state</th>
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<td><strong>Input per 18h</strong> (%) of the respective IEL subset</td>
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<tr>
<td>γδ</td>
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<td>UncTCRαβ</td>
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<td>CD8</td>
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<td>CD4</td>
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*At 18 h after transfer, the average frequency of donor CD3+ IELs was ~10% of CD3+ cells in peripheral lymphoid organs and blood, and ~0.5% in the SI-Ep (Fig. 4 A). Assuming that the donor population was an unbiased representation of host circulating T cells, then the total number of cells (donor plus host) entering the SI-Ep during that period was ~5% of IELs. This estimation is close to the frequency of CD69+ cells (~6%) in CD3+ IELs, a result that supports the above assumption.

*In the 18-h SI-Ep immigrant pool, ~11% were γδ, ~7% unTCRαβ, ~24% CD8+ and ~53% CD4+ (Fig. 4 A). These values were referred to the 5% input per 18 h, and then to the average frequency of each T cell subset in IELs (Table 1).

*The estimation of the frequency of immigrants retained in the SI-Ep was based on the frequency of donor cells that expressed CD69 at 44 h after transfer. For naïve immigrants (based on the analysis of RTEs), the percentage of CD69+ cells in each T cell subset was as follows: γδ, 19.6%; unTCRαβ, 13.3%; CD8+, 3.2%; CD4+, 4.9%. For cycling immigrants, >90% expressed CD69 in all T cell subsets. These values were then referred to the frequency of naïve and cycling cells in the 18-h pool of immigrants, which were ~90% and ~10%, respectively, in all subsets (Fig. 4 B).

*These ratios were determined from the estimations of the number of naïve and cycling immigrants retained in situ as described in c.

*We designate as progenies of the 18-h input all donor immigrants that expressed CD69 by days 4 to 8 after transfer, regardless of whether they had proliferated or not.

*The number of donor CD69+ cells in the SI-Ep was maximal by day 4 after transfer, and remained stable up to day 8 after transfer, except for γδ, whose maximal values were reached by days 6 to 8. The estimations were based on the analysis of 9 individually studied recipients.

*Ratios between undivided cells and the progenies of cells that had proliferated, were estimated based on the CFSE profiles, of which representative examples are shown in Fig. 7, and take into account that only a fraction of the undivided cells expressed CD69, while this molecule was expressed by >90% of proliferating cells.

*The average life span corresponds to values estimated in footnote f, to which the time period necessary to reach maximal values was added (about 7 d for γδ cells and 4 d for all the other subsets). Ranges are indicated in parenthesis.
In regard to developing TCRγδ cells, acquisition of α4β7 is thus neither associated with high-strength TCR signaling, as shown for a minor subset of SI-Ep–tropic γδ T cells (Jensen et al., 2009), nor with any other process restricting its expression to specific TCRγ families. This was demonstrated by the high SI-Ep tropism of Vγ4 cells that are poorly represented in resident IELs. Therefore, γδ development in the adult follows rules distinct from those in the fetus, characterized by the strict association of TCR Vγ families and homing to specific tissues (e.g., Vγ5 and skin). Moreover, the fact that major Vδ families are similarly expressed by Vγ7+ cells in thymus, LNs, and IELs (Pereira et al., 2000) suggests that SI-Ep tropism is also a general property of cells expressing this Vγ family. As such, TCRγδ RTEs migrate to the SI-Ep in a TCR repertoire–independent fashion and without selection for ligands expressed in this tissue. Thus, the predominance of Vγ7+ cells in IELs is not developmentally determined.

The evaluation of SI-Ep tropism in the general context of lymphocyte recirculation showed that many unconventional RTEs prone to colonize the SI-Ep travel through the hemo-lymphatic system before being eventually arrested in the SI-Ep, as indicated by the high number of (SI-tropic) Vγ7+ RTEs recovered from the thoracic duct, or present in PLNs and MLNs. The functional relevance of this traffic pattern became apparent with the recognition of the GALT as central sites of unconventional T cell activation, coupled to strong up-regulation of α4β7 and CCR9, as known for conventional T cells. The concomitant loss of CD62L indicated that the corresponding cycling blasts, identified in the thoracic duct, have been reprogrammed to migrate (almost) exclusively to the SI wall.

The high enrichment of Vγ7+ cells in cycling γδ blasts in MLNs, but not PLNs, suggests a strong link between GALT-selected and IEL repertoires, as demonstrated for CD8αβ T cells (Arstila et al., 2000). This link argues against compartmentalization of peripheral versus IEL TCRγδ T cells as exclusive, nonoverlapping populations (Chennupati et al., 2010). The finding that most Vγ7+ blasts in circulation expressed gut-tropic molecules indicated that the GALT is the main peripheral territory where cells of this Vγ family are activated. This raises the issue of where in the GALT Vγ7+ TDL blasts are generated, as the respective ligands are supposedly confined to the SI-Ep. In MLNs, cycling blasts did not display signs of retention, indicating that dendritic cells traveling from the SI wall to MLN (Farache et al., 2013) do not seem to carry antigens recognized by Vγ7+ T cells. PPs, whose structures include a layer of epithelial cells, contained both CD69+ and CD69−Vγ7+ blasts, but in-depth dynamic studies are necessary to formally show that Vγ7+ RTEs activated to cycle in PPs are precursors of the Vγ7+ cycling blasts that migrate through MLNs to the thoracic duct. Isolated lymphoid follicles in the SI-LP might be another source of these cells, as these structures share properties with PPs and are also in close contact with the SI-Ep (Cauley and Lefrançois 2013).

With respect to rules governing SI-Ep colonization under steady-state conditions, our studies provide two major findings.

First, despite their low frequency, GALT-related cycling immigrants are the major source of IELs, because they have a much higher retention and proliferation dynamics than naive immigrants. The preferential retention of cycling immigrants is best explained by the strong repertoire selection operating in the GALT, and not in the thymus. Indeed, although the SI-Ep environment might provide TCR-independent signals leading to cell arrest (Casey et al., 2012), the crucial triggering event appears to be TCR-mediated, as suggested by the selective retention and activation of Vγ7+ cells among naive γδ immigrants. In contrast to cycling immigrants, naive immigrants activated in situ have a poor proliferation potential, for reasons still unknown. Therefore, they only contribute to the respective IEL subsets by accumulation and do not differentiate into Granzyme Bhigh effectors, which require extensive proliferation in situ. If secretion of cytokine or antibacterial peptide does not require cell division, these might be functions of naive immigrants, whereas cycling immigrants are the sole precursors of Granzyme Bhigh IELs. Thus, priming in the GALT is a necessary step for the development of cytolytic responses in the intestinal mucosa.

Second, circulating cells have a very high capacity of short-term colonization of the SI-Ep under steady-state conditions, despite the very large number of resident IELs. As shown in this study, the few immigrants entering the SI-Ep every 18 h, in particular those cycling (~0.4% of IELs), generated in a short period of time (4 to 7 d) progenies accounting for 3% unconventional to 8–10% conventional cells of the respective resident IEL subsets. These results argue against the idea that the SI-Ep is a site of restricted accessibility.

These results suggest average life spans of resident IELs of ~30 to 40 d for unconventional and 15 to 20 d for conventional IELs. However, it should be noted that, being averages, these estimations do not preclude that a fraction of IELs might be long-lived (Chennupati et al., 2010), and that, likely, other selective events might operate, namely in situ competition for survival. Indeed, although the size of the progenies of the 18 h cohort of γδ immigrants stabilized by the first week after transfer, a fraction of them continued to divide (unpublished data), implying concomitant death of other cells. Thus, cell death appears to play an important role in IEL homeostasis. Because survival of γδ and uncTCRαβ IELs requires signaling through the Aryl Hydrocarbon receptor (Li et al., 2011), competition for its ligand could play a physiological role in the intraepithelial selection of the most fitted clones. Thus, “resident” IELs might be composed of clones with heterogeneous life spans, leaving room to the continuous integration of new gut-tropic cycling T cells developed upon on-going natural immune responses in the GALT. Indeed, in specific immune responses, most CD8 cells that seed the SI-Ep had a relatively short life span (Masopust et al., 2001).

Our estimations on life spans appear difficult to reconcile with the slow rate of redistribution of IELs in the SI-Ep of parabionts (Poussier et al., 1992). These authors found that, by day 38 post-surgical joining, the maximal exchange between partners was ~13% T cell chimerism in the SI-Ep (without
distinction between subsets), as compared with ~50% in LNss. Correcting for lag times required for the full establishment of anastomosis (~8 d) and the development of immune responses in the GALT (~7 d), this chimerism was in fact ~13% in 23 d. This would suggest (correcting for the 50% expected chimerism if access to the SI-Ep was unrestricted) an average life span of 100 d. The gap left between these and our estimations might, for the most part, be explained by severe thymic involution caused by surgical stress, which particularly impacts the dynamics of SI-Ep–tropic unconventional T cells, which are highly dependent on continuous thymic output. Studies involving parabiosis or intestinal grafts (Klonowski et al., 2004; Masopust et al., 2010), showing that memory T cells have poor SI-Ep tropism, are explained by the observation that up-regulation of α4β7 is transient (Masopust et al., 2010).

Our studies offer explanations for the predominance of unconventional T cells in IELs of SPF mice. One is the 10-fold higher proportion of both naive and cycling cells homing to the SI-Ep. Whereas for naive cells this is due to higher levels of tropic molecules, for cycling cells this is likely due to a higher frequency of antigen-reactive cells in the GALT (particularly cells of the Vγ7 family), and also that many CD4 T cells up-regulate α4β7 and notCCR9, and hence will preferentially be retained in the SI-LP. Other reasons are the higher rate of retention of unconventional naive immigrants (caused by higher frequency of antigen-reactive cells), and the higher proliferation dynamics of unconventional cycling immigrants, for reasons still unclear. The estimated differences in average life span of IEL subsets suggest that survival rates may also influence the respective homeostasis, in line with the observation that unconventional IELs express the highest levels of the anti-apoptotic factor BCL2 (Van Houten et al., 1997). Finally, the reversed CD4/CD8αβ ratio in normal IELs is best explained by the distinct proliferation dynamics of the respective cycling immigrants, although it should be pointed out that unconventional and conventional IELs do not compete for the same niches (Bandeira et al., 1997; Li et al., 2011), and that in mice kept in conventional conditions or in humans, conventional IELs predominate. Even in this case, conventional cells expand predominantly in the GALT and not in the SI-Ep (unpublished data).

Although we confirm the major role of α4β7 in SI-Ep homing, this is less clear for CCR9. First, a sizeable number of naive CD4 T cells, which lack CCR9, enter the SI-Ep every day. Second, blocking α4β7 drastically reduced the number of γδ T cells and cycling immigrants of all types, despite their high levels of CCR9. Thus, this molecule might instead contribute to retention in the SI-Ep.

In conclusion, our study demonstrates that although tropism for the SI-Ep is imprinted during thymic development, the immune system developed strategies that maximize the continuous influx to the SI-Ep of both conventional and unconventional cells capable of rapid proliferation and differentiation in situ into cytotoxic effectors. Our quantitative analyses help define the fundamental principles that guide trafficking and colonization of the SI-Ep under physiological conditions.

**MATERIALS AND METHODS**

**Mice.** CD45.1 and CD45.2 C57BL/6 mice were purchased from Charles River and kept in specific pathogen–free conditions in our house facilities. FVB RAG2p-GFP mice (Yu et al., 1999) were backcrossed into C57BL/6 mice for 13 generations, now designated as RAG2p-GFP C57BL/6 mice. Mice were cared for in accordance with Pasteur Institute guidelines in compliance with European animal welfare regulations, and all experimental studies were approved by the Pasteur Institute Safety committee in accordance with French and European guidelines and by the ethics Committee of Paris I (permits 2013–0002, 2010–0003, 2010–0004; permit 2005–0003 for thoracic duct cannulations).

**Cannulation of the thoracic duct.** 6 wk–5 mo-old mice were anesthetized and their thoracic ducts were exposed behind the left kidney. A carefully heated-curry polyethylene catheter (0.40 mm ID, 0.80 OD or 0.58 mm ID, 0.96 OD, depending on the size of the mouse; Portex UK) was inserted into the duct beneath the diaphragm, glued with Histoacryl (Braun), and exteriorized at the lower part of the ventral incision. Mice received 0.7 ml phosphate-buffer-saline per hour, via the tail vein, using an infusion pump (Harvard Apparatus). They were kept overnight on hamster wheels, which rotated periodically. Lymph was collected in ice-cold culture medium containing heparin. The average number of TDLs recovered during 20 h was 43 × 107 (±26) per mouse, and 50–60 × 106 TDLs were intravenously injected in the recipients.

**Isolation of mucosal lymphocytes.** The SI was flushed with PBS, and PPs were carefully removed. The intestine was opened and cut into 1-cm pieces. For IEL isolation, these fragments were incubated in 50 ml RPMI 1640 (Invitrogen) with 10% FCS, at 37°C and 5% CO2, under strong magnetic stirring for 1 h, followed by strong vortexing. To eliminate epithelial cells, the supernatant was filtered through a 70 μm cell strainer (1 g of short fibers of borosilicated glass wool; Thermo Fisher Scientific) packed into a 20-ml syringe. For LPL isolation, the fragments were first incubated for 15 min at 37°C with magnetic stirring in 50 ml Hanks’ balanced salt solution without CaCl2 and MgCl2, with 0.5 mM EDTA (Sigma-Aldrich), then twice in medium without EDTA. When the supernatant became clear, the fragments were incubated in 50 ml RPMI 1640 with 20% FCS and 2.5 mg collagenase (C2139; Sigma-Aldrich) for 20 min. To complete digestion, the medium was mixed with a 10-ml syringe for 5 min. Finally, IEL or LPL suspensions were filtered through a 40-μm cell strainer (BD), and then dispersed in 70% Percoll (GE Healthcare) overlaid with 30% Percoll and centrifuged at 1000 × g for 20 min at 2200 RPM without brake. Lymphocytes were collected at the interface. Routinely, 10–30 × 106 IELs or LPLs were collected per mouse.

**In vivo mAb treatment.** Anti-α4β7 mAb was purified by affinity chromatography using HiTrap Protein G column (GE Healthcare). TDLs were incubated for 30 min with 200 μg of the mAb, and the preparation was injected into the recipients.

**Intrathymic injections of biotin.** The use of biotin to track thymic emigrants was first performed by Carlson et al. (2006). 100 μg of biotinamidohexa- noic acid3-sulfo-N-hydroxysuccinimide ester sodium salt (Sigma-Aldrich) was first performed by Carlson et al. (2006). 100 μg of biotinamidohexa-noc acid3-sulfo-N-hydroxysuccinimide ester sodium salt (Sigma-Aldrich) were injected into thymic lobes of anesthetized mice after a small incision of the sternum. 10-10 to 1–106 TDLs or LPLs were collected per mouse. In vivo mAb treatment.

**Flow cytometry.** For CFSE or Violet stain (Invitrogen) cell tracer labeling, 107/ml TDLs were incubated in PBS+3% FCS and 5 μM cell tracer for 10 min at 37.5°C with gentle stirring. For cell surface staining, fluorescent mAbs were purchased from BD, eBioscience, or BioLegend. Anti-CCR9 mAb was purified by affinity chromatography using HiTrap Protein G column (GE Healthcare). TDLs were incubated for 30 min with 200 μg of the mAb, and the preparation was injected into the recipients.

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Determination of the total number of CD3+ cells per organ. Values were calculated as follows: Spleen, 20 million; total LN, 45 million (twice the sum of MLN, axillary, brachial, and inguinal LN cells; Zatz and Lance, 1970). IELs were 50 million (Rocha et al., 1991). LPs were 35 million, as assessed from tissue sections with the methodology described for IELs (Rocha et al., 1991).

Statistical analysis. Data were calculated as mean ± SD. Statistical significance was performed using two-tailed Student’s t test with 95% confidence intervals, under the assumption of equal variances between groups.

Online supplemental material. Fig. S1 shows the hemolymphatic cycle of gut-tropic T cells. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20122588/DC1.

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REFERENCES


Figure S1. The hemolymphatic cycle of gut-tropic T cells. For clarity, only the circuits of γδ (Vγ7 and Vγ4) and CD4 T cells, representative of unconventional and conventional T cells, are depicted. The hemolymphatic cycle of naive T cells: RTEs (or naive cells in general) of all cell types are naive (CD44 low) and express high levels of CD62L. They continuously recirculate from blood through LN, whose efferent lymphatics converge to the thoracic duct (lower half of the body), which drains into systemic blood circulation. Recirculation through the GALT also includes PPs, whose efferent lymphatics have the peculiarity of draining into MLNs. Because RTEs also express α4β7, they can also circulate through the SI wall, including the SI-Ep. They enter this site via blood vessels, and exit again probably also via the blood. As such, circulation through the SI wall is here included as part of the general hemolymphatic circuit followed by naive cells. However, the rate of circulation through the SI-Ep is higher for unconventional than conventional RTEs, because the former express higher levels of α4β7, as depicted. Also, γδ RTEs of all families, which express high levels of both CD62L and α4β7, circulate without preference through LN and SI-Ep, irrespective of whether they bear TCR prone to recognize ligands in the SI-Ep. Thus, Vγ7 RTEs, many of which are prone to colonize the SI-Ep, circulate freely through LN; conversely, Vγ4 RTEs, which are poorly represented in the SI-Ep, efficiently circulate through this site. For RTEs of all types, this general circuit can be "broken" if, upon TCR-mediated ligand recognition, they are either arrested in the SI-Ep, or reprogrammed in the GALT to exclusively home to the SI-Ep. Therefore, colonization of the SI-Ep involves two circuits: the thymus–SI-Ep pathway (dashed arrows) followed by naive cells (including RTEs), and the GALT–SI-Ep pathway (solid arrows) followed by cells that have been previously activated in the GALT. 

Thymus–SI-Ep pathway: RTEs can enter the SI-Ep, either directly via the blood or, probably for most cells, after rounds of circulation through secondary lymphoid organs. Vγ7 T cells have a higher probability of being arrested and activated through TCR-mediated interactions, as indicated by the expression of CD69. However, these cells proliferate poorly and do not contribute to the pool of cytotoxic IELs, represented by yellow granules containing high amounts of granzyme B. Vγ4 and CD4 T cells have a low probability of being arrested and will return to circulation. GALT–SI-Ep pathway: Recirculation through the GALT (solid arrows) is central for the development of Vγ7 and CD4 T cell–mediated immune responses against mucosal antigens, coupled to strong up-regulation of α4β7 and loss of CD62L. However, whereas Vγ7 T cells are activated and proliferate upstream MLN, one possible site being PPs, CD4 T cells do it in both MLNs and PPs. Activated cells reach the thoracic as cycling blasts and will home almost exclusively to the gut wall. In the SI-Ep, cycling Vγ7 T cells expand far more than CD4 homologues, thereby becoming predominant, especially in the pool of Granzyme B high IELs. In contrast, as also depicted, Vγ4 T cell–mediated immune responses occur in contexts leading to complete loss of α4β7, and hence will not migrate into the SI-Ep.