Commitment of Immature CD4\(^+\)8\(^+\) Thymocytes to the CD4 Lineage Requires CD3 Signaling but Does Not Require Expression of Clonotypic T Cell Receptor (TCR) Chains

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Summary

As a consequence of positive selection in the thymus, immature CD4\(^+\)8\(^+\) double-positive (DP) thymocytes selectively terminate synthesis of one coreceptor molecule and, as a result, differentiate into either CD4\(^+\) or CD8\(^+\) T cells. The decision by individual DP thymocytes to terminate synthesis of one or the other coreceptor molecule is referred to as lineage commitment. Previously, we reported that the intrathymic signals that induced commitment to the CD4 versus CD8 T cell lineages were markedly asymmetric. Notably, CD8 commitment appeared to require lineage-specific signals, whereas CD4 commitment appeared to occur in the absence of lineage-specific signals by default. Consequently, it was unclear whether CD4 commitment, as revealed by selective termination of CD8 coreceptor synthesis, occurred in all DP thymocytes, or whether CD4 commitment occurred only in T cell receptor (TCR)–CD3-sigaled DP thymocytes. Here, we report that selective termination of CD8 coreceptor synthesis does not occur in DP thymocytes spontaneously. Rather, CD4 commitment in DP thymocytes requires signals transduced by either CD3 or \(\zeta\) chains, which can signal CD4 commitment even in the absence of clonotypic TCR chains.

Abbreviations used in this paper: DN, double negative; DP, double positive; SP, single positive; TSA, thymic shared antigen.

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1Immature CD4\(^+\)8\(^+\) (double-positive [DP]) cells differentiate in the thymus into mature CD4\(^+\)8\(^-\) or CD4\(^-\)8\(^+\) (single-positive, SP) T cells by the process of positive selection. Consequently, positive selection of DP thymocytes requires that synthesis of either CD4 or CD8 coreceptor molecules be terminated, an event referred to as lineage commitment. Several models of lineage commitment have been proposed (1–13) and have been actively debated for years. The instructional model of lineage commitment (1, 2) postulates that lineage-specific signals transduced by surface coreceptor molecules, together with TCR signals, terminate synthesis of the inappropriate coreceptor. The stochastic/selection model (3–7) postulates that TCR-sigaled thymocytes randomly terminate synthesis of one or the other coreceptor molecule, and, because such cells are short-lived, they require a subsequent TCR signal to become long-lived cells that can differentiate into maturity. Both the instructional and stochastic/selection models of lineage commitment presume that identical rules govern CD4 commitment and CD8 commitment with the only difference being the identity of their target coreceptor molecule. In contrast, the asymmetric commitment model (8) postulates that commitment to the CD4 and CD8 lineages are consequences of very different signaling events. That is, CD8 commitment requires TCR and CD8-specific lineage signals, whereas CD4 commitment results from the absence of CD8-specific lineage signals.

The asymmetric commitment model was originally based on the molecular definition of lineage commitment in DP thymocytes as the selective termination of synthesis of one coreceptor molecule, and was prompted by experiments assessing coreceptor synthesis in individual DP thymocytes. By use of the coreceptor reexpression assay, we observed that commitment of DP thymocytes to the CD8 lineage (i.e., termination of CD4 synthesis) strictly required specific TCR recognition of intrathymic MHC class I determinants. In contrast, we observed that commitment of DP thymocytes to the CD4 lineage (i.e., termination of CD8 synthesis) required both CD3 and CD8-specific signals.
CD3 Signaling in CD4 Commitment

Recently, we determined that DP thymocytes that have undergone lineage commitment have a distinct phenotype relative to the majority of DP thymocytes that have not yet undergone lineage commitment. We found that all lineage-committed DP thymocytes, including those committed to the CD4 lineage, were CD5+CD69+ and so had presumably experienced a TCR signaling event in the thymus, indicating that TCR–CD3 signaling was involved in thymocyte commitment to either T cell lineage (20). In particular, we wished to assess whether CD4 commitment, as demonstrated by surface TCR–CD3 complexes, was dependent on TCR–CD3 signaling or whether it occurred spontaneously in immature DP thymocytes. Thus, these results indicated that lineage commitment did not occur spontaneously in immature DP thymocytes.

Results

To assess the possibility that DP thymocytes spontaneously terminated CD8 coreceptor synthesis even in the absence of TCR–CD3 signals, we examined DP thymocytes from TCRαβ mice by the coreceptor reexpression assay. TCRαβ thymocytes cannot express conventional αβ TCR complexes and, consequently, cannot differentiate beyond the DP stage of development (21). To enrich for DP thymocytes that might have committed to the CD4 or CD8 T cell lineages, we electronically sorted for CD4+8- and CD4-8+ transitional cell populations and utilized the coreceptor reexpression assay to determine the coreceptor molecules they were actively synthesizing (Fig. 1A and B). In the coreceptor reexpression assay, preexisting surface CD4 and CD8 coreceptor molecules are removed from the sorted cells by treatment with low doses of pronase, and the stripped cells then placed into single cell suspension cultures for 14 h. Metabolic activity of cultured cells is inhibited at 4°C, so that cell surface coreceptor reexpression does not occur (Fig. 1A and B, middle columns). However, cells cultured at 37°C do reexpress the CD4 and/or CD8 coreceptor molecules that they are actively synthesizing. Indeed, we have previously demonstrated that coreceptor reexpression in this assay requires active coreceptor transcription and protein synthesis (8). Interestingly, virtually all CD4+8- sorted cells from TCRαβ DP thymocytes reexpress both CD4 and CD8 coreceptors and so reappeared as DP cells (Fig. 1A, top). Identical results were obtained with CD4+8- sorted cells from TCRαβ mice (Fig. 1B, top). That is, none of the DP thymocytes present in TCRαβ mice had selectively terminated either CD4 or CD8 coreceptor synthesis, indicating that none had undergone lineage commitment. Thus, these results indicated that lineage commitment did not occur spontaneously in immature DP thymocytes but might be dependent upon signals transduced by surface TCR–CD3 complexes.

To assess directly the role of TCR–CD3 signals in inducing lineage commitment in DP thymocytes, we assessed DP thymocytes from experimentally induced RAG2- mice. RAG2- mice fail to express any clonotypic TCR chain because they are unable to recombine any TCR gene locus.
As a result, RAG2\(^8\) thymocytes are arrested at the CD4\(^{-}\)8\(^{−}\) (double-negative, DN) stage of development (23). However, RAG\(^8\) thymocytes can be induced to differentiate further into DP cells by either sublethal \(\gamma\)-irradiation (26, 27) or by injection of anti-CD3\(\varepsilon\) mAb (28, 29) (Fig. 1, A and B, left column). Induced RAG\(^8\) DP thymocytes did not further differentiate into phenotypically mature T cells as thymocytes from stimulated RAG2\(^2\) mice that appeared CD4\(^{-}\)8\(^{+}\) or CD4\(^{+}\)8\(^{+}\) (Fig. 1, A and B, left columns) were predominantly precursor cells that spontaneously became CD4\(^{+}\)8\(^{+}\) in overnight culture (data not shown; reference 30). Even though sublethal \(\gamma\)-irradiation and anti-CD3\(\varepsilon\) injection both induced generation of RAG\(^8\) DP thymocytes (Fig. 1), the two modes of stimulation did not have identical effects. That is, sublethal \(\gamma\)-irradiation did not detectably stimulate CD3 signal transduction as revealed by the absence of CD5 upregulation, whereas injection of anti-CD3\(\varepsilon\) mAb did stimulate CD3 signal transduction and CD5 upregulation (Fig. 2). Assessment of CD4\(^{-}\)8\(^{lo}\) and CD4\(^{lo}\)8\(^{+}\) sorted cells from \(\gamma\)-irradiated RAG2\(^2\) mice by the coreceptor reexpression assay revealed that none had undergone lineage commitment (Fig. 1, A and B). In contrast, assessment of CD4\(^{-}\)8\(^{lo}\) sorted cells from anti-CD3\(\varepsilon\)-induced RAG2\(^2\) mice revealed the presence of CD4-committed DP thymocytes that had selectively terminated CD8 coreceptor synthesis, as well as the presence of uncommitted DP thymocytes (Fig. 1 A.). The CD4-committed thymocytes that were present in anti-CD3\(\varepsilon\)-induced RAG2\(^2\)

Figure 1. Lineage commitment in sorted CD4\(^{-}\)8\(^{lo}\) and CD4\(^{lo}\)8\(^{+}\) thymocytes from experimental mice. Purified populations of CD4\(^{-}\)8\(^{lo}\) thymocytes (A) and CD4\(^{lo}\)8\(^{+}\) thymocytes (B) were obtained by electronic cell sorting according to the indicated sorting gates superimposed on the starting thymocyte populations (left column). Sorted thymocyte populations were stripped of surface coreceptor molecules by treatment with low doses of pronase, after which they were placed in suspension cultures at 4°C (middle panels) or 37°C (right panels) for 12-16 h and restained for CD4 and CD8 surface expression. The coreceptor reexpression assay detects the coreceptor molecules that individual thymocytes synthesized during the 37°C culture, and is dependent upon new transcription and new protein synthesis (8). Sorted thymocytes that reexpress both CD4 and CD8 coreceptor proteins are lineage-uncommitted cells; those reexpressing only CD4 are CD4 committed; and those reexpressing only CD8 are CD8 committed. Cells cultured at 4°C do not reexpress surface coreceptor molecules so that their CD4-CD8 histograms reflect whatever coreceptor molecules that potentially remain after pronase treatment (middle columns). As we have previously described (8), the anti-CD4 mAb used to prepare thymocytes for cell sorting minimally interferes with stripping of surface CD4 molecules by pronase, resulting in a small number of residual CD4 molecules remaining on the cell surface. Consequently, to highlight changes in coreceptor reexpression during 37°C cultures, histogram boxes were drawn based on the 4°C profiles of each sorted and pronase-stripped cell population. The frequency of cells in each box is indicated. The number of the thymocytes obtained in these experimental mice were the following: TCR\(\alpha\)8 (9 \(\times\) 10\(^7\) cells), \(\gamma\)-irradiated RAG2\(^2\) (4 \(\times\) 10\(^7\) cells), anti-CD3\(\varepsilon\) mAb-injected RAG2\(^2\) (1.1 \(\times\) 10\(^8\) cells), anti-CD3\(\varepsilon\) mAb-injected RAG-TCR\(\gamma\)\(\varepsilon\) (8 \(\times\) 10\(^7\) cells), and anti-Tac mAb-injected RAG-TTac (4 \(\times\) 10\(^7\) cells).
mice expressed the phenotype of newly committed thymocytes in that they were HSAhi, thymic shared antigen (TSA)-1hi (data not shown). In contrast, anti-CD3ε-induced RAG2ε thymocytes had no CD8-committed cells among either CD4ε8lo or CD4ε8hi sorted cell populations (Fig. 1, A and B). Thus, these results (a) confirm that DP thymocytes do not undergo lineage commitment in the absence of TCR-CD3 signals, and (b) demonstrate that CD3 signals stimulated by anti-CD3ε mAbs are sufficient to induce DP thymocytes to selectively terminate CD8 coreceptor synthesis and to commit to the CD4 lineage, even in the absence of clonotypic TCR chains.

To determine whether signals transduced by TCRζ chains were able to induce CD4 commitment, we assessed lineage commitment in DP thymocytes from RAG2ε mice that expressed a chimeric transgenic protein consisting of the external and transmembrane domains of human CD25 and the cytosolic domains of TCRζ (24). The extracellular domain of this transgenic protein is recognized by anti-Tac mAb. Injection of anti-Tac mAb into RAG2ε-TTζε mice induced the generation of DP thymocytes (Fig. 1 A), as previously reported (24), and signaled them to upregulate CD5 expression (Fig. 2). We then assessed DP thymocytes from anti-Tac-induced RAG2ε-TTζε mice for the presence of lineage committed cells. We found that CD4ε8lo sorted thymocytes from these mice did contain CD4-committed cells, but did not contain any CD8-committed cells in either CD4ε8lo or CD4ε8hi sorted cell populations (see Fig. 1, A and B). These results demonstrate that signals transduced by the cytosolic portion of TCRζ chains are sufficient to induce DP thymocytes to selectively terminate CD8 coreceptor synthesis and to undergo CD4 commitment.

Next, we wished to evaluate the relationship between CD5 upregulation and CD4 commitment in anti-CD3ε-signalized RAG2ε thymocytes. In vivo injection of a single dose of either 10 or 250 μg of anti-CD3ε mAb–induced substantial numbers of DP thymocytes in RAG2ε mice when assayed 8 d later (Fig. 3). While both injection doses induced differentiation to the DP stage, we reasoned that only the high dose might persist long enough in vivo to stimulate a subsequent CD3 signal after DP thymocytes appeared. Indeed, only DP thymocytes from high dose injected animals had upregulated CD5 expression, and only DP thymocytes from high dose injected animals contained CD4-committed thymocytes (Fig. 3). DP thymocytes from low dose injected animals were CD5lo and remained uncommitted (Fig. 3). We conclude that CD4 commitment requires CD3 signals in DP thymocytes that are of sufficient intensity to upregulate surface CD5 expression.

Finally, having observed that a single injection of antibody was sufficient to stimulate CD3 or TCRζ chains to transduce signals that upregulated CD5 surface expression and induced CD4 commitment but not CD8 commitment, we assessed whether CD8-committed cells might appear in RAG2ε thymi upon antibody restimulation. In Fig. 4, RAG2ε mice were injected with anti-CD3ε mAb on both days 0 and 8, and then assessed 4 d later on day 12. Thymocytes were sorted into CD4ε8lo and CD4ε8hi popu-
simulations and then assessed for coreceptor synthesis by the coreceptor reexpression assay. We found that CD4^+8^lo thy-mocytes contained CD4-committed cells that had selectively terminated CD8 coreceptor synthesis (Fig. 4, middle row), but neither sorted population contained CD8-committed cells (Fig. 4, middle and bottom rows). Thus, CD8-committed cells did not appear in RAG2^+^ thymi despite a second antibody injection and despite assessment on day 12 after the initial injection of antibody (Fig. 4). Indeed, we also failed to detect CD8-committed thymocytes on days 28 and 35 after antibody injection (data not shown).

Discussion

The present study demonstrates that immature DP thymocytes do not spontaneously terminate synthesis of either CD4 or CD8 coreceptor molecules. Rather, selective termination of coreceptor synthesis by immature DP thymocytes requires signals transduced by either CD3 or TCRζ chains, and can occur in signaled DP thymocytes that lack clonotypic TCR chains. Interestingly, CD3-signaled DP thymocytes upregulated CD5 expression and selectively terminated CD8 coreceptor synthesis, but did not selectively terminate CD4 coreceptor synthesis. Thus, CD4 commitment is induced in DP thymocytes by CD3 signals that are of sufficient intensity to upregulate CD5 expression.

The results of the present study are not readily compatible with either instructional (1, 2) or stochastic/selection (3–7) models of lineage commitment. That is, the instructional model cannot explain the presence of any lineage-committed RAG2^+^ thymocytes in response to lineage-neutral CD3 and TCRζ signals, whereas the stochastic/selection model cannot explain why CD3 and TCRζ signals only induced RAG2^+^ thymocytes to become CD4 committed without inducing an equal number to become CD8 committed. In contrast with these two models of lineage commitment, the present results are concordant with the asymmetric commitment model of lineage commitment (8, 13).

That is, our results are consistent with the concept that CD4 commitment, unlike CD8 commitment, can occur in the absence of lineage-specific signals. Importantly, the present results extend the asymmetric commitment model by demonstrating that CD4 commitment does not occur spontaneously in unsignaled DP thymocytes, but rather is induced.

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\text{CD4}^+8^\text{lo} \text{ Sorted Thymocytes}
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<table>
<thead>
<tr>
<th>RAG^-</th>
<th>anti-CD3e i.p.</th>
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<td>250 μg</td>
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\begin{array}{c|cc}
\text{Sorting Gate} & 4^\circ \text{C} & 37^\circ \text{C} \\
\hline
\text{CD4} & 1 & 0 \\
\text{CD8} & 0 & 1 \\
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\end{array}
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\text{Total Thymocytes}
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\text{Untreated} \quad 4^\circ \text{C}
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\begin{array}{c|cc}
\text{CD4} & 1 & 0 \\
\text{CD5} & 0 & 1 \\
\text{CD5} & 0 & 1 \\
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Figure 3. Correlation between induction of CD4 commitment and surface CD5 upregulation. RAG^- mice received one intraperitoneal injection of either 250 μg or 10 μg of affinity-purified anti-CD3e mAb. 8 d later, thymocytes were sorted according to the indicated gates and assessed for lineage commitment by the coreceptor reexpression assay (left panels). Unsorted thymocytes were placed in culture for 12 h at 4°C, at which temperature thymocyte phenotype is stable, and then assessed for surface CD5 expression (right panels). Solid line indicates CD5 expression on experimental thymocytes. Shaded curve represents negative control staining of experimental thymocytes with an irrelevant mAb. The dotted line represents CD5 expression on normal B6 thymocytes stained at the same time as a positive control and is shown for comparison. The number of thymocytes obtained on day 8 were 1–1.5 × 10^6 cells and 3–4 × 10^7 cells with the injection of 250 μg and 10 μg, respectively.

Figure 4. CD8-committed thymocytes do not appear in RAG2^+^ thymi even after two injections of anti-CD3 mAb. RAG2^+^ mice were injected with 250 μg of affinity-purified anti-CD3e mAb on both day 0 and 8. On day 12, thymocytes were harvested, sorted into CD4^+8^lo and CD4^+8^hi populations, and assessed by the coreceptor reexpression assay for appearance of CD4-committed and CD8-committed cells. Numbers in each box represent the frequency of thymocytes falling in that box.
by lineage-neutral signals transduced by CD3 and/or TCR ζ chains.

Importantly, we found that CD3 signaling did not induce all DP thymocytes in the present study to become CD4 committed, as only a small minority of CD3-signaled RAG2Δ thymocytes terminated CD8 coreceptor synthesis, even though all DP thymocytes had upregulated CD5 surface expression. This observation is consistent with our recent finding that only a small fraction of CD5hi DP thymocytes termin-ated CD5lo DP thymocytes to become CD5hi at which point they developmentally await the induction of lineage-specific signals. If lineage-specific signals are generated, perhaps by Notch proteins (12), CD5hi DP thymocytes terminate CD4 coreceptor synthesis and become CD8 committed. But if lineage-specific signals are not generated, CD5hi DP thymocytes terminate CD8 coreceptor synthesis and become CD4 committed. We do not know how long CD5hi DP thymocytes await the appearance of lineage-specific signals before terminating CD8 coreceptor synthesis, and we do not know whether there are intrathymic signals that regulate the timing of this event.

Finally, the present results are remarkable in their demonstration that CD3-signaled DP thymocytes could undergo CD4 commitment even in the absence of clonotypic TCR chains. Of course, DP thymocytes express surface molecules in addition to clonotypic TCR chains that can stimulate CD3 signaling, such as CD2, CD5, Thy-1, and Ly6 (32–34). Consequently, it is conceivable that engagement of such nonclonotypic molecules by intrathymic ligands can inefficiently mimic clonotypic TCR chains in their ability to stimulate CD3 signals that induce CD5hi DP thymocytes to become CD5hi, and so eventually to become CD4 committed. The absence of CD5hi DP thymocytes and CD4-committed cells in TCRαβ mice does not rule out intrathymic signaling by nonclonotypic molecules because surface CD3 expression is probably too low on TCRαβ thymocytes to transduce such signals. Indeed, stimulation of CD3 signals by nonclonotypic receptors may provide one explanation for the appearance of small numbers of CD4-committed DP thymocytes in MHC-deficient thymi (8).

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