In vivo fate mapping identifies pre-TCRα expression as an intra- and extrathymic, but not prethymic, marker of T lymphopoiesis

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Expression of the pre–T cell receptor α (pTα) gene has been exploited in previous studies as a molecular marker to identify tiny cell populations in bone marrow (BM) and blood that were suggested to contain physiologically relevant thymus settling progenitors (TSPs). But to what extent these cells genuinely contribute to thymopoiesis has remained obscure. We have generated a novel pTαiCre knockin mouse line and performed lineage-tracing experiments to precisely quantitate the contribution of pTα-expressing progenitors to distinct differentiation pathways and to the genealogy of mature hematopoietic cells under physiological in vivo conditions. Using these mice in combination with fluorescent reporter strains, we observe highly consistent labeling patterns that identify pTα expression as a faithful molecular marker of T lineage commitment. Specifically, the fate of pTα-expressing progenitors was found to include all αβ and most γδ T cells but, in contrast to previous assumptions, to exclude B, NK, and thymic dendritic cells. Although we could detect small numbers of T cell progenitors with a history of pTα expression in BM and blood, our data clearly exclude these populations as physiologically important precursors of thymopoiesis and indicate that they instead belong to a pathway of T cell maturation previously defined as extrathymic.

The pre-TCRα (pTα) chain is an essential and invariant subunit of the pre-TCR (von Boehmer, 2005). The only known physiological function of pTα protein is to associate with nascent TCRβ chains in committed T lineage progenitors to form a functional pre-TCR, which provides essential signals to promote development of αβ thymocytes and to attune αβ/γδ lineage choice. In line with this highly restricted function, pTα expression is largely confined to immature thymocytes. However, pTα message has also been detected in lineage-negative (Lin−) BM cells of wild-type and athymic nude mice (Bruno et al., 1995), which has given rise to the idea that pTα expression in BM may mark the enigmatic progenitors destined for settling the thymus. So far, neither identity nor full characteristics of thymus settling progenitors (TSPs) have been determined with certainty, leaving an embarrassing gap in our current schemes of T lymphopoiesis (Petrie and Kincade, 2005; Bhandoola and Sambandam, 2006; Bhandoola et al., 2007; Zlotoff and Bhandoola, 2011). Characterization of pTα-expressing BM cells, which seem to proffer tantalizing TSP candidates, thus appears imperative.

Cell surface expression of pTα depends on the presence of a functional TCRβ chain and members of the CD3 complex, which may not be available for complex formation at early developmental stages. Moreover, physiological pre-TCR surface expression is too weak to allow
purification and further characterization of pre-TCR–positive cells. In an early attempt to overcome this obstacle, a transgenic mouse line was generated, which expressed a human CD25 surface marker (hCD25) under the control of a short regulatory element from the pTα-encoding Ptcra locus (Gounari et al., 2002). The analysis of such pTα/hCD25 reporter mice resulted in several high-profile publications (Gounari et al., 2002; Martin et al., 2003; Krueger and von Boehmer, 2007) reporting the identification and characterization of the common lymphoid progenitor 2 (CLP-2) and the circulating T cell progenitor (abbreviated CTP by Krueger and von Boehmer [2007]), which were commended to comprise physiologically relevant TSPs in BM and blood, respectively. However, these conclusions were based on experiments that did not provide information on to what extent pTα-expressing cells in BM and blood would genuinely contribute to thymopoiesis under in vivo steady-state conditions. Moreover, although a live marker like hCD25 can be useful to identify individual cells with active pTα expression, it does not allow the elucidation of in vivo differentiation pathways and precursor-product relationships. To directly quantify the contribution of pTα-expressing progenitor cells to thymopoiesis and to determine their in vivo commitment status, we have generated a novel knockin mouse line expressing an improved version of Cre recombinase (iCre) under the control of the endogenous Ptcra locus. In combination with fluorescent reporter mice, Ptcra-controlled iCre expression results in irreversible activation of fluorescent protein expression, providing a heritable lineage marker that indicates current and past Ptcra activity. Analysis of our pTα<i>Cre</i> reporter mice revealed highly consistent labeling patterns with recombination of floxed reporter alleles in αβ T lineage cells at near 100% efficiency. Using this in vivo fate mapping system, we reveal a previously unappreciated restriction in the developmental fate of pTα-expressing progenitor populations, arguing against a physiologically relevant CLP-2 stage in T lymphopoiesis. In fact, our data contest any appreciable contribution of cells with a history of pTα expression from BM or blood to canonical pathways of thymopoiesis and thus refute key conclusions from previous studies using conventional pTα/hCD25 reporter mice (Gounari et al., 2002; Martin et al., 2003; Krueger and von Boehmer, 2007).

RESULTS
Generation of pTα<i>Cre</i> knockin mice for lineage-tracing experiments
In vivo lineage tracing based on Cre/loxP technology provides a powerful genetic marking method, which can be used to permanently label specific cell subsets and to directly visualize cell fate decisions in a noninvasive manner within the intact organism (Hadjantonakis et al., 2003; Branda and Dymecki, 2004). To exploit this technique for fate mapping of pTα-expressing progenitor populations, we introduced a mini-gene carrying a codon-optimized version of Cre recombinase (iCre) into the first exon of the pTα-encoding Ptcra gene locus (Fig. 1 A). Particular attention was attached to the design of the construct to assure maximal Cre recombinase expression and activity, while strictly preserving pTα-specific regulation, as described in detail in Materials and methods.

Insertion of the iCre-encoding DNA sequences into the first exon of Ptcra was predicted to prevent expression of a functional pTα chain. In line with this prediction, homozygous pTα<i>Cre</i> mice exhibited the same characteristic defects in thymopoiesis (Fig. 1 B) as described previously for mice lacking functional pTα chains (Fehling et al., 1995). Importantly, heterozygous pTα<i>Cre</i> mice were phenotypically indistinguishable from wild-type littermates (Fig. 1 B and not depicted), confirming the well-established notion that loss of one Ptcra allele does not affect T cell development (Fehling et al., 1995).

To visualize iCre expression, pTα<i>Cre</i> knockin mice were intercrossed with R<sub>osaf</sub><i>EYFP</i> (Srinivas et al., 2001) or Rosatd<i>tdRFP</i> (Luche et al., 2007) reporter lines, the choice dependent on compatibility with fluorescent antibodies in multicolor FACS experiments. Both reporter lines gave equivalent results. Cre-mediated excision of a transcriptional stopper resulted in irreversible activation of the respective reporter gene. Importantly, because of the irreversibility of the recombination event, Cre-expressing cells are heritably marked, i.e., all descending cells remain labeled, irrespective of their extent Cre expression status. The majority of αβ T cells depend on pre-TCR-mediated B-selection during their development in the thymus. However, some αβ T cells can mature in the absence of a functional pTα chain (Fehling et al., 1995). Thus, it remained to be determined how many αβ T progenitors normally pass through a pTα-expressing stage. Analysis of pTα<i>Cre</i> reporter mice revealed essentially complete labeling of CD3<sup>+</sup>TCRαβ<sup>+</sup> cells in thymus, spleen, and lymph node (Fig. 1 C). Pan-RFP or pan-YFP mice carrying a constitutively active reporter allele (see Materials and methods) served as positive control, highlighting near saturation of labeling efficiencies in αβ T cells from pTα<i>Cre</i> reporter mice. Importantly, there was no significant variation in labeling efficiencies between individual reporter mice. This is most obvious in comparison with conventional Lck-Cre transgenics (Hennet et al., 1995), which may exhibit strong interindividual variation in recombination efficiencies (Fig. 1 D) and even in lineage fidelity (not depicted), most likely as the result of variegated transgene expression, a phenomenon typical for multicopy transgenes inserted outside their natural genomic context (Martin and Whitelaw, 1996). Interestingly, much less variation has been observed in a recent systematic study using the same lck-Cre transgenic and Rosa-tdRFP reporter strains (Shi and Petrie, 2012), suggesting a particular vulnerability of the transgenic system to as yet undefined experimental settings. Our pTα<i>Cre</i> knockin mice proved devoid of such problems and thus well suited for lineage-tracing experiments.

History of pTα<i>Cre</i> expression in γδ T cells
Approximately 10–20% of γδ T cells express functional TCRβ chains in the cytoplasm (Dudley et al., 1995; Burtrum
As shown in Fig. 2A, ~90% of CD3⁺TCRγδ⁺ cells in thymus, spleen, and lymph node are consistently labeled in pTαCre reporter mice and thus have a history of pTα expression. Approximately the same percentage of reporter-positive cells is found among dendritic epidermal T cells (DETCs; Fig. 2B), a specialized T cell population in murine skin (Hayday, 2009; Havran and Jameson, 2010), which can be readily identified because of the expression of a largely invariant Vγ5Vδ1 TCR (nomenclature according to Hayday et al. [1985]). The fact that the percentage of DETCs with a history of pTαCre expression is not significantly reduced in comparison with conventional γδ T cells is noteworthy, as DETCs develop in a single wave from a fetal precursor population beginning on day 14 of gestation (Havran and Allison, 1990), and thus well before pTα-controlled differentiation of αβ thymocytes.

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Although the overwhelming majority of γδ T cells is derived from a pTα-expressing precursor population, we consistently observed reduced labeling frequencies in γδ compared with αβ T cells. In contrast to αβ T cells, which are in
essence fully labeled, we found within γδ T cell populations from all organs analyzed a discrete reporter-negative subset of ~10%. This difference in reporter expression was not caused by lack of Rosa26 transcription in a specific cell subset, as virtually all γδ T cells were labeled in pan-RFP control mice carrying a constitutively active Rosa26RFP allele (Fig. 2, A and C). Intracellular staining for TCRβ chains revealed that TCRβ-positive γδ T cells were enriched in the reporter-positive rather than reporter-negative γδ T cell subset (Fig. 2 D). Lack of pTα expression in γδT precursor cells can thus be formally excluded as an explanation for the presence of functional TCRβ chains in a significant percentage of γδ T cells (Bosco et al., 2008).

pTα<sup><big>Cre</big></sup> expression is confined to T progenitors lacking B cell, NK cell, and myeloid lineage potential

If pTα was expressed in a T lineage precursor population with physiologically relevant CLP activity, as suggested previously (Gounari et al., 2002; Martin et al., 2003), one should find a significant fraction of B cells, NK cells, and possibly DCs permanently labeled in pTα<sup><big>Cre</big></sup> reporter mice. Although mature CD3<sup>+</sup> T cells in lymph node and spleen were reporter positive, no cells in the CD19<sup>+</sup> B cell compartment were labeled (Fig. 3 A). Even in the thymus, where some B lymphopoiesis occurs in close proximity to T cell development (Akashi et al., 2000), the tiny population of mature B cells was consistently reporter negative (Fig. 3 B). These in vivo findings are incompatible with the view that B cells pass through a pTα<sup><big>Cre</big></sup>-expressing precursor stage during normal, steady-state hematopoiesis.

In the CD3<sup>−</sup>CD19<sup>−</sup> compartment of spleen and lymph node, which contains NK cells and cells of myeloid descent, we consistently found a small, but discrete population of reporter-positive cells (Fig. 3, A and C). Importantly, the labeled population completely disappeared both in spleen and lymph nodes when pTα<sup><big>Cre</big></sup> reporter mice were bred on...
intermediate progenitors (CIPs) to be described below. Collectively, the absence of labeled cells in spleen and lymph nodes of RAG- and CD3-deficient pTαCre reporter mice demonstrates that neither NK cells nor myeloid cells normally pass through a pTαCre-expressing precursor stage.

No evidence for a "lymphoid past" of thymic DCs

The developmental origin of DC subsets, and in particular their relationship to the lymphoid lineage, has remained a complex and controversial issue (Shortman and Naik, 2007; Liu and Nussenzweig, 2010). For instance, detection of pTα transscripts by RT-PCR in purified mouse plasmacytoid cells and in a subset of thymic DCs has been proposed to indicate a lymphoid past, i.e., a lymphoid developmental origin of these cells (Corcoran et al., 2003). The analysis of pTαCre reporter mice does not support such speculations. In the thymus, neither CD11c+CD11b+CD19− cells contained a significant fraction of reporter-positive CD3−CD19− cells may comprise circulating counterparts of BM T lineage committed to develop these cells. However, the observed marker expression is also compatible with the view that a significant fraction of reporter-positive CD3−CD19− cells may comprise circulating counterparts of BM T lineage committed to develop these cells.
fraction of reporter-positive cells (Fig. 4, A and B). Equivalent results were obtained upon analysis of splenic DC subsets (not depicted). Our data demonstrate that pTα expression is no appropriate molecular marker to distinguish DC sub-populations and that DCs are not derived from a pTαCre-expressing precursor population. These observations are fully congruent with recent fate mapping experiments using either LangerinDTR-EGFP or IL-7R iCre knockin mice, which both provided compelling in vivo evidence for a non-lymphoid origin of thymic DCs (Schlenner et al., 2010; Luche et al., 2011).

Onset of pTαCre expression in early thymopoiesis

The observed T lineage-restricted labeling pattern in pTαCre reporter mice unveils a previously unappreciated link between pTα expression and T lineage commitment, i.e., the complete extinction of all alternative differentiation fates in pTα-expressing progenitor cells. By carefully monitoring reporter expression during early thymopoiesis, we can thus directly visualize the developmental stage at which individual cells have completed T lineage commitment. As shown in Fig. 5 A, essentially all immature CD4+CD8− double-positive (DP) and more mature CD4+ or CD8+ single-positive thymocytes are reporter positive, demonstrating that all of these αβ T lineage committed cells have gone through a pre-TCR–dependent β-selection step (Hayday and Pennington, 2007). In contrast, the CD4+CD8− double-negative (DN) compartment contains a significant fraction of cells lacking signs of present or past pTα expression (Fig. 5 A). Based on CD25 and CD44 expression, the DN population can be subdivided into four developmentally successive stages (DN1–4), with DN2 and DN3 often being further subdivided into developmentally early (E) and late (L) fractions (Ceredig and Rolink, 2002; Rothenberg et al., 2008). Analysis of these DN subsets in pTαCre reporter mice reveals a continuous increase in the percentage of labeled cells with progressing maturity (Fig. 5 B). Although few cells in the DN2E compartment exhibit the pTα expression mark, the number of labeled cells gradually increases to >97% in the post-β-selection DN4 subset. This labeling pattern demonstrates that T lineage commitment can be completed in some cells as early as DN2. In contrast, most cells in this compartment are reporter negative, consistent with experimental evidence that DN2 contains cells, which, when tested in vitro or in cell transfer assays, can still differentiate along the NK or DC lineages (Shen et al., 2003; Rothenberg et al., 2010; Yui et al., 2010). The observed labeling pattern in pTαCre reporter mice is fully in line with microarray data provided by the Immunogenomic Genome Project, which identify DN2L cells (Immmgen nomenclature, preT.DN2-3) as the first DN subset with detectable pTα message and DN3E (Immmgen nomenclature, preT.DN3A) as the subset with highest pTα expression levels.

The DN1 subpopulation constitutes a heterogeneous mixture of cells, which can be divided into five distinct subsets (DN1a–e) based on surface expression of CD117 (Kit) and CD24 (HSA; Porritt et al., 2004). Canonical T cell progenitors are confined to the CD117+high subsets DN1a and DN1b (Porritt et al., 2004), which correspond to early T lineage progenitors (ETPs), generally considered the earliest intrathymic T lineage precursors (Allman et al., 2003; Benz et al., 2008; Luc et al., 2012). Consistent with lack of reporter expression in DN2E, the DN1a+b/ETP ancestors are reporter negative (Fig. 5, C and E). In contrast, the vast majority of more mature DN1d and DN1e cells are labeled, and DN1c cells contain reporter-positive and -negative subsets (Fig. 5 C), indicative of their heterogeneous composition (Porritt et al., 2004; Luche et al., 2011). Importantly, when pTαCre reporter mice were bred on RAG−−/− or CD3ε−−/− backgrounds, the fraction of labeled cells in DN1 dropped dramatically, whereas the labeling index in combined stages DN2 + DN3 remained high (Fig. 5 D), indicating that the vast majority of labeled cells within the DN1 compartment are developmentally advanced populations, which are dependent on V(D)J recombination and a functional TCR–CD3 complex. The finding that DN1a+b/ETP populations are homogenously reporter negative (Fig. 5, C and E) is of key importance because this
In accordance with published data on pTα mRNA expression (Bruno et al., 1995), we found a small population of reporter-positive cells (1.9 ± 0.5%) within the Lin−BM population of pTαiCre reporter mice (Fig. 6, A–C). For analysis of BM and blood, we frequently had to switch between RosaRFP and RosaYFP reporter mice to conform to available fluorescent antibodies. Equivalence of both reporter systems was demonstrated with pTαiCre mice carrying both a RosaRFP and a RosaYFP allele (Fig. 6 B and not depicted). As pointed out above, reporter-positive cells cannot be precursors of the thymic ETP population because the latter is homogeneously labeled. Therefore, the result effectively excludes all pTαiCre-expressing prethymic progenitors as physiologically relevant ETP precursors. The absence of labeling among ETPs is again supported by microarray data from the Immunological Genome Project, which mark the ETP population as negative for pTα expression.

In BM and blood, pTαiCre-labeled cells comprise T lineage precursors of an extrathymic maturation pathway. pTα-expressing cells in BM and blood have been promoted as physiologically relevant TSP candidates (Gounari et al., 2002; Martin et al., 2003; Krueger and von Boehmer, 2007). In accordance with published data on pTα mRNA expression (Bruno et al., 1995), we found a small population of reporter-positive cells (1.9 ± 0.5%) within the Lin− BM population of pTαiCre reporter mice (Fig. 6, A–C). For analysis of BM and blood, we frequently had to switch between RosaRFP and RosaYFP reporter mice to conform to available fluorescent antibodies. Equivalence of both reporter systems was demonstrated with pTαiCre mice carrying both a RosaRFP and a RosaYFP allele (Fig. 6 B and not depicted). As pointed out above, reporter-positive cells cannot be precursors of the thymic ETP population because the latter is homogeneously labeled. Therefore, the result effectively excludes all pTαiCre-expressing prethymic progenitors as physiologically relevant ETP precursors. The absence of labeling among ETPs is again supported by microarray data from the Immunological Genome Project, which mark the ETP population as negative for pTα expression.
reporter negative (Fig. 5, C and E). Although most experimental data favor ETPs as the earliest canonical intrathymic T progenitor population (Allman et al., 2003; Porritt et al., 2004; Benz et al., 2008), the formal possibility remains that prethymic cells with a history of pTα reporter expression contribute substantially to thymopoiesis by bypassing the ETP stage. Does the analysis of reporter-positive cells in BM and blood support such a view?

Chemokine receptors CCR7 and CCR9 are critical for efficient homing of TSPs to the thymus (Schwarz et al., 2007; Krueger et al., 2010; Zlotoff et al., 2010). Moreover, all TSP activity in BM and blood has been shown to reside in a Lin− cell subset coexpressing CD27 and CD135 (Flk2/Flt3; Serwold et al., 2009; Saran et al., 2010) but lacking Thy−1high and B220+ cells (Serwold et al., 2009). A significant fraction of fluorescently labeled cells in pTαCre reporter mice is positive for CCR7 and/or CCR9, and the majority of reporter-positive cells express CD27, as predicted for cells with presumed TSP activity (Fig. 6 D). However, >99% of reporter-positive cells lack Flt3 expression, leaving at best spurious numbers of reporter-positive cells as TSP candidates.

pTαCre−labeled Lin− BM cells are ~99% positive for CD2, and most reporter-positive cells express Thy−1 at very high levels (Fig. 6, D and E). Lin− Thy−1high BM cells have been described extensively before (Dejbakhsh-Jones and Strober, 1999; Dejbakhsh-Jones et al., 2001; Chatterjea-Matthes et al., 2003; García-Ojeda et al., 2005). These cells contain firmly T lineage committed progenitors, which have been shown in adoptive transfer experiments to adhere to an extrathymic pathway of T cell maturation (Dejbakhsh-Jones et al., 2001; García-Ojeda et al., 2005). Based on CD2 surface expression, Thy−1high cells are divided into two developmentally successive subsets, a CD2−CD5−CD16−CD122+ population, termed committed T cell progenitor (CTP), which gives rise in vivo and in vitro within hours to the CD2−CD5−CD16−CD122+ subset, termed CIP (García-Ojeda et al., 2005). The vast majority of pTαCre−labeled cells reproduce the complete Thy−1highCD2−CD5−CD16−CD122+ phenotype of CIPs, indicating identity with CIPs.

In pTαCre reporter mice, ~0.5–1.0% of CTPs and ~90% of CIPs are fluorescently labeled (Fig. 6 F; histograms in second row), a labeling pattern consistent with the reported precursor–progeny relationship between both cell subsets. Moreover, the number of CIPs has been reported to be dramatically reduced in Rag2−/− and young athymic nude (FoxN1−/−) mice (Chatterjea-Matthes et al., 2003). Remarkably alike, pTαCre−labeled cells are virtually absent in Rag2−/−, CD3ε−/− and young athymic nude reporter mice (Fig. 6 F) but gradually reappear on nude background with increasing age, coincident with the reappearance of an increasingly prominent CIP population (Fig. 6 F; second row from bottom). The absence of labeled cells in pTαCre reporter mice on CD3ε−/− and Rag2−/− backgrounds indicates that survival of pTα–expressing BM progenitors is contingent on prompt pre-TCR–mediated β-selection within the BM, consistent with their proposed extrathymic maturation program.

Analogous observations were made when analyzing pTα reporter expression in peripheral blood of pTαCre mice. The Lin− blood fraction consistently contained ~1.0% of reporter-positive cells, which were largely confined to a discrete Thy−1highCD2+ population with a cell surface phenotype closely resembling the CIP population in BM (Fig. 7 A and B). Of note, this reporter-positive population was absent in Rag2− and CD3ε-deficient pTαCre mice (Fig. 7 C). In blood of athymic nude mice, the number of both Thy−1highCD2+ and pTαCre−labeled cells was again, like in BM, age dependent (Fig. 7 C).

BM progenitors with a history of pTαCre expression are devoid of TSP activity

The CD135−negative phenotype of reporter-positive cells and their virtual absence in pTαCre mice on RAG− and CD3ε−deficient backgrounds argue against cells with a history of pTα expression as physiologically important TSPs. To directly assay for TSP activity, we performed competitive complementation transfer assays. Our experimental approach, outlined in Fig. 8 A, took advantage of the availability of pTαCre mice with distinct reporter alleles (RosaRFP and RosaYFP). In brief, Lin− RFP+ and Lin− YFP+ cells were sorted from BM of pTαCre/WT × RosaRFP/WT and pTαCre/WT × RosaYFP/WT reporter mice, respectively. For subsequent use as competitor population, we also sorted the complementary Lin− BM fractions completely devoid of RFP+ or YFP+ cells, respectively (for sorting gates, see Fig. S2). Approximately 7,000 sorted RFP+ cells were mixed with 350,000 Lin− YFP− competitor cells and injected i.v. into nonirradiated Ilt7ar−/− mice, whose thymus have been shown to be highly receptive for T progenitor settling independent of irradiation (Fig. 8 A, left; Prockop and Petrie, 2004). In an analogous fashion, we tested sorted Lin− YFP+ BM cells in competition with Lin− RFP− BM cells (Fig. 8 A, right). Importantly, the injected ratio between test and competitor population (7,000:350,000 = 2%) was chosen to appropriately reflect the actual abundance of each subset in BM of pTαCre reporter mice (Fig. 6, B and C). The relative contribution of test versus competitor population to thymopoiesis was evaluated by analyzing the origin of DP thymocytes 2 wk after transfer, a timepoint sufficiently early to allow direct capture of the most proximal progenitor activity, as established in previous studies with Ilt7ar−/− mice (Chatterjea-Matthes et al., 2003; Serwold et al., 2009; Saran et al., 2010). As DP thymocytes exhibit a history of pTα expression (Fig. 5 A), donor-derived DP thymocytes can be easily identified as fluorescent cells. Moreover, the observed ratio between RFP+ and YFP+ DP cells directly reveals the relative contribution of test versus competitor population. Two independent transfer experiments gave exactly the same results (Fig. 8 B and C). In all recipient mice successfully reconstituted with RFP+ test/YFP− competitor cells, 100% of donor-derived DP thymocytes were YFP+, whereas no RFP+ thymocytes were detectable, indicating exclusive contribution of reporter-negative BM cells to thymopoiesis. An analogous complementary set of data were obtained in mice injected with a mixture
Figure 6. Characterization of reporter-positive cells in BM. (A) Gating scheme to identify reporter-positive cells in Lin\(^-\) BM. The number in the histogram refers to the percentage of reporter-positive cells. (B) Flow cytometric analysis of dual reporter expression in Lin\(^-\) BM cells from pTc\(^{CreWT}\) x Rosa\(^{RFP/YFP}\) mice, harboring both an RFP and an YFP reporter allele. Dot plot to the left shows labeling pattern in a representative animal, and the graph to the right summarizes data from 11 animals; each star corresponds to an individual mouse; pregating as in A. (C) Mean percentage of reporter-positive cells in Lin\(^-\) BM of mice with different genetic backgrounds. Designations below graphs refer to the age of foxN1\(^-\) mice in the respective cohort. Error bars denote SD (pTc\(^{CreWT}\) x Rosa\(^{RFP/WT}\) or YFP/WT on WT background, \(n = 15\); on CD3\(^-\) background, \(n = 16\); on Rag2\(^-\) background, \(n = 11\); on foxN1\(^-\) background, younger than 50 d, \(n = 7\); on foxN1\(^-\) background, 4–6 mo old, \(n = 3\)). (D) Cell surface phenotype of reporter-positive Lin\(^-\) cells (green histograms). Black line histograms refer to the expression pattern of the respective surface marker on total Lin\(^-\) cells (red gate in A). Numbers indicate percentages of cells in each gate. Each histogram is representative of three independent experiments. (E) Kit\(\)/Sca-1 and Thy-1/CD2 cell surface phenotype of reporter-positive and -negative Lin\(^-\) cells. Numbers indicate percentages of cells in each quadrant. Dot plots are representative of two independent experiments. (F) Reporter expression in Lin\(^-\)Thy-1\(^{low/}\) and previously described CTP and CIP populations (García-Ojeda et al., 2005). Color codes refer to gated Thy-1/CD2 subsets, as indicated on top of each histogram. Numbers indicate percentages of cells in each gate. Data are representative of at least five animals of each genotype.
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however, the conclusions were based on cell transfer and in vitro differentiation assays and did not provide information to what extent pTα expresing cells in BM and blood genuinely contribute to thymopoiesis under in vivo steady-state conditions. The present lineage-tracing study was designed to fill this knowledge gap. To our surprise, our data turned out to refute major findings and key conclusions of the aforementioned studies.

In mature cells, we found pTαiCre-mediated labeling strictly confined to the T lineage. No labeled cells were observed in lymph node, spleen, BM, and blood when reporter mice were bred on RAG- or CD3ε-deficient genetic backgrounds, demonstrating complete lack of pTαiCre expression in cells with in vivo NK or myeloid differentiation fates. Also plasmacytoid and thymic DCs were reporter negative, and no labeled B lymphocytes were observed. Our fate mapping data thus highlight pTα as an exquisitely T lineage-specific marker, whose expression indicates firm commitment, perfectly consistent with its restricted physiological function in T-committed precursor cells.

DISCUSSION

Detection of pTα message in Lin- BM cells of wild-type and athymic nude mice has given rise to speculation that such cells may belong to the long-sought, but still elusive TSP population (Bruno et al., 1995). Several publications, all based on a single line of transgenic reporter mice, seemed to provide experimental support to this view (Gounari et al., 2002; Martin et al., 2003; Krueger and von Boehmer, 2007). The reporter, encoding an hCD25 surface marker under the control of a short (9 kb) pTα promoter fragment randomly inserted into the mouse genome as multicopy transgene, was found to mark small cell subsets in BM and blood, which were proposed to represent physiologically meaningful maturation stages between the CLP and early intrathymic precursor populations. However, the conclusions were based on cell transfer and in vitro differentiation assays and did not provide information to what extent pTα-expressing cells in BM and blood genuinely contribute to thymopoiesis under in vivo steady-state conditions. The present lineage-tracing study was designed to fill this knowledge gap. To our surprise, our data turned out to refute major findings and key conclusions of the aforementioned studies.

In mature cells, we found pTαiCre-mediated labeling strictly confined to the T lineage. No labeled cells were observed in lymph node, spleen, BM, and blood when reporter mice were bred on RAG- or CD3ε-deficient genetic backgrounds, demonstrating complete lack of pTαiCre expression in cells with in vivo NK or myeloid differentiation fates. Also plasmacytoid and thymic DCs were reporter negative, and no labeled B lymphocytes were observed. Our fate mapping data thus highlight pTα as an exquisitely T lineage-specific marker, whose expression indicates firm commitment, perfectly consistent with its restricted physiological function in T-committed precursor cells.
enzymatic reporter (iCre) into the endogenous Ptcra gene locus to preserve all known and unknown genetic elements possibly controlling physiological pTα expression, the hCD25 reporter was inserted randomly into the mouse genome as multicopy transgene. Moreover, reporter expression was controlled by just 9 kb of pTα-5' flanking sequence, unlikely to contain all cis-regulatory elements required for faithful genetic and epigenetic regulation of pTα expression at all developmental stages from HSCs to mature T cells. Transgene copy number, genomic insertion site and a phenomenon termed transgene variegation are infamous for insidiously perturbing expression of conventional transgenes (Martin and Whitelaw, 1996; Montoliu et al., 2000). With regard to the CLP-2, one can thus imagine a scenario in which a few marker-positive cells, devoid of CLP activity, coexpress pTα, accounting for positive RT-PCR results at the population level, whereas the majority of hCD25+ CLP-2 cells are aberrantly labeled, lacking endogenous pTα expression, but exhibiting CLP activity. The reported aberrant expression of the huCD25 reporter in 30% of thymic TCRγδ cells and in B lineage committed CD19+ cells, clearly negative for endogenous

The failure to detect labeled cells outside the T lineage necessarily implies the absence of pTα<sup>iCre</sup> expression in cells with physiologically relevant CLP activity. This result is in striking contrast to the concept of a pTα-expressing CLP-2 stage in early T lymphopoiesis. CLP-2 cells have been identified in BM of pTα/hCD25 transgenic mice as an hCD25+B220<sup>−</sup> population with efficient thymic immigration ability and robust CLP activity (Gounari et al., 2002; Martin et al., 2003). Based on these data, we expected to find at least some labeled B, NK, or DCs in pTα<i>Cre</i> reporter mice, which was clearly not the case. We conclude that either B220<sup>−</sup>Kit<sup>−</sup> CLP-2 cells do not exhibit CLP activity in vivo or cells with CLP activity within the CLP-2 population do not express pTα at significant levels, which would seem paradoxical because pTα/hCD25 reporter expression is the defining feature of these cells and led to their identification in the first place.

What could be the basis for this striking discrepancy between our results and data obtained with conventional pTα/hCD25 reporter mice? Evidence suggests that aberrant expression of the transgenic hCD25 reporter may account for much of the confusion. Although we have targeted our sensitive enzymatic reporter (iCre) into the endogenous Ptena gene locus to preserve all known and unknown genetic elements possibly controlling physiological pTα expression, the hCD25 reporter was inserted randomly into the mouse genome as multicopy transgene. Moreover, reporter expression was controlled by just 9 kb of pTα-5' flanking sequence, unlikely to contain all cis-regulatory elements required for faithful genetic and epigenetic regulation of pTα expression at all developmental stages from HSCs to mature T cells. Transgene copy number, genomic insertion site and a phenomenon termed transgene variegation are infamous for insidiously perturbing expression of conventional transgenes (Martin and Whitelaw, 1996; Montoliu et al., 2000). With regard to the CLP-2, one can thus imagine a scenario in which a few marker-positive cells, devoid of CLP activity, coexpress pTα, accounting for positive RT-PCR results at the population level, whereas the majority of hCD25+ CLP-2 cells are aberrantly labeled, lacking endogenous pTα expression, but exhibiting CLP activity. The reported aberrant expression of the huCD25 reporter in 30% of thymic TCRγδ cells and in B lineage committed CD19+ cells, clearly negative for endogenous

Figure 8. pTα<i>Cre</i>-labeled BM cells lack TSP activity. (A) Outline of the competitive complementation transfer experiment. Approximately 7,000 Lin<sup>−</sup>RFP<sup>+</sup> cells sorted from pooled BM of female pTα<i>Cre</i>WT × Rosa<sup>RFP</sup>WT mice and injected i.v. into an unconditioned IL-7Rα<sup>−/−</sup> female mouse (left). In the reciprocal experiment, ~7,000 Lin<sup>−</sup>-YFP<sup>−</sup> cells sorted from pooled BM of the pTα<i>Cre</i>WT × Rosa<sup>RFP</sup>WT mice were mixed with ~350,000 Lin<sup>−</sup>-YFP<sup>−</sup> cells sorted from pooled BM of the pTα<i>Cre</i>WT × Rosa<sup>RFP</sup>WT mice and also injected i.v. into an unconditioned IL-7Rα<sup>−/−</sup> female mouse (right). On day 14 after injection, thymocytes of recipient mice were isolated and analyzed for the ratio of red versus yellow donor cells in CD4/CD8 thymic subsets. (B) Cytfluorometric analysis of recipient thymi from two representative IL-7Rα<sup>−/−</sup> mice, reconstituted with RFP<sup>+</sup>/YFP<sup>−</sup> (left) or YFP<sup>+</sup>/RFP<sup>−</sup> (right) Lin<sup>−</sup> donor BM cells 14 d earlier. Total numbers of recovered thymocytes were 37 x 10<sup>6</sup> and 28.4 x 10<sup>6</sup>, respectively. Two independent experiments gave identical results: fluorescently labeled thymocytes were derived exclusively (100%) from the reporter-negative donor cell fraction in 4/4 recipients of RFP<sup>+</sup>/YFP<sup>−</sup> and in 7/7 recipients of YFP<sup>+</sup>/RFP<sup>−</sup> Lin<sup>−</sup> cells. (C) Total number of thymocytes in IL-7Rα<sup>−/−</sup> recipients 14 d after receiving RFP<sup>+</sup>/YFP<sup>−</sup> (open circles) or YFP<sup>+</sup>/RFP<sup>−</sup> Lin<sup>−</sup> cells (closed circles). Control recipients were injected with PBS only (closed triangles).
pTα message (Gounari et al., 2002; Martin et al., 2003), supports this explanation.

Importantly, and in agreement with hCD25 reporter studies (Gounari et al., 2002; Martin et al., 2003), we do find Lin- cells with a history of pTα expression in BM of pTαCre reporter mice, which are mostly Kit- and a few of which even express B220 (Fig. 6 D), reminiscent of the CLP-2 surface phenotype. However, labeled cells are absent in mice on Rag2-/- or CD3e-/- genetic backgrounds, indicating that BM cells with a history of pTα expression pass through an obligatory extrathymic β-selection stage and thus cannot serve as precursors of early thymopoiesis. We further validated this conclusion in competitive complementation transfer assays, which demonstrated that pTαCre-labeled BM cells do not contribute to thymopoiesis to any measurable extent (Fig. 8).

In fact, our data strongly suggest that BM cells with a history of pTαCre expression are largely identical with CIPs, which arise from CTPs and represent a T lineage committed population that belongs to an extrathymic pathway of maturation (García-Ojeda et al., 2005).

In agreement with data obtained from the analysis of huCD25 reporter mice (Krueger and von Boehmer, 2007), we do find Lin- cells with a history of pTα expression in peripheral blood of adult pTαCre reporter mice on wild-type as well as nude background. These cells closely resemble in surface phenotype pTαCre-labeled cells in BM, suggesting that they represent circulating counterparts of CIPs. The vast majority of labeled cells in adult blood belong to a discrete Thy-1hiCD2^+ population (Fig. 7 A). Although labeled cells completely lack B220 and Flt3 surface expression, a substantial fraction stains positive for IL-7Rα and Sca-1 (Fig. 7 B). A population of Thy-1hiSca-1IL-7Rα^B220^ Flt3^−^ cells has been identified in pTα/hCD25 transgenic mice based on hCD25 reporter expression. The cells, termed circulating T cell progenitors (also abbreviated CTPs) were shown to be T committed and claimed to represent “T cell precursors (also abbreviated CTPs) described by Krueger and von Boehmer (2007). Our data do not support this conclusion because all cells with a history of pTαCre expression disappear in knockin reporter mice when bred on Rag2-/- or CD3e-/- backgrounds. Circulating T cell progenitors (also abbreviated CTPs) described by Krueger and von Boehmer (2007) and CTPs described by Dejbakhsh-Jones and Strober (1999), Dejbakhsh-Jones et al. (2001), and García-Ojeda et al. (2005) may thus not just share acronyms, but represent cells of the same extrathymic maturation pathway. Collectively, our data refute the concept of pTα expression as a marker for cells with physiologically relevant TSP activity tout ensemble. Instead, we propose that pTα-expressing cells in BM and adult blood belong to an extrathymic pathway of T cell maturation, similar to pTα-expressing cells in gut and liver (Bruno et al., 1995), which would also not be considered TSP candidates. To what extent T lineage committed progenitors in fetal blood (Rodewald et al., 1994), which contain pTα-expressing cells (Bruno et al., 1995), are en route to the thymus remains to be investigated.

Two more issues may merit brief discussion. First, our lineage-tracing study provides conclusive evidence that ~90% of CD3+ TCRγδ^+ cells in thymus, spleen, and lymph nodes pass through a pTα-expressing developmental stage. The demonstration of pTα expression in γδ progenitors as such may not come as a surprise because earlier experiments have provided correspondent hints. For instance, an augmented frequency of in-frame TCRβ rearrangements in γδ T cells has been suggested to indicate pre-TCR-mediated β-selection in the γδ lineage (Dudley et al., 1995). In line, intracellular TCRβ expression in a fraction of TCRγδ^+ thymocytes was reported to correlate with increased proliferation (Wilson and MacDonald, 1998). Although the latter finding has been disputed in another study using pTα^-/- mice (Aifantis et al., 1998), pTα deficiency was observed to correlate with an increased percentage of intracellular TCRβ^+ γδ cells, again suggesting pre-TCR-mediated effects on the γδ lineage. Although all these studies point to pTα expression in at least some γδ progenitors, our data provide not only direct proof in mice with unperturbed T lymphopoiesis, but also for the first time a precise in vivo quantification. Whether the consistently observed absence of pTαCre labeling in ~10% of TCRγδ cells delineates a functionally distinct γδ subset or simply indicates stochastic deviation of a fixed percentage of γδ progenitors from the common αβ/γδ developmental path before initiation of pTα expression is currently under investigation.

Finally, the strict T lineage specificity of pTαCre expression commends our knockin mice as a novel tool for the conditional genetic modification of αβ T lineage cells. So far, T lineage–specific gene inactivation has been dependent on the availability of mice carrying randomly inserted Cre transgenes, like lck-Cre transgenics (Hennet et al., 1995), which suffer from problems inherent in classical transgenesis. In contrast, pTαCre knockin mice afford consistent recombination efficiencies of essentially 100%, do not violate lineage fidelity, and do not exhibit significant interindividual variation neither in efficacy nor pattern of recombination. This advantageous combination of favorable features should make pTαCre knockin mice a preferred tool for studies requiring faithful and proficient T lineage–specific gene modification.

MATERIALS AND METHODS

Generation of pTαCre knockin mice. To achieve optimal concordance between pTα expression and Cre activity, we opted for a knockin approach and constructed a targeting vector, which upon homologous recombination would insert a Cre recombinase–encoding expression cassette into the first exon of the pTα-encoding Petra locus (Fig. 1 A, top). To optimize pTα controlled expression of Cre recombinase, the expression cassette was designed as a mini-gene, containing a splice donor site (SA), a short intron, a splice acceptor site (SA), a cDNA encoding Cre recombinase with its trans-
Analysis of thymic DCs. DCs were isolated as published (Feyerabend et al., 2009). In brief, thymus were minced with scissors into small pieces and digested in 1 ml PBS containing 0.2 mg/ml Collagenase D (Roche), 0.1 mg/ml Dispase I (Roche), and 25 mg/ml DNase I (Sigma-Aldrich) for 10 min at 37°C while shaking in a thermostatic mixer at 800 rpm. The supernatant containing released cells was collected, and enzymatic activities were inhibited by adding an equal volume of PBS containing 5% FCS and 5 mM EDTA. Additional cells were collected by four to five rounds of repeated tissue digestion and harvest. Pooled cells were counted, and three million cells were stained with a mixture of biotinylated antibodies directed against CD3 (500A2), CD4 (GK1.5), CD19 (1D3), TER119, and CD49b (DX5) and the following DC-specific antibodies: anti–CD11c–APC-Cy7 (N418), anti–CD11b–PE-Cy7, anti–MHC class II–APC (M5/114.15.2), anti–B220–PE-Cy5.5 (RA3-6B2), and anti–PDCA1–FITC (eBio-927). Cells stained with biotinylated antibodies were revealed by secondary staining with Streptavidin–eFluor 450 and electronically excluded. DC subsets were identified within the eFluor 450–negative cell fraction as CD11c+B220–CD11b– lymphoid DCs (lyDCs), CD11c–MHC class II+B220–CD11b+ myeloid DCs (myDCs) and CD11c–MHC class II–B220+PDCA1+ plasmacytoid DCs according to reported surface phenotypes (Colonna et al., 2004; Wu and Shortman, 2005). The designation lyDC or myDC originally referred to the suggested origin of these DC populations from lymphoid or myeloid pathways, respectively. LyDCs are also named CD8+ and myDCs CD8– conventional DCs (Shortman and Heath, 2010).

Analysis of DETCs. DETCs were isolated from mouse ears, which were minced with scissors into small pieces and digested in 1 ml protease solution (200 mg/ml Collagenase D1, 2 mg/ml Dispase I, and 5 mg/ml DNase I in PBS) for 15 min at 37°C while shaking in a thermostatic mixer at 800 rpm. Supernatant containing released cells was harvested and kept on ice. Remaining tissue was subject to a second round of digestion with fresh protease solution, again for 15 min at 37°C while shaking at 800 rpm. Supernatants of successive digests were pooled and adjusted to 5 mM EDTA to antagonize cell aggregation. After a 5-min incubation period on ice, cells were passed through a 70-µm filter, washed once, and resuspended in staining buffer. Cells were stained with antibodies specific for CD45 (30-F11), CD3 (145-2C11), and VγVδ (F536).

Analysis of thymic B cells. To enrich for thymic B cells, total thymocytes were stained with biotinylated rat antibodies against CD4 (GK1.5) and CD8 (S3-6.7) and depleted using anti–rat IgG–conjugated magnetic Dynabeads (Invitrogen) according to the manufacturer’s instruction. Remaining cells were stained with Streptavidin–APC-Cy7 (BD), anti–CD19–FITC (1D3), and anti–IgM (1B4-B1) antibodies. Mature thymic B cells were identified in the pregated Cy7–negative population as CD19+IgM+ cells.

Analysis of DN thymocytes. To enrich for most immature thymocyte populations, total thymocytes were stained with a mixture of biotinylated antibodies directed against CD3e (500A2), CD8α (S3-6.7), CD11b (M1/70), CD19 (1D3), NK1.1 (PK136), Gr1 (RB6-8C5), TCRβ (HSD7-597), TCRγδ (GL3), TER119, CD11c (HL3), and B220 (RA-6B2), followed by depletion with Dynabeads according to the manufacturer’s instruction. Remaining cells were stained with directly conjugated antibodies against relevant surface molecules and always with a second anti–CD3e–specific antibody (145-2C11) as well as with Streptavidin–QD605 to facilitate gating on the Lin– population and to permit electronic exclusion of remaining Lin+ cells.

Analysis of Lin+ BM cells. To enrich for Lin+ progenitor populations, BM cells were stained with a mixture of biotinylated antibodies directed against CD3e (500A2), CD8α (S3-6.7), CD11b (M1/70), CD19 (1D3), NK1.1 (PK136), Gr1 (RB6-8C5), TCRβ (HSD7-597), TCRγδ (GL3), TER119, and CD11c (HL3), followed by depletion with Dynabeads according to the manufacturer’s instruction. Antibodies against CD4 and B220 were deliberately omitted from the lineage mix as relevant precursor populations, like the CLP-2, have been reported to express these surface markers (Martin et al., 2003). Remaining cells were stained with a mixture of directly
labeled antibodies against relevant surface molecules, Streptavidin-QD605, and a second anti-CD3ε antibody (145-2C11) conjugated to APC or APC-Cy7. Streptavidin-QD605 and the additional anti-CD3ε antibody were used to rigorously exclude Lin− cells, in particular mature T cells, and to facilitate electronic gating on the Lin− population.

Analysis of progenitors in peripheral blood. Peripheral blood was drawn from tail veins into EDTA-containing microtubes (Sarstedt). Blood from several mice was pooled, diluted 1:1 with PBS, and carefully underlaid with Ficoll-Paque Plus (GE Healthcare) at a ratio of 3:1 (vol/vol). Samples were centrifuged in a swing-out bucket for 30 min at 20°C. The buffy coat layer was collected and transferred into 10 ml of staining buffer. Cells were pelleted by centrifugation, resuspended in staining buffer, and counted, excluding dead cells with Trypan Blue. Cells were stained with a mixture of biotinylated antibodies directed against the lineage markers CD3 (500A2), CD8a (S3-6.7), CD11b (M1/70), CD19 (1D3), NK1.1 (PK136), GR1 (RB6-8C5), TCRβ (H57-597), TCRγδ (GL3), TER119, and CD11c (HL3) and directly labeled antibodies against specific cell surface molecules. Lin− cells were retrieved by depletion into young (6–12 wk old), untreated IL-7Rα−/− recipient mice. CD3ε−/− recipient mice were injected i.v. into young (6–12 wk old), untreated IL-7Rα−/− recipients (competitive competition). We injected each of three recipients with 6 × 10^3 Lin− females. In the first experiment, we injected each of three recipients with 8 × 10^3 Lin− males. In the second experiment, we injected each of four recipients with 8 × 10^3 Lin− males. In the third experiment, we injected each of four recipients with 8 × 10^3 Lin− males.

Adaptive cell transfer into IL-7Rα−/− recipients (competitive complementation transfer assay). BM cells from eight female pTαCre/WT × RosaRFP/WT and eight female pTαCre/WT × RosaYFP/WT mice were stained with the following mixture of biotinylated, lineage-specific antibodies: anti-CD3 (500A2), CD19 (1D3), CD11c (HL3), TCRγδ (GL3), NK1.1 (PK136), TER119, GR1 (RB6-8C5), and CD11b (M1/70). Stained cells were depleted using anti–rat IgG-conjugated magnetic Dynabeads according to the manufacturer’s instruction. Antibodies against CD4 and B220 were deliberately omitted from the lineage mix.

Analysis of progenitors in peripheral blood. Peripheral blood was drawn from tail veins into EDTA-containing microtubes (Sarstedt). Blood from several mice was pooled, diluted 1:1 with PBS, and carefully underlaid with Ficoll-Paque Plus (GE Healthcare) at a ratio of 3:1 (vol/vol). Samples were centrifuged in a swing-out bucket for 30 min at 20°C. The buffy coat layer was collected and transferred into 10 ml of staining buffer. Cells were pelleted by centrifugation, resuspended in staining buffer, and counted, excluding dead cells with Trypan Blue. Cells were stained with a mixture of biotinylated antibodies directed against the lineage markers CD3 (500A2), CD8a (S3-6.7), CD11b (M1/70), CD19 (1D3), NK1.1 (PK136), GR1 (RB6-8C5), TCRβ (H57-597), TCRγδ (GL3), TER119, and CD11c (HL3) and directly labeled antibodies against specific cell surface molecules. Lin− cells were retrieved by depletion into young (6–12 wk old), untreated IL-7Rα−/− recipient mice. CD3ε−/− recipient mice were injected i.v. into young (6–12 wk old), untreated IL-7Rα−/− recipients (competitive competition). We injected each of three recipients with 6 × 10^3 Lin− females. In the first experiment, we injected each of three recipients with 8 × 10^3 Lin− males. In the second experiment, we injected each of four recipients with 8 × 10^3 Lin− males. In the third experiment, we injected each of four recipients with 8 × 10^3 Lin− males.

Online supplemental material. Fig. S1 shows a comprehensive cytofluorometric characterization of pTαCre reporter−positive cells residing within the splenic and lymph node CD3−/CD19− population. Fig. S2 depicts the sorting strategy and postsort data for tester and competitor cell subsets, which were used as donor populations for thymic reconstitution of IL-7Rα−/− recipients (competitive complementation assay). Table S1 describes all antibodies used for flow cytometry. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20122609/DC1.

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