Mammalian Target of Rapamycin Complex 2 Regulates Invariant NKT Cell Development and Function Independent of Promyelocytic Leukemia Zinc-Finger

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Mammalian Target of Rapamycin Complex 2 Regulates Invariant NKT Cell Development and Function Independent of Promyelocytic Leukemia Zinc-Finger

Nicolas Prevot,* Kalyani Pyaram,* Evan Bischoff,* Jyoti Misra Sen,† Jonathan D. Powell,‡ and Cheong-Hee Chang* The mammalian target of rapamycin (mTOR) senses and incorporates different environmental cues via the two signaling complexes mTOR complex 1 (mTORC1) and mTORC2. As a result, mTOR controls cell growth and survival, and also shapes different effector functions of the cells including immune cells such as T cells. We demonstrate in this article that invariant NKT (iNKT) cell development is controlled by mTORC2 in a cell-intrinsic manner. In mice deficient in mTORC2 signaling because of the conditional deletion of the Rictor gene, iNKT cell numbers were reduced in the thymus and periphery. This is caused by decreased proliferation of stage 1 iNKT cells and poor development through subsequent stages. Functionally, iNKT cells devoid of mTORC2 signaling showed reduced number of IL-4-expressing cells, which correlated with a decrease in the transcription factor GATA-3-expressing cells. However, promyelocytic leukemia zinc-finger (PLZF), a critical transcription factor for iNKT cell development, is expressed at a similar level in mTORC2-deficient iNKT cells compared with that in the wild type iNKT cells. Furthermore, cellular localization of PLZF was not altered in the absence of mTOR2 signaling. Thus, our study reveals the PLZF-independent mechanisms of the development and function of iNKT cells regulated by mTORC2.

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Abbreviations used in this article: 7-AAD, 7-aminoactinomycin D; BM, bone marrow; CATtg, β-catenin transgenic; iNKT, invariant NKT; KO, knockout; mTOR, mammalian target of rapamycin; mTORC1, mTOR complex 1; PLZF, promyelocytic leukemia zinc-finger; WT, wild type.

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mTORC2 REGULATES iNKT CELL DEVELOPMENT AND FUNCTION

Rictor antibodies (trimethoprim-sulfamethoxazole) and were fed autoclaved food. under pathogen-free conditions before and after BM transplantation. After 1 wk, recipient mice were euthanized and thymi were processed to obtain primary cell suspensions. In vivo BrdU incorporation

Materials and Methods

Mice

C57BL/6Ncr were purchased from the National Cancer Institute (01C55), and mice deficient in Rictor in T cells (RictorCΔCre/ΔCre) have been described previously (24). Bone marrow chimera mice

Bone marrow chimera mice

mice deficient of TSC1, an mTORC1 suppressor, iNKT population is reduced in size. Although one study depicted a massive apoptosis during the iNKT cell lineage expansion (19) in the deficient mice, the other study reported defective terminal iNKT cell differentiation and predominance of NK-1 effector lineage over NKT-17 (20). TSC1 also promotes iNKT cell anergy in response to Ag stimulation (21). More direct evidence was provided by two recent independent studies that used mice deficient in Raptor that is a component of mTORC1 complex (22, 23). These impairments were associated with a defect in the nuclear localization of PLZF. Given the fact that the two mTOR complexes work as a two-signal system and with studies demonstrating a critical role for mTORC1 in iNKT cell development, the question that arises is whether mTORC2 plays a similar role for iNKT cell maturation. It is especially of great interest because at the opposite of mTORC1, upstream events of mTORC2 are yet to be defined. This study reveals an important role of mTORC2 for iNKT cell development. We demonstrate in this study that, in the absence of Rictor that is a component of mTORC2, iNKT cell numbers were decreased in a cell-intrinsic manner. Unlike mTORC1 deficiency, mTORC2 is required for the proliferation of iNKT cells at the stage 1 to progress to the next stage. Moreover, IL-4-expressing iNKT cells were reduced in Rictor-deficient iNKT cells, which is likely caused by a reduction in the expression of transcriptional factor GATA-3. Surprisingly, neither the expression level nor the cellularity of iNKT cells was also observed (22, 23). These impairments were associated with a defect in the nuclear localization of PLZF. Given the fact that the two mTOR complexes work as a two-signal system and with studies demonstrating a critical role for mTORC1 in iNKT cell development, the question that arises is whether mTORC2 plays a similar role for iNKT cell maturation. It is especially of great interest because at the opposite of mTORC1, upstream events of mTORC2 are yet to be defined. This study reveals an important role of mTORC2 for iNKT cell development. We demonstrate in this study that, in the absence of Rictor that is a component of mTORC2, iNKT cell numbers were decreased in a cell-intrinsic manner. Unlike mTORC1 deficiency, mTORC2 is required for the proliferation of iNKT cells at the stage 1 to progress to the next stage. Moreover, IL-4 expressing iNKT cells were reduced in Rictor-deficient iNKT cells, which is likely caused by a reduction in the expression of transcriptional factor GATA-3. Surprisingly, neither the expression level nor the cellularity of iNKT cells was decreased in Rictor-deficient iNKT cells. Therefore, we report that mTORC2 regulates iNKT cell development independent of PLZF.

In vitro stimulation assay

Freshly isolated cells (105 cells) were stimulated with 50 ng/ml PMA (Sigma-Aldrich) and 500 ng/ml ionomycin (Sigma-Aldrich) for 5 h in the CO2 incubator in FACS tubes with loosened caps. Monensin (Sigma-Aldrich) at a final concentration of 3 μM was added during the last 3 h of stimulation. Cells were then washed twice in FACS buffer (2% FBS, 1% PBS), and stained for flow cytometry analysis as described earlier.

In vivo BrdU incorporation

Mice were injected i.p. with 0.3 ml of 1 mg/ml BrdU solution (Sigma) every 4 h for three times. Eighteen hours after the last injection, mice were euthanized and thymi were processed to obtain primary cell suspension as described earlier. After surface staining, cells were stained for BrdU incorporation using BrdU flow kit (BD Biosciences), as per manufacturer’s instructions.

Apoptosis assay

Apoptosis rate of freshly isolated thymic cells was studied by flow cytometry using a PE-conjugated Annexin V Ab and Apoptosis Detection Kit (eBioscience), following the manufacturer’s recommendation.

Statistical analysis

Data for all experiments were analyzed with Prism software (GraphPad, San Diego, CA). Unpaired Student t test was used for comparison of experimental groups. The following p values were considered statistically significant: \( p < 0.05 \), \( * p < 0.01 \), and \( ** p < 0.001 \).

Results

Rictor controls T cell development

To study the role of mTORC2 in iNKT cell development, we used Rictor conditional KO mice (RictorCΔCre/ΔCre) designated T-RictorCΔCre/ΔCre) that were previously reported (9). CD4 promoter-driven Cre was used to study the effect of Rictor deficiency during T cell development. We first measured the total cell numbers in the thymus and the spleen from T-RictorCΔCre/ΔCre mice and compared them with the wild type (WT) mice. We observed decreased cell numbers in the thymus, but not in the spleen of T-RictorCΔCre/ΔCre mice compared with the WT mice (Fig. 1A). We then assessed and compared the...
subsets of thymocytes between the T-Rictor−/− and WT mice by analyzing the percentages and cell numbers of DN, DP, SPCD4, and SPCD8 cells. Interestingly, although the percentages of thymic DP, SPCD4, and SPCD8 were comparable between the two groups (Fig. 1B, 1C), careful examinations of these subpopulations revealed that the total cell numbers of thymic DP and SPCD4 T cells were significantly lower in the T-Rictor−/− mice (Fig. 1C). Next, we calculated and compared the selection efficiency of SPCD4 and SPCD8 cells using the ratio of the percentages of cells of interest to the percentages of DP (Fig. 1D). A ratio of 1 would indicate the equivalent selection efficiency between T-Rictor−/− and WT cells. The data demonstrated that Rictor plays a modest role for SPCD4 T cell development, whereas SPCD8 T cell development was not affected in T-Rictor−/− mice.

**Rictor is important for iNKT cell development and homeostasis**

Next, we assessed iNKT cell development in Rictor-deficient mice. We compared the iNKT cell compartment in the thymus, spleen, and liver between the T-Rictor−/− and WT mice. The percentages as well as the cell numbers of CD1d-tetramer+ iNKT cells were greatly reduced in the T-Rictor−/− thymus (Fig. 2A, 2B). In contrast with the conventional T cells for which the developmental defect is limited to the thymus, both the percentages and the cell numbers of iNKT cells were significantly decreased in the spleen as well as in the liver of the T-Rictor−/− mice (Fig. 2A, 2B).

![FIGURE 1. Rictor controls T cell development.](http://www.jimmunol.org/)

**Cell-intrinsic defect of Rictor-deficient iNKT cells**

To study whether the developmental defect of Rictor KO iNKT cells is cell intrinsic, we performed mixed BM chimera experiments. Equal proportions of Rictor KO (CD45.2) BM cells were transferred together with WT (CD45.1/CD45.2) BM cells to irradiated hosts (CD45.1) and analyzed for T cell development. Rictor KO cells were poorly reconstituted in the thymus as shown by the percentages and the recovery of total cells from each donor (Fig. 3A). We then compared the iNKT compartment in the thymus, spleen, and liver. Very few iNKT cells from Rictor KO donor were detected in the thymus, as well as in the spleen or liver of the chimeric mice (Fig. 3B). Moreover, similar to our observations from Rictor KO mice, the thymic selection efficiency was lowest for iNKT cells followed by CD4 T cells, whereas the efficiency of Rictor KO CD8 T cells was slightly reduced (Fig. 3C). Together, our data demonstrate that Rictor controls iNKT development in a cell-intrinsic manner.

**Rictor is required for optimum proliferation of stage 1 iNKT cells**

A reduced thymic iNKT cell output in the absence of Rictor could be explained by at least two independent and nonexclusive possibilities. First, Rictor-deficient cells might undergo a higher rate of spontaneous apoptosis. Alternatively, iNKT lineage expansion is reduced in the absence of Rictor. To test these two possibilities, we first assessed apoptotic cell death by staining cells for Annexin V and 7-aminoactinomycin D (7-AAD). In WT mice, the most immature stage 0 iNKT cells showed greater cell proportion that underwent apoptosis (Annexin V− 7-AAD−) than stages 1–3 (Fig. 4A). Although the percentages of apoptotic immature iNKT cells, namely, stage 0 cells, were slightly lower in the T-Rictor−/− mice, the difference was not statistically significant (Fig. 4A). T-Rictor−/− iNKT cells in stages 1–3 had comparable fractions of apoptotic cells to the WT iNKT cells. Furthermore,
both WT and T-Rictor\(^{-/-}\) iNKT cells showed similar proportions of apoptotic cells after stimulation with anti-CD3, suggesting that cell death was not altered in T-Rictor\(^{-/-}\) mice (data not shown). Overall, our data suggest that an increased rate of spontaneous apoptosis in absence of functional mTORC2 is unlikely to explain the reduced iNKT population observed in T-Rictor\(^{-/-}\) mice.

We next measured the proliferation capacity of T-Rictor\(^{-/-}\) cells by using two approaches. First, we measured the expression of Ki-67 in each stage of cells to assess the cell-cycling activity reflecting proliferation. It is reported that stage 1 iNKT cells undergo high proliferation, whereas the fully mature Stage 3 cells are quiescent in the absence of stimuli (11, 25). Consistent with the reported studies, our data demonstrated that most of the stage 0 iNKT cells from WT mice were Ki-67\(^+\), indicating that they were in an active phase of their cell cycle (Fig. 4B). As iNKT cells matured, a significant fraction of cells became Ki-67\(^+\) and stage 3 cells were mostly Ki-67\(^-\). T-Rictor\(^{-/-}\) iNKT cells showed a similar pattern of Ki-67\(^+\) cells except that stage 1 cells had a significant reduction of Ki-67\(^+\) cells compared with WT (Fig. 4B, 4C), indicating that the stage 1 iNKT cells in T-Rictor\(^{-/-}\) mice might undergo decreased rates of proliferation. To further confirm this difference in cell-cycling activity, we performed in vivo BrdU incorporation experiments. Consistent with the Ki-67 data, stage 1 iNKT cells from the T-Rictor\(^{-/-}\) thymus showed a significantly lower percentage of BrdU\(^+\) cells than those from the WT thymus (Fig. 4D). Thus, these results indicate that Rictor is important for

**FIGURE 2.** Stage-specific defect in NKT cell development in T-Rictor\(^{-/-}\) mice. (A) Representative TCR\(^{\beta}\) and CD1d tetramers profiles of cells from the thymus, spleen, and liver were compared between T-Rictor\(^{-/-}\) (KO) and WT mice. Numbers in the dot plots indicate the percentages of iNKT cells. (B) Summary of iNKT cell percentages (top) and numbers (bottom) in indicated tissues. (C) Representative CD1d tetramers and CD24 profiles of total thymocytes derived from KO and WT thymus (left). CD24\(^+\) cells were further analyzed for stages 1–3 using CD44 and NK1.1 (right). (D) The percentages and cell numbers of iNKT cells at each stage were shown. (E) Selection efficiency of stage 0 cells from DP. Numbers of stage 0 (S0) cells were divided by the numbers of DP from WT and KO mice. (F) Stage-specific cell generation. Cell numbers of each stage were divided by the numbers of the previous stage. S0, S1, S2, and S3 indicate stages 0, 1, 2, and 3, respectively. Inset shows S1/S0. Data shown are mean \(\pm\) SEM from 12 pairs of mice. *\(p < 0.05\), **\(p < 0.01\), ***\(p < 0.001\), ****\(p < 0.0001\).
stage 1 iNKT cells to proliferate and progress to stage 2 during iNKT cell maturation.

It is known that Wnt signaling pathway functions similarly to mTOR and overexpression of active dephosphorylated form of β-catenin leads to a significant increase in iNKT cells (26). This raises a question whether Wnt and mTOR signaling may regulate each other so that constitutively active Wnt signaling may restore the defect of T-Rictor−/− iNKT cell development. To test this, we crossed T-Rictor−/− mice with the transgenic mice expressing active dephosphorylated form of CATtg, resulting in CATtg3 KO. We found that iNKT cell development in CATtg3 KO mice was not rescued (Supplemental Fig. 1), suggesting that mTORC2 and Wnt signaling pathway seem to work independent of each other.

Rictor regulates the generation of iNKT cells expressing IL-4, but not IFN-γ or IL-17

Having observed that the iNKT cell maturation is controlled by mTORC2, we next asked whether the Rictor deficiency also affects the effector function of iNKT cells. iNKT cells are defined by their ability to secrete various cytokines like IL-4, IFN-γ, and IL-17. In addition, previous studies have demonstrated that cytokine production varies with thymic iNKT cell development, and these cells produce different cytokines at maximum levels at different developmental stages (27–29). Rictor/mTORC2 has been shown to be important for Th2 cell differentiation, but not for Th1 or Th17 phenotypes in conventional CD4 T cells. We therefore asked whether Rictor also regulates the generation of IL-4–expressing iNKT cells. To test this, we stimulated thymocytes including the thymic iNKT cells with PMA and ionomycin; then the expression of IL-4, IFN-γ, and IL-17 was measured by intracellular cytokine staining. Assessment of the cytokine expression showed that IL-4– but not IFN-γ– or IL-17–expressing cells were decreased in iNKT cells from T-Rictor−/− mice compared with that in WT iNKT cells (Fig. 5).

Considering cytokine expression has been reported to be maturation dependent, we further assessed the cytokine production at each stage of iNKT cells. IL-4–expressing cells were reduced in all the stages of iNKT development in the T-Rictor−/− mice compared with the WT mice, whereas a modest decrease in IFN-γ–expressing
cells was observed only in stage 2 T-Rictor−/− iNKT cells (Supplemental Fig. 2). Highest levels of IL-17 were produced by stage 2 cells in both the strains and interestingly, a significantly higher percentage of IL-17+ stage 2 iNKT cells was observed in T-Rictor−/− mice. However, stage 2 cells represent a very small fraction of total iNKT cells; therefore, overall IL-17 expression pattern was comparable between WT and T-Rictor−/− mice. Together, our data on the cytokine expression indicate that Rictor primarily controls the differentiation of IL-4-expressing iNKT cells.

It is known that PLZF is the most critical transcription factor for the development as well as IL-4 expression of iNKT cells as illustrated in PLZF−/− mice (12). In addition, PLZF overexpression was shown to induce IL-4 production in CD4 T cells (30). Therefore, we asked whether Rictor controls the expression of PLZF, which, in turn, affects iNKT cell development and IL-4 expression. Expression of PLZF in total iNKT cells as well as at each stage of iNKT cell development showed that the absence of Rictor did not interfere with the expression of PLZF (Fig. 6A). However, it is possible that PLZF function may be compromised in the absence of Rictor. In fact, PLZF localization, but not the expression level, was found to be affected in mTORC1-deficient iNKT cells (22). We found that the cellular distribution of PLZF was similar between the WT and T-Rictor−/− iNKT cells, which was mostly confined to the nucleus (Fig. 6B). Thus, unlike mTORC1 deficiency, absence of Rictor does not affect either the PLZF expression or its nuclear localization.

It is known that the transcription factors T-bet, GATA-3, and RAR-related orphan receptor γt (RORγt) control the differentiation of Th1, Th2, and Th17 cells, respectively. Furthermore, the same transcription factors are expressed in iNKT cells generating functionally distinct iNKT cells (31). Therefore, we compared the expression of T-bet, GATA-3, and RORγt. There was no difference in RORγt- or T-bet-expressing cell populations between the two groups (Fig. 6C). However, the frequencies of GATA-3-expressing iNKT cells were significantly lower among the T-Rictor−/− iNKT cells than the WT cells (Fig. 6C, 6D). Therefore, the reduction in GATA-3-expressing iNKT cells in T-Rictor−/− mice correlated with less IL-4+ iNKT cells observed. Together, Rictor controls the generation of GATA3-expressing iNKT cells, which, in turn, is responsible for differentiation of IL-4-producing cells.

Discussion

In this study, we reveal a critical role of mTORC2 in the iNKT development and maturation. We observed that, in the absence of functional mTORC2 due to Rictor deficiency in the T cells, early iNKT cell development is impaired in the thymus as well as in the peripheral organs including the spleen and the liver. Although

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**FIGURE 5.** Rictor controls the generation of IL-4-expressing iNKT cells. (A) Total thymocytes including thymic iNKT cells were stimulated for 5 h as described in the Materials and Methods. IL-4 and IFN-γ (left) and IL-17 and IFN-γ (right) expression from total NKT cells are shown. Numbers in the dot plots indicate the percentages of corresponding quadrants. (B) Summary of iNKT cells expressing indicated cytokines. Data shown are mean ± SEM from seven pairs of mice. **p < 0.01.

**FIGURE 6.** Reduction of GATA-3-expressing iNKT cells in the absence of Rictor. (A) Intracellular PLZF expression in each stage of thymic iNKT cells was compared. (B) Intracellular PLZF (red) staining of FACS-sorted thymic iNKT cells from WT and T-Rictor−/− mice. Nuclei were stained with DAPI (blue). (C) PLZF, RORγt, T-bet, and GATA-3 expression were analyzed in thymic iNKT cells, and (D) summary of cells expressing GATA-3 is shown. Data shown are mean ± SEM from three pairs of mice. **p < 0.01.
mTORC1 deficiency also results in reduced iNKT cell numbers, mTORC1 and mTORC2 appear to play a different role during iNKT cell development. In mTORC1-deficient mice, the percentage of stage 0 and 1 iNKT cells are higher, whereas the percentage of stage 3 iNKT cells were greatly reduced (22, 23). In contrast, we observed that iNKT cells from T-Rictor−/− mice display a stage 1–specific defect in proliferation. T-Rictor−/− iNKT cells showed the higher percentage of stage 1 cells, but significantly lower level of stage 2 cells compared with the WT. Stage 3 cells were comparable between the two groups of mice.

This indicates that the initial stages of iNKT development require both mTORC1 and mTORC2, and as cells mature, mTORC2 is especially critical for the transition from stage 1 to stage 2. Interestingly, more mature long-term resident thymic stage 3 iNKT subset seems to depend solely on mTORC1 for their survival. This differential dependence on the two mTOR complexes by the different developmental stages of iNKT cells may be dictated by their different metabolic needs as they proceed through the maturation process, thus changing their responsiveness to either mTORC1 or mTORC2. A more striking difference was revealed with PLZF. Unlike mTORC1-deficient NKT cells in which PLZF nuclear localization was impaired, we observed no difference either in the expression level or the cellular localization of PLZF in iNKT cells deficient of Rictor. Thus, mTORC1 and mTORC2 control the iNKT cell development and maturation by mechanisms dependent and independent of PLZF, respectively.

Nevertheless, there appear to be similarities between mTORC1- and mTORC2-mediated iNKT cell development. Both mTORC1 and mTORC2 indeed incorporate upstream proliferation signals, and thus promote the cell-cycle activity and cell proliferation (Fig. 4). Deficiency in either mTORC1 or mTORC2 would lead to poor proliferation. Interestingly, we report in this article that lack of functional mTORC2 induces a greater developmental defect in iNKT cells than in conventional CD4 and CD8 T cells. Given the fact that iNKT lineage cells undergo two consecutive rounds of expansion in the thymus (DN-to-DP transition and then stage 0 to stage 2 for iNKT commitment) to become fully mature and functional cells, it is not surprising that iNKT cells rely more on mTORC1 and mTORC2 signaling. Conventional CD4 T cells, in contrast, undergo the second round of expansion during differentiation into the Th cell subsets in the periphery. During this differentiation and expansion stage, the two mTOR complexes have been shown to be requisite regulators for different Th cell lineage numbers and function.

It is well established that mTORC1 and mTORC2 signals promote Th1 and Th2 responses, respectively, in conventional CD4 T cells (9). Unlike conventional CD4, Th cell differentiation programming that is initiated upon Ag exposure in the periphery, iNKT cells express cytokines during their differentiation and maturation in the thymus (27). It is known that stage 1 cells express IL-4; then both IL-4 and IFN-γ are produced by more mature stage 2 and 3 cells. Therefore, decreased stage 1 cell proliferation would lead to the reduction of IL-4+ but not IFN-γ+ cells, which we have shown in this study. In line with this assumption, absence of functional mTORC2 in iNKT cells greatly decreases IL-4+ cells, particularly in stages 2 and 3 (Fig. 5 and Supplemental Fig. 1). A recent study proposed simultaneous generations of three effector types of NKT cells, which are designated NKT1, NKT2, and NKT17 (31). According to this new model, mTORC2 signaling is important for the differentiation of NKT2, but not NKT1 and NKT17, which mirrors the requirement of mTORC2 signaling for Th2 but not Th1 or Th17 cells. The main difference is that development and effector iNKT cell generation is tightly linked and occurs in the thymus.

In conclusion, mTORC2, together with mTORC1, is an indispensable modulator of iNKT cell development and function by promoting the active proliferation during iNKT cell maturation in the thymus. Further studies to identify signaling molecules and pathways that regulate the mTOR complexes should shed light on the molecular mechanisms to control iNKT cell development.

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Disclosures

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