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The highly conserved self-degradation pathway known as autophagy plays important roles in regulating T lymphocyte homeostasis. Recently, we found that T lymphocytes lacking the autophagy-related gene Atg5 or Atg7 have defective survival and contain expanded mitochondria and endoplasmic reticulum (ER); however, whether these defects are caused by impaired autophagy or by defects in their autophagy-independent signaling pathway of Atg5 or Atg7 in T lymphocytes remains unknown. Furthermore, the function of the microtubule-associated protein L chain 3 (LC3) conjugation system in T lymphocytes remains unclear. To address these questions, we generated conditional knockout mice with specific deletion of Atg3, a ubiquitin enzyme E2-like molecule involved in the LC3 conjugation system, in T lymphocytes. Atg3-deficient T lymphocytes displayed a phenotype similar to those of Atg7- and Atg5-deficient T cells. The survival of Atg3-deficient naïve CD4+ and CD8+ T cells was defective. Furthermore, the mitochondria and ER were expanded in Atg3-deficient T cells. Interestingly, mitochondrial and ER content did not change instantly upon inducible deletion of Atg3 in mature T lymphocytes in vitro. Instead, it began to expand 10 d after inducible deletion of Atg3 in mature T lymphocytes, and mitochondrial content continued to increase on day 18. Cell death began to increase 24 d after inducible deletion of Atg3. These data show that the LC3 conjugation system is essential for autophagy in T lymphocytes. Our data suggest that autophagy promotes T lymphocyte survival by regulating organelle homeostasis and that the decreased survival of autophagy-deficient T cells is due to the temporal accumulation of these autophagy-related defects. The Journal of Immunology, 2011, 186: 000–000.
Atg5- and Atg7-deficient T cells are due to impairments in autophagy machinery or in the signaling capacity of the Atg5/Atg7 molecules and to further investigate the functions of the LC3 conjugation system in T lymphocytes, we generated Atg3 conditional knockout mice.

In this study, we show that the autophagy pathway is impaired in Atg3-deficient T lymphocytes. Survival is defective and organelle homeostasis is abnormal in Atg3-deficient T cells. Furthermore, we use an inducible deletion system to demonstrate a temporal accumulation of mitochondria and ER beginning 10 d after the deletion of Atg3. Accordingly, we show that cell death does not begin to increase until >3 wk after deletion of Atg3. Our results demonstrate that the LC3 conjugation system is indispensable for autophagy in T lymphocytes. We also show that autophagy regulates organelle homeostasis and is essential for T cell survival. Importantly, our findings provide clear evidence that the phenotype of autophagy-deficient T cells is due to the temporal accumulation of autophagy-related defects.

Materials and Methods

Generation of Atg3 conditional knockout mice

The bacterial artificial chromosome clone RP23-444N1, which contains the Atg3 genomic sequence, was obtained from BACPAC Resources Center at Children’s Hospital Oakland Research Institute (Oakland, CA) and was used as a template to clone the genomic fragments long arm (LA), short arm (SA), and exon fragment (Exon) by PCR. The exon fragment is flanked by two loxP sites, allowing for deletion in Cre-expressing cells at the genomic level. The primer sequences are as follows: LA forward primer with SacII restriction site, 5′-GCCCGGGGCTCCTGACTCA-TAAGCTCAGACACCAACAGTA-3′; LA reverse primer with NotI restriction site, 5′-GGCGGCGCCGGCACTTTGGTCTTCCATAGAAGGCTC-3′; Exon forward primer with Smal restriction site, 5′-GCCGGGTTTATTAATTCTAGAAAGAAAGATCATGCTACT-3′; Exon reverse primer with SalI restriction site, 5′-GCCCCGGGTGTTTATTAAATTTCAAGAAGAAAAAGATCATGCTACT-3′; and SA forward primer with SalI restriction site, 5′-GCGTCGACAGTAAAAGAAAATT-TTACTTATAAGAAGAAAAGATCATGCTACT-3′; and SA reverse primer with SalI restriction site, 5′-GCGTCGACGGGTGTCTTATGCTAGAAAGATCATGCTACT-3′. PCRs were performed using BIO-X-ACT Long DNA Polymerase (Bioline, Taunton, MA). All cloned fragments were inserted into the pGKneoF2L2DTA targeting vector (26). The resulting pGKneoF2L2DTA-Atg3 construct was sequenced. Three mutations were found in the Exon or SA fragments. EF1 embryonic stem (ES) cell clones were screened for homologous recombination at the Atg3 genomic locus by PCR. The primers used for screening are as follows: forward Atg3 screening primer F4500, 5′-CGATGGCATCTTATGCTGAGCAATG-3′; and reverse Atg3 screening primer R450, 5′-TTCATGGGACATGATATTTTTCTGCTGAC-3′. This pair of primers was later used to screen the Atg3 f/+ or Atg3f/f mice. The targeted ES clone 3D11 was amplified by PCR using forward primer FE8, 5′-CTCTATGGCTTCTGAGGCGGAAAGA-3′, to amplify a 313-bp product from the genomic DNA was extracted. The fragment from Atg3 exon 8 and exon 9 was amplified by PCR using primers RE9, 5′-AGAAGAAAAGATTCTTATGCT-3′, and reverse primer R2 and further confirmed by PCR using primers F4500 and R450. The DNA gel shows results from the PCR using primers F4500 and R450 using ES cell genomic DNA as templates (left panel). The right panel shows PCR screening results using genomic DNA from mouse tails as templates. The PCR product of floxed Atg3 is 866 bp, and the PCR product of wild-type Atg3 is 748 bp. The PCR product of floxed Atg3 is 866 bp, and the PCR product of wild-type Atg3 is 748 bp. C. Deletion efficiency in Atg3 f/fLck-Cre mice. The expression of Atg3 in T cells was analyzed by Western blot. Samples of thymocytes or enriched T cells from Atg3 f/fLck-Cre mice were sorted by flow cytometry to >98% purity, and genomic DNA was extracted. The fragment from Atg3 exon 8 and exon 9 was amplified by PCR using primers FEB and R9. Atg7 exon 14 PCR was used as a control. D. The expression of Atg3 in T cells was analyzed by Western blot. Samples of thymocytes or enriched T cells from Atg3 f/fLck-Cre and Atg3 f/f control mice are shown in the left panel. The right panel shows 4-OHT–treated splenocytes from Atg3 f/fLck-Cre and Atg3 f/f control mice. The numbers at the right side represent Mr of protein markers. +, Nonspecific bands. DT, dihydrothiazole; E, exon; F, flippanse recognition target (FRT); L, loxP; x, Xbal restriction site.

Flow cytometry analysis

The phenotype of Atg3 f/fLck-Cre mice was analyzed in sex- andagematched 5–8-wk-old mice. Thymus, lymph node (LN), and spleen were isolated from Atg3 f/fLck-Cre mice and Atg3 f/f wild-type control mice, and CD4+ and CD8+ cells were sorted by flow cytometry to >98% purity, and genomic DNA was extracted. The fragment from Atg3 exon 8 and exon 9 was amplified by PCR using primers FEB and R9. Atg7 exon 14 PCR was used as a control. The expression of Atg3 in T cells was analyzed by Western blot. Samples of thymocytes or enriched T cells from Atg3 f/fLck-Cre and Atg3 f/f control mice are shown in the left panel. The right panel shows 4-OHT–treated splenocytes from Atg3 f/fLck-Cre and Atg3 f/f control mice. The numbers at the right side represent Mr of protein markers. +, Nonspecific bands. DT, dihydrothiazole; E, exon; F, flippanse recognition target (FRT); L, loxP; x, Xbal restriction site.
cell suspensions were prepared. RBCs were lysed with ACK buffer. Thymocytes were suspended in anti-Fc receptor Ab supernatant (2.4G2) and stained with anti-CD4-PE, anti-CD8-FITC, and 7-aminomycin D (7-AAD) (BD Pharmingen, San Jose, CA). For analysis of double-negative (DN) thymocytes, thymocytes were stained with anti-CD4–allophycocyanin, anti-CD8–allophycocyanin, anti-CD4–allophycocyanin, anti-CD4–FITC, anti-CD25–PE, and 7-AAD. Spleenocytes and LN cells were suspended in 2-4G2 supernatant and stained with anti-CD4–PE, anti-CD8–FITC, and 7-AAD. Alternatively, spleenocytes or LN cells were stained with anti-CD4–allophycocyanin (or anti-CD8–allophycocyanin), anti-CD62L–PE, anti-CD4–FITC, and 7-AAD on ice for 15 min. Cells were then washed, and the samples were analyzed by flow cytometry using FACScan, FACStar Plus, or FACSCanto flow cytometers (BD Biosciences). All Abs were from Biolegend (San Diego, CA) or eBioscience (San Diego, CA).

**Autophagy analysis**

Splenocytes from Atg3f/fLck-Cre and Atg3f/f mice were stimulated with anti-CD3 mAb (2C11; 5 μg/ml) or cultured in RPMI 1640 medium overnight. The CD3 activated and unstimulated control T cells were stained with anti-CD4–FITC or anti-CD8–FITC. After washing, the cells were treated with 0.1% saponin (Sigma-Aldrich, St. Louis, MO) in PBS containing 0.5% BSA for 10 min on ice and then intracellularly stained with rabbit anti-LC3 Ab (MBL International, Woburn, MA) for 30 min on ice. After washing, anti-rabbit–Cy3 Ab (Jackson ImmunoResearch Laboratories, West Grove, PA) was added and incubated on ice for another 30 min. Z-stack images were acquired at 1 μm apart using 100× oil objective by a Zeiss Axio Observer D1-based imaging station (Zeiss) equipped with a CoolSNAP HQ CCD camera (Roper Scientific, Tucson, AZ) and recorded with MetaMorph 7.6 software (Universal Imaging, West Chester, PA). Three-dimensional deconvolution of the images was performed using AutoQuant X software (Media Cybernetics Bethesda, MD). LC3 puncta of three-dimensional deconvolution images was quantified by MetaMorph 7.6 software (Universal Imaging). A 1.5× background fluorescence intensity was used to set up the threshold for the images of each cells. Only the pixel of the LC3 image, which is >4, was considered as an LC3 punctum. The numbers of LC3 puncta per cell were counted, and a total of 30 cells from each group were analyzed. Starvation was induced by culturing the splenocytes in HBSS (Invitrogen, Carlsbad, CA) overnight. Then, T lymphocytes were purified using a mouse T cell negative enrichment kit (StemCell Technologies, Vancouver, BC, Canada), and cell lysates were prepared for LC3 Western blot analysis.

**Electron microscopy analysis**

FACS-sorted CD4+ and CD8+ T cells from spleen and LN of Atg3f/fLck-Cre and Atg3f/f mice were fixed in 4% glutaraldehyde buffer overnight, and electron microscopy (EM) samples were prepared as described previously (20). Micrographs were taken with a Philips LS 410 electron microscope. The cytosol membrane structures were quantified and presented as the membrane score. The EM picture of each cell was divided into 12 equal sections according to a clock face. The membrane score was counted as each section containing membrane structure(s) for each cell.

**Apoptosis analysis**

The freshly isolated splenocytes were stained for surface markers using anti-CD4–allophycocyanin, anti-CD8–PE/Cy7, and anti-CD44–allophycocyanin Abs in 2.4G2 supernatant buffer overnight, and electron microscopy (EM) samples were prepared as described previously (20). Micrographs were taken with a Philips LS 410 electron microscope. The cytosol membrane structures were quantified and presented as the membrane score. The EM picture of each cell was divided into 12 equal sections according to a clock face. The membrane score was counted as each section containing membrane structure(s) for each cell.

**FIGURE 2.** Impaired autophagy in Atg3-deficient T cells. A and B, LC3 puncta formation in Atg3-deficient T cells. Splenocytes from Atg3f/fLck-Cre mice and Atg3f/f control mice were stimulated with anti-CD3 Ab or cultured in complete RPMI 1640 medium overnight. LC3 puncta were intracellularly stained with rabbit anti-LC3 Ab and Cy3-labeled donkey anti-rabbit Ab. Z-stack images were captured and spaced at 1 μm apart using 100× oil objective in a Zeiss Axio Observer D1-based imaging station (Zeiss). A total of 30 cells in each group were analyzed. Representative images were shown in A, and the numbers of LC3 puncta were quantified (cut off at pixel >4). C, The level of LC3 II in Atg3-deficient T cells under starvation condition. Splenocytes from Atg3f/fLck-Cre and Atg3f/f mice were cultured in HBSS in starvation (Starv) condition or complete medium overnight. The freshly isolated splenocytes were stained for surface markers using anti-CD4–allophycocyanin, anti-CD8–PE/Cy7, and anti-CD44–allophycocyanin Abs in 2.4G2 supernatant on ice for 15 min. Cells were then washed, resuspended in binding buffer, and stained with Annexin V-PE or Annexin V-FITC (BD Biosciences). Samples were analyzed using an FACSCanto flow cytometer (BD Biosciences). Caspase-9 activity was detected by fluorochrome inhibitor of caspases.

**FIGURE 3.** Thymocyte development in Atg3-deficient mice. A, Total of five Atg3f/fLck-Cre, three Atg3−/−Lck-Cre, and four Atg3f/f control mice. B, Thymocyte subpopulations in Atg3f/fLck-Cre mice. Thymocytes from Atg3f/fLck-Cre, Atg3−/−Lck-Cre, and Atg3f/f mice were stained with anti-CD4–FITC, anti-CD4–PE, and 7-AAD. The cells were gated on the 7-AAD– population. Numbers represent the frequency of each gated subpopulation. C, DN subpopulations in Atg3-deficient mice. Thymocytes from Atg3f/fLck-Cre, Atg3−/−Lck-Cre, and Atg3f/f mice were stained with anti-CD4–allophycocyanin, anti-CD8–allophycocyanin, anti-CD3–allophycocyanin, anti-CD44–FITC, anti-CD25–PE, and 7-AAD. The samples were gated on CD4+, CD8−, CD3−, and 7-AAD–negative cells. Numbers represent the frequency of each gated subpopulation. Both B and C flow cytometry analyses were repeated three times. *p = 0.018, **p = 0.031.
(FLICA) apoptosis detection kit (ImmunoChemistry Technologies, Blooming- 
ton, MN) according to the manufacturer’s instructions. Briefly, the spleno- 
cytes were incubated with caspase-9 FLICA (carboxyfluorescein [FAM]-LEHD-fluoromethyl ketone) at 37 °C for 30 min. After washing, the 
cells were further stained with surface markers as described above. The 
cells were analyzed by flow cytometry after another washing.

**In vitro inducible Atg3 deletion**

The splenocytes or LN cells from Atg3fl/fl ER-Cre or Atg3fl/fl control mice 
were cultured with 200 nM 4-hydroxytamoxifen (4-OHT; Sigma-Aldrich) 
for 3 d with IL-7 (1 ng/ml; PeproTech, Rocky Hill, NJ). For longer cul-
turings, 1 ng/ml IL-7 was added every other day, and the medium was 
changed when necessary.

**Mitochondria and ER staining**

Splenocytes from Atg3fl/fl Lck-Cre or 4-OHT–treated Atg3fl/fl ER-Cre spleno-
cytes and Atg3fl/fl control splenocytes were incubated with 100 nM Mito-
Tracker Green (Invitrogen, Molecular Probes) or 1 μM ER-Tracker Blue-
White DPX (Invitrogen, Molecular Probes) in RPMI 1640 medium at 37 °C 
for 30 min. Cells were washed with RPMI 1640 medium and then stained 
with anti-CD4–allophycocyanin, anti-CD8–PE/Cy7, anti-CD44–allophy-
cocyanin/Cy7, and 7-AAD. The geometric mean intensity of fluorescence 
was used to represent the volume of mitochondria or ER. The mitochon-
dria and ER of Atg3fl/fl ER-Cre splenocytes and Atg3fl/fl control splenocytes 
were analyzed on different days after 4-OHT treatment. The samples were 
analyzed using an FACScanto flow cytometer (BD Biosciences).

**Reactive oxygen species production analysis**

Splenocytes from Atg3fl/fl Lck-Cre mice or Atg3fl/fl control mice were in-
cubated with 2.5 μM dihydroethidium (DHE; Sigma-Aldrich) at 37 °C for 
1 h. Cells were washed and stained with anti-CD4–allophycocyanin and 
anti-CD8–FITC or anti-CD4–FITC. The mean fluorescence intensity of the 
PE channel represented the DHE staining activity. The samples were an-
alyzed using an FACStar flow cytometer (BD Biosciences).

**Western blot**

The T lymphocytes from Atg3fl/fl or Atg3fl/fl Lck-Cre mice were enriched 
using a mouse T cell enrichment kit (StemCell Technologies). Cell purity 
was determined by flow cytometry to be >95%. Total cell lysates were 
prepared in sample buffer (30 mM Tris-Cl [pH 6.8], 0.5% 2-ME, 2% SDS, 
0.2% bromophenol blue, and 10% glycerol). The samples were separated 
by SDS-PAGE and then transferred to Immobilon-FL polyvinylidene 
difluoride membranes (Millipore, Billerica, MA). Membranes were blocked 
with 5% nonfat milk and then incubated with primary Ab in PBS contain-
ing 3% BSA (Sigma-Aldrich) and 0.5% Tween 20 at 4°C overnight. The next day, the membranes were washed and incubated with Alexa Fluor 680-labeled anti-rabbit Ab (Invitrogen) or IRDye 800-labeled anti-goat Ab (Rockland Immunocchemicals, Gilbertsville, PA) at room temperature for 1 h in PBS containing 3% BSA and 0.5% Tween 20. The blots were visualized using the Odyssey Infrared Imaging System and analyzed using Odyssey software (LI-COR Biosciences, Lincoln, NE). Atg3 rabbit polyclonal Ab was from Sigma-Aldrich. Anti-actin Ab was from Santa Cruz Biotechnology (Santa Cruz, CA). Anti-LC3 Ab (anti-LC3A/B, strong reactivity with LC3A/B-11) was from Cell Signaling Technology (Danvers, MA).

**Proliferation assay**

The splenocytes from Atg3^{fl/fl} or Atg3^{fl/fl}Lck-Cre mice were incubated with 5 μM CFSE (Invitrogen) in 5% FCS-PBS for 5 min at room temperature. Cells were washed with 5% FCS-PBS three times and stimulated with soluble anti-CD3 (2C11; 5 μg/ml) or anti-CD3 plus anti-CD28 (2 μg/ml; Biolegend) for 72 h. The cells were then stained with anti-CD4–allophycocyanin, anti-CD8–allophycocyanin/Cy7, and 7-AAD in 2.4G2 supernatant on ice for 15 min. After washing, the samples were analyzed by flow cytometry. The 7-AAD-negative cells were gated and analyzed. Unstimulated cells were used to gate the CFSE-diluted cells.

**Statistical analysis**

Two-tailed Student t tests were used to compare the means of different samples.

**Results**

**Generation of Atg3 conditional knockout mice**

Our previous data from Atg5 knockout fetal liver transfer experiments and Atg7^{fl/fl}Lck-Cre mice suggested that autophagy is essential for T lymphocyte survival (25) and that autophagy mediates developmental regulation of organelle homeostasis (20, 21). Two ubiquitin-like pathways direct the process of autophagy, and the results from studying Atg5- or Atg7-deficient T lymphocytes may only reflect the requirement of one of these pathways in T lymphocyte survival. To investigate the function of the LC3 pathway in T lymphocytes, an Atg3 conditional knockout mouse line was generated. The gene encoding Atg3, which is located on chromosome 16, is 30,895 bp long, and the mRNA transcript is 2014 bp. Atg3 consists of 12 exons encoding 315 aas. Because another gene, named Slc35a5, oriented in the opposite direction is located 200 bp upstream of Atg3 on chromosome 16, the deletion of exon 1 of Atg3 may affect the function of this upstream gene. Atg3 is an E2-like molecule, and its E2-like conjugating enzyme active site cysteine is encoded by exon 10 (30). We thus chose to target the 1345 bp region beginning upstream of exon 8 and ending in the intron region downstream of exon 10 (Fig. 1A). The deletion of exon 8 to exon 10 results in an out-of-frame mutation in exon 11 and the introduction of a stop codon in exon 11. In total, this targeting strategy results in the deletion of ~100 aa.

As shown in Fig. 1A, two loxP sites were inserted upstream of exon 8 and downstream of exon 10. As a result, we expected a genomic deletion of 1345 bp of Atg3 in Cre-expressing cells. EF1 ES cells in which positive homologous recombination occurred between the targeting construct and the Atg3 genomic locus were selected by PCR screening for the loxP site downstream of exon 8 (Fig. 1B, left panel). The germline transmitted mice were screened and bred with FLPeR mice to delete the neomycin resistance cassette. Mice homologous for the floxed Atg3 allele (Atg3^{fl/fl}, Fig. 1B, right panel) were then bred with Lck-Cre mice to generate Atg3^{fl/fl}Lck-Cre mice, in which Atg3 is specifically deleted in T lymphocytes, or bred with ER-Cre mice to delete Atg3^{fl/fl}ER-Cre mice, in which Atg3 can be inducibly deleted. The efficiency of deletion of Atg3 was analyzed in sorted Atg3^{fl/fl}Lck-Cre CD4+ or CD8+ T lymphocytes by PCR amplification of the sequence from exon 8 and exon 9. The deletion efficiency was >90% in CD4+ T cells and >80% in CD8+ T cells at the genomic level (Fig. 1C). The deletion efficiency was further confirmed at the protein level by Western blot. Atg3 protein was absent in Atg3^{fl/fl}Lck-Cre thymocytes and purified Atg3^{fl/fl}Lck-Cre splenic naive T cells (Fig. 1D, left panel). Furthermore, in the Atg3^{fl/fl}ER-Cre inducible deletion model, Atg3 was efficiently deleted in Atg3^{fl/fl}ER-Cre splenocytes upon treatment with 4-OHT for 3 d (Fig. 1D, right panel). Together, these data demonstrate the successful generation of T lymphocyte-specific (Atg3^{fl/fl}Lck-Cre) and inducible (Atg3^{fl/fl}ER-Cre) models of deletion of Atg3.

**Atg3 is essential for autophagy in T lymphocytes**

Our previous data showed that TCR stimulation induces autophagy in T lymphocytes (20). To determine whether the autophagy pathway remains intact or is impaired in Atg3-deficient T cells, splenocytes from Atg3^{fl/fl}Lck-Cre and control mice were stimulated with anti-CD3, and LC3 puncta were quantified by intracellular staining using anti-LC3 Ab. The number of LC3 puncta in CD3-stimulated Atg3-deficient CD4+ T cells was much lower than that in control CD4+ T cells (Fig. 2A, 2B). Similar results were observed in Atg3-deficient CD8+ T lymphocytes (data not shown).

**FIGURE 5. Survival defect in Atg3-deficient T cells.** A, Freshly isolated splenocytes from Atg3^{fl/fl}Lck-Cre and Atg3^{fl/fl} control mice were stained with anti-CD4–allophycocyanin, anti-CD8–PE/Cy7, anti-CD4–FITC, Annexin V-PE, and 7-AAD. Annexin V and 7-AAD staining was analyzed in CD4+ and CD8+ subpopulations. B, Increased caspase-9 activity in Atg3-deficient T cells. Splenocytes from Atg3^{fl/fl}Lck-Cre and Atg3^{fl/fl} mice were incubated with caspase-9 FLCIA and analyzed by flow cytometry. The cells were gated on CD4+ T cell population. Data are representative of three experiments. C, Survival defect in Atg3-deficient T cells is partially rescued by zVAD. Splenocytes from Atg3^{fl/fl}Lck-Cre and Atg3^{fl/fl} mice were cultured in RPMI 1640 medium containing 10% FBS with or without IL-7 (1 ng/ml) or IL-7 in combination with zVAD (20 μM) for 48 h. The cells were stained with anti-CD4–allophycocyanin, anti-CD8–FITC, anti-CD4–allophycocyanin/Cy7, and 7-AAD. The 7-AAD+ cells are dead cells (p < 0.05, zVAD treatment versus RPMI culture). CD44hi, CD44low; CD48hi, CD48low.
Consistent with the LC3 punctum formation results, the level of LC3 II was also reduced in Atg3-deficient T cells under starvation conditions (Fig. 2C).

It was reported that the LC3-binding protein p62/SQSTM1 is constantly degraded by the autophagy pathway and accumulates in autophagy-deficient cells (31, 32). p62 was accumulated in Atg3-deficient T lymphocytes, whereas Atg3 wild-type naive T cells expressed background levels of p62 (Fig. 2D). The ultrastructure of Atg3-deficient T cells was further analyzed by EM. EM pictures show that some membrane structures that are not characteristic of autophagosomes accumulated in Atg3-deficient T cells (Fig. 2E, 2F). The above results demonstrate that Atg3 is required for autophagy in T lymphocytes.

Atg3 is essential for T lymphocyte survival

Atg3/Lck-Cre mice appear similar to Atg3f/f littermates. No obvious abnormalities were found in Atg3f/f mice, suggesting that the mutations introduced in the targeting construct in the intron region between exon 7 and exon 8 do not affect the function of Atg3. The thymic cellularity of Atg3f/fLck-Cre mice was ~50% of that of Atg3f/f and Atg3f/+Lck-Cre mice (Fig. 3A); however, the frequencies of DN, double-positive, and single-positive thymocytes in Atg3f/f Lck-Cre mice were comparable to those in Atg3f/f control mice (Fig. 3B, 3C). These results suggest that the loss of Atg3 did not obviously alter thymocyte development. Together with our previous findings in Atg7f/fLck-Cre mice (20) and Atg5 knockout fetal liver transfer experiments (25), these results are

**FIGURE 6.** Abnormal organelle homeostasis in Atg3-deficient T cells. A–C. Mitochondria in Atg3-deficient T cells. Splenocytes from Atg3f/fLck-Cre and Atg3f/f control mice were incubated with 100 nM Mito-Tracker Green at 37°C for 30 min. After washing, the splenocytes were stained with anti-CD4-allophycocyanin, anti-CD8-PE/Cy7, anti-CD44-allophycocyanin/Cy7, and 7-AAD. Each subpopulation was gated on 7-AAD− cells. A. FACS profiles of Mito-Tracker Green staining of Atg3-deficient T cells. Shaded profiles, Atg3f/f T cells; open profiles, Atg3f/fLck-Cre T cells. B. The mean fluorescence intensity (MFI) of Mito-Tracker Green from 3 pairs of Atg3f/fLck-Cre and Atg3f/f mice. C. The ratio of Mito Tracker MFIs in Atg3-deficient cell populations to those in corresponding wild-type cell populations. CD19+ cells were used as a negative control. The bar figures are mean ± SD from six pairs of Atg3f/f and Atg3f/fLck-Cre mice.

D–F. Atg3-deficient T cells produce elevated levels of ROS. Splenocytes from Atg3f/fLck-Cre and Atg3f/f control mice were incubated with DHE for 1 h at 37°C. After washing, the cells were stained with Abs described above. The fluorescence intensity of the PE channel represents ROS production. All samples were gated on 7-AAD− cells. D. FACS profiles of DHE staining. Shaded profiles, Atg3f/f T cells; open profiles, Atg3f/fLck-Cre T cells. E. MFIs of DHE staining. Shown is mean ± SD from three pairs of Atg3f/fLck-Cre and Atg3f/f mice. F. The ratio of DHE MFIs in Atg3-deficient cells to those in corresponding wild-type cells. Data are mean ± SD from five pairs of mice. CD19+ cell population was used as a negative control.

G–I. Expanded ER in Atg3-deficient mice. Splenocytes from Atg3f/fLck-Cre and Atg3f/f control mice were incubated with 1 μM ER-Tracker Blue-White DPX at 37°C for 30 min. The cells were stained and analyzed as described above. G. FACS profiles of ER-Tracker Blue-White staining. Shaded profiles, Atg3f/f T cells; open profiles, Atg3f/fLck-Cre T cells. H. The MFIs of ER-Tracker Blue-White staining. Data are mean ± SD from three pairs of Atg3f/fLck-Cre and Atg3f/f mice. I. The ratio of ER-Tracker Blue-white MFIs in Atg3-deficient cells to those in corresponding wild-type cell populations. Data are mean ± SD from five pair of Atg3f/fLck-Cre and Atg3f/f mice. CD19+ cell population is used as a negative control. *p < 0.01, **p < 0.05, ***p < 0.05, Atg3f/fER-Cre to Atg3f/f.
consistent with the observations that thymocyte development is largely normal in the absence of autophagy.

Splenic cellularity was decreased in Atg3f/fLck-Cre mice. The total splenic cellularity of Atg3f/fLck-Cre mice was ~60% of that of control Atg3f/f mice (Fig. 4A). Furthermore, the frequency and absolute number of both CD4+ and CD8+ splenic T cells were decreased in Atg3f/fLck-Cre mice. The frequency and number of CD4+ T cells in Atg3f/fLck-Cre mice were 50 and 30%, respectively, of those in the control mice. The frequency and number of CD8+ T cells in Atg3f/fLck-Cre mice were 20 and 10%, respectively, of those in the control mice (Fig. 4B, 4C). The splenic cellularity and the number of CD4+ or CD8+ T cells in Atg3f/f Lck-Cre mice were not significantly different from those in Atg3f/f mice (Fig. 4A, 4C).

We next examined the CD44 and CD62L expression patterns in Atg3f/fLck-Cre splenocytes and LN cells. The frequency of memory-like T cells (CD62Llow and CD44hig) among splenocytes and LN cells was increased within both the CD4+ and CD8+ compartment of Atg3f/fLck-Cre mice but not significantly changed in Atg3f/fLck-Cre mice (Fig. 4D, 4E). These results were consistent with the lymphopenic environment in Atg3f/fLck-Cre mice.

The above results suggest that survival is defective in Atg3-deficient T cells. To test this hypothesis, freshly isolated splenocytes were stained with Annexin V and 7-AAD. As shown in Fig. 5A, the frequency of Annexin V+ cells among naive (CD44low) CD4+ or CD8+ T cells was two times higher in Atg3f/fLck-Cre mice than that in Atg3f/f mice. To further examine the apoptotic defect in Atg3-deficient T cells, the active form of caspase-9 was analyzed in freshly isolated T cells from Atg3f/fLck-Cre and Atg3f/f mice. Increased active caspase-9 was found in Atg3f/fLck-Cre T cells (Fig. 5B). These data suggest that the impaired survival of Atg3-deficient T cells is related to caspase activation.

The impaired survival in Atg3-deficient T cells was further characterized in vitro. To decrease the spontaneous T lymphocyte death, IL-7 was added in the culture. IL-7 greatly enhanced the survival of Atg3f/f wild-type T cells in vitro compared with RPMI 1640 medium only culture (Fig. 5C). More dead cells were found in Atg3-deficient T cells in in vitro culture. The frequency of apoptosis among Atg3-deficient T cells was greater than that among wild-type cells even in the presence of IL-7 (Fig. 5C). To further characterize the cell death of Atg3-deficient T cells, the pan-caspase inhibitor zVAD was used in cell survival assay. As shown in Fig. 5C, zVAD partially rescued the survival defect in Atg3-deficient T cells in the presence of IL-7, suggesting that the death of Atg3-deficient T cells may be mediated by the apoptosis pathway (Fig. 5C). Collectively, these results demonstrate that Atg3 and autophagy are essential for the survival of T lymphocytes.

**FIGURE 7.** Defective proliferation in Atg3-deficient T lymphocytes. A. Splenocytes from Atg3f/f and Atg3f/fLck-Cre mice were stimulated with CFSE and stimulated with soluble anti-CD3 (5 μg/ml) or soluble anti-CD3 plus anti-CD28 (2 μg/ml) for 72 h or were left unstimulated as resting cell CFSE control. After staining for surface markers and 7-AAD, the samples were analyzed by flow cytometry. The cells without any stimulation were used to define the CFSE dilution gate. Numbers inside the figures represent the frequency of cells within each gate. B. Activation of Atg3-deficient T cells. Splenocytes from Atg3f/f and Atg3f/fLck-Cre mice were stimulated with soluble anti-CD3 Ab (5 μg/ml) plus anti-CD28 Ab overnight. The cells were stained with anti-CD4–allophycocyanin, anti-CD8–allophycocyanin/Cy7, anti-CD25–FITC, and anti-CD69–PE and analyzed by flow cytometry. Numbers represent the frequency of cells within each gate.

Atg3 regulate organelle homeostasis in T lymphocytes

Using a T cell-specific Atg7 deletion model, we previously showed that autophagy mediates the developmental regulation of mitochondrial content (20) and ER homeostasis (21). We thus analyzed mitochondrial and ER homeostasis in the Atg3 T cell-specific deletion system. Splenocytes from Atg3f/fLck-Cre mice were stained with the cell permeable mitochondria- or ER-specific staining reagents Mito-Tracker Green or ER-Tracker Blue-White, respectively. As shown in Fig. 6A, 6B, 6G, and 6H, both mitochondria and ER were expanded in Atg3-deficient mature CD4+ or CD8+ naive T lymphocytes. The mitochondria and ER in Atg3-deficient naive T cells were increased to >150% of wild-type control cells as shown in Fig. 6C and 6F. These data suggest that inhibition of autophagy in these cells affected mitochondrial and ER homeostasis. Because the mitochondria were expanded in Atg3-deficient T cells, we next analyzed reactive oxygen species (ROS) production in Atg3f/fLck-Cre mice. Naive Atg3-deficient CD4+ or CD8+ T cells produced more ROS than corresponding wild-type control cells (Fig. 6D, 6F), suggesting that the abnormal expansion of mitochondria in the absence of Atg3 may drive overproduction of ROS.

**Atg3-deficient T cells cannot proliferate efficiently**

To further assess the function of Atg3-deficient T cells, splenocytes from Atg3f/fLck-Cre and Atg3f/f control mice were stimulated with anti-CD3 Ab. All analyzed cell populations were gated on 7-AAD-negative cells to exclude dead cells. CFSE dilution was only analyzed in gated live cells. Both CD4+–AAD− and CD8+–AAD− cells from wild-type Atg3f/f mice proliferated efficiently (Fig. 7A). The frequency of proliferating cells was >90% when wild-type cells were stimulated with soluble anti-CD3 Ab alone or in combination with anti-CD28 Ab. In contrast, Atg3-deficient CD4+–AAD− and CD8+–AAD− T cells did not proliferate efficiently; the frequency of proliferating cells among these populations was <60% (Fig. 7A). Although Atg3-deficient T cells did
not proliferate as well as wild-type T cells, Atg3-deficient CD4+ and CD8+ T cells expressed CD69 and CD25 after anti-CD3 Ab stimulation (Fig. 7B). These data indicate that autophagy may regulate T lymphocyte proliferation but that it does not affect their activation.

**Cumulative defects in autophagy-deficient T cells**

Our previous data and the above results indicate that autophagy is essential for T cell survival and that autophagy mediates the regulation of organelle homeostasis. These data were all obtained using T cell-specific deletion models or Atg5 knockout fetal liver transfer experiments. To further investigate the functions of autophagy in mature T cells, Atg3f/f mice were bred with ER-Cre mice to generate Atg3f/fER-Cre mice, in which Atg3 can be inducibly deleted. As shown in Fig. 1D (right panel), Atg3 was deleted in ER-Cre+ cells upon in vitro treatment with 200 nM 4-OH tamoxifen for 3 d. After 4-OHT treatment, apoptosis was analyzed in Atg3-deficient naive CD4+CD44low or CD8+CD44low T cells. On day 3 after 4-OHT treatment, the majority of naive T cells from both Atg3f/f and Atg3f/fER-Cre mice were apoptotic. More than 50% of the naive CD4+ or CD8+ T cells were Annexin V+, and ~50% of the naive CD4+ cells and 60% of the naive CD8+ T cells were 7-AAD+. (Fig. 8A, upper left panel). No significant differences were found between 4-OHT–treated Atg3f/f and Atg3f/fER-Cre cells (Fig. 8A). This spontaneous death of naive T cells during the 3-d culture period was rescued by the addition of 1 ng/ml IL-7 (Fig. 8A, upper right panels). The results of carrier control ethanol treatment were shown in Fig. 8A, lower panels. Analysis of apoptosis on days 7, 10, and 18 after 4-OHT–mediated deletion of Atg3 in the presence of IL-7 showed no difference in Annexin V and 7-AAD staining between CD4+ and CD8+ T cells from Atg3f/f and Atg3f/fER-Cre mice (data not shown). In contrast, when the cells were cultured for >24 d, ~13% of Atg3-deficient CD4+ T cells and 25% of Atg3-deficient CD8+ T cells were 7-AAD+, whereas <3% of control CD4+ and 5% of CD8+ T cells were 7-AAD+ (Fig. 8B). These results suggest that although acute loss of Atg3 does not affect T cell survival, accumulation of defects during long-term cultures may result in the death of autophagy-deficient T cells.

Experiments using the Lck-Cre system have demonstrated that autophagy is essential in maintaining the homeostasis of mitochondria and ER in T cells. As the Lck-Cre induced deletion of autophagy genes occurs at early stage of thymocyte development, the defects in autophagy-deficient T cells may be due to cumulative effects. To investigate the accumulation of autophagy defect, the organelle homeostasis was thus analyzed in the ER-Cre inducible deletion system. No change in mitochondrial volume was detected on day 3 after inducible deletion of Atg3; however, mitochondrial volume began to increase on day 10 and further expanded by days 18 and 28 after inducible deletion of Atg3 in naive CD4+ or CD8+ T cells. Similarly, no change in ER content was detected on day 3 after inducible deletion of Atg3; however, ER volume was expanded in Atg3f/fER-Cre CD4+ and CD8+ T cells on day 10 after inducible deletion of Atg3 (Fig. 9). These results demonstrate that excess mitochondria and ER accumulate over time in Atg3-deficient T cells and suggest that these cumulative defects in organelle homeostasis may cause cell death in Atg3- and autophagy-deficient naive T cells.
of Atg3 f/fER-Cre and Atg3 f/f mice and representative of two experiments. This is consistent with a well-described phenomenon of T lymphocytes expressing CD62Llow. Mature Atg3-deficient T cells display increased cell death and have a phenotype similar to that of Atg5- and Atg7-deficient T cells. We have previously shown that T lymphocytes lacking Atg5 or Atg7 have impaired survival and disrupted organelle homeostasis (20, 21, 25), suggesting that autophagy regulates T lymphocyte homeostasis (33). However, our results show that Atg3-deficient T cells have an in vivo phenotype similar to that of Atg5- and Atg7-deficient T cells. Mature Atg3-deficient T cells display increased cell death and expansion of mitochondria and ER. Atg3 conditional KO mice have impaired survival and disrupted organelle homeostasis (33). However, this is independent of autophagy-independent functions of Atg5 or Atg7. Furthermore, Atg5 and Atg7 are both involved in the same conjugation pathway even though Atg7 also participates in the second conjugation pathway. Therefore, the defects in Atg5- or Atg7-deficient T cells might be due to the defect from one conjugation pathway. Thus, it is important to test the function of the second conjugation pathway of autophagy in T cell survival. To this end, we have generated Atg3 conditional knockout mice.

Our results show that Atg3-deficient T cells have an in vivo phenotype similar to that of Atg5- and Atg7-deficient T cells. Mature Atg3-deficient T cells display increased cell death and expansion of mitochondria and ER. Atg3 conditional KO mice have more memory-like phenotype T lymphocytes expressing CD62Llow and CD44high. This is consistent with a well-described phenomenon termed lymphopenia-driven proliferation that occurs in many T cell-deficient mouse strains (34). Similar to other mammalian cells, the Atg3 is indispensable for autophagy in T lymphocytes. In this study, we used an ER-Cre inducible deletion system to address the acute and cumulative effects of deletion of Atg3 in naive T cells. Interestingly, we found no survival defect in naive T cells until 24 d after deletion of Atg3, suggesting that the acute deletion of Atg3 does not affect these cells; rather, accumulation of abnormally expanded organelles causes the increased cell death observed in Atg3-deficient naive T cells.

Previous studies have shown that the Atg12 and LC3 conjugation systems regulate each other. The Atg12 pathway regulates the LC3 pathway, and the LC3 pathway is required for the maturation of the autophagosome (35). Atg12–Atg5 conjugates function as a ubiquitin-protein ligase (E3)-like enzyme and enhance the generation of LC3- phosphatidylethanolamine (10, 12). Atg3 interacts with Atg12 and facilitates the formation of the Atg12–Atg5 complex (30). Our data suggest that Atg3 deficiency impairs autophagy in T lymphocytes, resulting in dysregulation of mitochondrial and ER homeostasis. A recent publication showed that Atg12 conjugates with Atg3, and Atg12–Atg3 complex regulates mitochondrial homeostasis through a mitophagy-independent pathway in mouse embryonic fibroblasts (36). Our results reported in this study, together with our previous findings in Atg5- or Atg7-deficient T cells, indicate that autophagy pathways are essential for maintaining lymphocyte physiological function. The Atg3ER-Cre inducible deletion system provides a novel method to further investigate the functions of autophagy in T lymphocytes. After inducible deletion of Atg3, no acute defects were observed in T cell function. T cells in which Atg3 had been inducibly deleted survived similar to wild-type T cells, and mitochondria and ER were not expanded at early time points; however, if the Atg3-deficient T lymphocytes were cultured for longer periods of time (>2 to 3 wk), the organelles were gradually expanded, and the frequency of cell death began to increase. These effects may be related to the basic functions of autophagy. Generally, the physiological function of autophagy is to provide cells with energy during starvation, growth factor withdrawal, or other stress conditions and to remove long-lived proteins or damaged, aged, or excess organelles. The temporal accumulation of mitochondria and ER after deletion of Atg3 suggests that the survival and proliferation defects observed in Atg5-, Atg7-, and Atg3-deficient T cells are indirect effects of impaired autophagy. After expanded organelles accumulate to a certain level, the cells may not be able to compensate for these abnormalities, and the survival defects become apparent. The relationships among autophagy, cell death, and cell survival are complex (37). Our previous data and the results presented in this study demonstrate that autophagy is essential for the survival of T lymphocytes (20, 25). IL-7 upregulates the expression of Bcl-2 to promote the survival of T lymphocytes (38); however, IL-7 does not rescue the survival defect in Atg3-deficient T cells. The enhanced activation of caspase-9 and the fact that pan-caspase inhibitor zVAD partially rescues the survival defect in Atg3-deficient T cells suggest that the cell death in autophagy-deficient T cells is due to the abnormal activation of the apoptotic pathway; however, other factors related to impaired autophagy may also affect the survival of T lymphocytes. Interestingly, abolishing the Atg12–Atg3 conjugates inhibits cell death by increasing the expression of Bcl-2 member Bcl-xL in mouse embryonic fibroblasts (36). However, this is independent of autophagy because the disruption of the conjugates of the Atg12 and Atg3 complex does not affect the starvation-induced autophagy (36).

In summary, our results indicate that Atg3 and LC3 conjugation are essential for autophagy in T lymphocytes. The homeostasis of organelles in Atg3-deficient T cells is abnormal, and the survival of Atg3-deficient T cells is defective. By using an inducible deletion model, we have provided clear evidence that the survival defect and organelle expansion phenotypes in Atg3-deficient T cells are temporally accumulated effects of impaired autophagy.

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Disclosures

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