Ubiquitin ligase MARCH 8 cooperates with CD83 to control surface MHC II expression in thymic epithelium and CD4 T cell selection

Haiyin Liu,[1] Reema Jain,[2,4] Jing Guan,[3,5,6] Vivian Vuong,[1] Satoshi Ishido,[7,8] Nicole L. La Gruta,[3,5,6] Daniel H. Gray,[2,4] Jose A. Villadangos,[1,3] and Justine D. Mintern[1]

[1]Department of Biochemistry and Molecular Biology, Bio21 Molecular Science and Biotechnology Institute, [2]Department of Medical Biology, and [3]Department of Microbiology and Immunology, Peter Doherty Institute for Infection and Immunity, The University of Melbourne, Parkville, Victoria 3010, Australia
[4]The Walter and Eliza Hall Institute of Medical Research, Parkville, Victoria 3052, Australia
[5]Infection and Immunity Program and [6]Department of Biochemistry and Molecular Biology, Biomedicine Discovery Institute, Monash University, Clayton, Victoria 3800, Australia
[7]Laboratory of Integrative Infection Immunity, Showa Pharmaceutical University, Machida, Tokyo 194-0042, Japan
[8]Department of Microbiology, Hyogo College of Medicine, Hyogo 663-8131, Japan

Major histocompatibility complex class II (MHC II) expression is tightly regulated, being subjected to cell type–specific mechanisms that closely control its levels at the cell surface. Ubiquitination by the E3 ubiquitin ligase MARCH 1 regulates MHC II expression in dendritic cells and B cells. In this study, we demonstrate that the related ligase MARCH 8 is responsible for regulating surface MHC II in thymic epithelial cells (TECs). *March8*$^{-/-}$ mice have elevated MHC II at the surface of cortical TECs and autoimmune regulator (AIRE)$^{-}$ medullary TECs (mTECs), but not AIRE^{+} mTECs. Despite this, thymic and splenic CD4^{+} T cell numbers and repertoires remained unaltered in *March8*$^{-/-}$ mice. Notably, the ubiquitination of MHC II by MARCH 8 is controlled by CD83. Mice expressing a mutated form of CD83 (*Cd83*$^{anu/anu}$ mice) have impaired CD4^{+} T cell selection, but deleting *March8* in *Cd83*$^{anu/anu}$ mice restored CD4^{+} T cell selection to normal levels. Therefore, orchestrated regulation of MHC II surface expression in TECs by MARCH 8 and CD83 plays a major role in CD4^{+} T cell selection. Our results also highlight the specialized use of ubiquitinating machinery in distinct antigen–presenting cell types, with important functional consequences and implications for therapeutic manipulation.

INTRODUCTION

MHC II antigen presentation plays a critical role in CD4^{+} T cell function and hence regulation of adaptive immunity. In the thymus, presentation of self-antigens by thymic epithelial cells (TECs) and DCs is responsible for the positive and negative selection of CD4^{+} T cells (Klein et al., 2014). Minor alterations in MHC II expression or the repertoire of self-antigens presented by TECs or DCs can profoundly affect the capacity of the immune system to respond to infection or susceptibility to infection (Nakagawa et al., 1998; Peterson et al., 2008; Mohan and Unanue, 2012). Characterization of the mechanisms that regulate the generation, surface expression, and turnover of MHC II in TECs and DCs is thereby required to fully understand how a healthy CD4^{+} T cell repertoire develops.

Ubiquitination is a critical posttranslational mechanism that regulates MHC II trafficking and levels at the cell surface (Cho and Roche, 2013; Moffat et al., 2013). This has

primarily been studied in DCs, where in resting cells, MHC II is trafficked to the surface but then delivered to lysosomes and degraded, whereas DC activation results in reduced MHC II delivery to lysosomes and accumulation at high levels on the cell surface (Villadangos et al., 2005). This pattern of MHC II trafficking is regulated in mouse and human DCs via the oligoubiquitination of a single conserved lysine (K225) in the C-terminal cytosolic tail of the MHC II β chain (Ohmura-Hoshino et al., 2006b; Shin et al., 2006; van Niel et al., 2006; De Gassart et al., 2008). Ubiquitination of MHC II is performed by members of the membrane-associated RING-CH (MARCH) family of E3 ubiquitin ligases. MARCH proteins were originally identified as the mammalian homologues of the viral immunosuppressive membrane ubiquitin ligases K3 and K5 (Goto et al., 2003; Bartee et al., 2004). 11 members have been described (Ohmura-Hoshino et al., 2006a), with MARCH 1 being responsible for ubiquitinating MHC II. This function was initially described in an overexpression study (Ohmura-Hoshino et al., 2006b) and confirmed with analysis of *March1*-deficient

Correspondence to Justine D. Mintern: jmintern@unimelb.edu.au; or Jose A. Villadangos: j.villadangos@unimelb.edu.au

Abbreviations used: AIRE, autoimmune regulator; cTEC, cortical TEC; FIP, fluorescence internalization probe; MARCH, membrane-associated RING-CH; mTEC, medullary TEC; SHIP, specific hybridization internalization probe; SP, single positive; TEC, thymic epithelial cell.

The Rockefeller University Press $30.00
J. Exp. Med. 2016 Vol. 213 No. 9   1695–1703
www.jem.org/cgi/doi/10.1084/jem.20160312

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DCs (Young et al., 2008; Walseng et al., 2010; Oh et al., 2013) and B cells (Matsuki et al., 2007; Oh et al., 2013). Whether MARCH 1–mediated ubiquitination also regulates MHC II trafficking in TECs and whether this contributes to CD4^{+} T cell selection is unclear. Studies in mice lacking functional CD83 suggested this to be the case. Mice that express functionally impaired CD83 or lack CD83 altogether exhibit dramatically impaired CD4^{+} T cell selection (Fujimoto et al., 2002; Tze et al., 2011). The mechanism involved is proposed to involve CD83-dependent regulation of MHC II ubiquitination (Tze et al., 2011). CD83 was proposed to sequester MARCH 1 in TECs, preventing it from ubiquitinating MHC II and thereby promoting high MHC II expression at the cell surface. Although an attractive hypothesis, this mechanism has not been validated in vivo. MARCH 1 is not active in TECs (Oh et al., 2013), and therefore, the target for CD83 remains undefined, as is the role of MHC II ubiquitination in antigen presentation mediated by TECs.

Herein, we have identified MARCH 8, the most closely related family member of MARCH 1 (Bartee et al., 2004), as the major E3 ubiquitin ligase responsible for MHC II trafficking in TECs, a process that is regulated by CD83, with important consequences for thymic CD4^{+} T cell selection.

RESULTS AND DISCUSSION
MARCH 8 controls MHC II trafficking in TECs
MARCH 1–mediated MHC II ubiquitination accelerates MHC II internalization and/or delivery to lysosomal compartments in DCs, and as a consequence, the absence of MARCH 1 increases the surface expression of MHC II in splenic or thymic DCs (Fig. 1 A; Walseng et al., 2010; Oh et al., 2013). The absence of MARCH 1 did not affect MHC II expression in TECs (Fig. 1 A; Oh et al., 2013), suggesting that either ubiquitination does not play a role in regulating MHC II expression in these cells or another E3 ubiquitin ligase is active in TECs. If the latter, a potential candidate is MARCH 8, which is closely related to MARCH 1 and is capable of MHC II ubiquitination in transfected cells (Ohmura-Hoshino et al., 2006b; Lapaque et al., 2009; Tze et al., 2011). To investigate this, we generated $March8^{-/-}$ mice (Fig. 1 B; refer to the Mice section of Materials and methods for details) and analyzed MHC II expression in DCs and TECs. MAR CH 8 deficiency caused increased MHC II expression in TECs but not in DCs (Fig. 1 C). TECs and DCs lacking both MARCH 1 and MARCH 8 expressed similar MHC II levels as their counterparts, lacking only MARCH 1 or MARCH 8, respectively (Fig. 1 C and not depicted), indicating the two E3 ligases play nonredundant roles. Neither MARCH 1 nor MARCH 8 deficiency impacted MHC I expression in DCs and TECs, respectively (Fig. 1 D).

TECs can be divided into two major types: cortical (cTEC) and medullary (mTEC). In turn, mTECs can be subdivided into immature cells that express low levels of MHC II (mTEC[low]) and more mature cells that express higher MHC II levels (mTEC[high]; Gray et al., 2007; Rossi

et al., 2007). A subtype of mTEC[high] expresses autoimmune regulator (AIRE), a transcription factor that induces ectopic gene expression, required for effective negative selection of tissue-reactive thymocytes (Mathis and Benoist, 2009). Analysis of TEC subsets showed that MARCH 8 regulates surface MHC II expression in both cTECs and AIRE[−] mTECs but not in AIRE[+] mTEC[high] (Fig. 1 E). Given that overexpressed MARCH 8 can ubiquitinate CD86 in HeLa cells (Bartee et al., 2004), we also assessed whether this molecule was a physiological substrate of MARCH 8. This was not the case as CD86, in addition to closely related CD80, was unaltered on the surface of $March8^{-/-}$ TECs (Fig. 1 F).

Ubiquitination of surface MHC II is responsible for controlling its surface turnover. We therefore monitored the rate of surface MHC II turnover in cells lacking MARCH E3 ligases. To do this, we used a specific hybridization internalization probe (SHIP) assay that we have previously used to monitor the internalization of surface receptors (Reuter et al., 2015). Measurement of surface MHC II turnover in wild-type DCs by SHIP showed that these cells internalized ∼30% of their surface MHC II molecules within 30 min (Fig. 2 A). Internalization was significantly reduced for $March1^{-/-}$ DCs (Fig. 2 A). This supports observations that ubiquitinated MHC II molecules are more readily lost from the cell surface, either because of their enhanced endocytosis from the plasma membrane or reduced recycling back to the cell surface (Cho and Roche, 2013; Moffat et al., 2013). Examination of MHC II turnover in TECs showed that surface MHC II is more stable in these cells than in DCs but nevertheless was regulated by MARCH 8 ubiquitination, as its deficiency in TECs caused significantly reduced MHC II internalization (Fig. 2 B). Therefore, MARCH 8, but not MARCH 1, is active in TECs and is the E3 ubiquitin ligase responsible for the posttranslational regulation of surface MHC II trafficking in these cells.

The absence of MARCH 8 does not significantly alter the CD4^{+} T cell repertoire
To examine the consequence of MARCH 8 deficiency and elevated MHC II TEC levels on thymic function, we assessed CD4^{+} T cell selection in $March8^{-/-}$ mice. The proportion and number of CD4^{+} single-positive (SP) thymocytes (Fig. 3 A) as well as the proportion and number of CD4^{+} splenic T cells (Fig. 3 B) were unaltered in the absence of MARCH 8. In addition, CD4^{+} SP thymocytes from $March8^{-/-}$ mice displayed no evidence of an altered phenotype, with normal levels of CD3 and CD4 and the activation markers CD5, CD69, Nur77, CD25, and Qa-2 (Fig. 3 C). This was also the case for splenic CD4^{+} T cells (Fig. 3 D). The proportion of FoxP3^{+} regulatory T cells (T reg cells) in the thymus and spleen were similar in wild-type and $March8^{-/-}$ mice (Fig. 3 E). Finally, the lack of MARCH 8 had no impact on MHC II–mediated selection of OT-II CD4^{+} OVA-specific TCR transgenic T cells (Fig. 3 F).

To analyze the potential impact of MARCH 8 deficiency on the CD4^{+} T cell repertoire in more detail, we
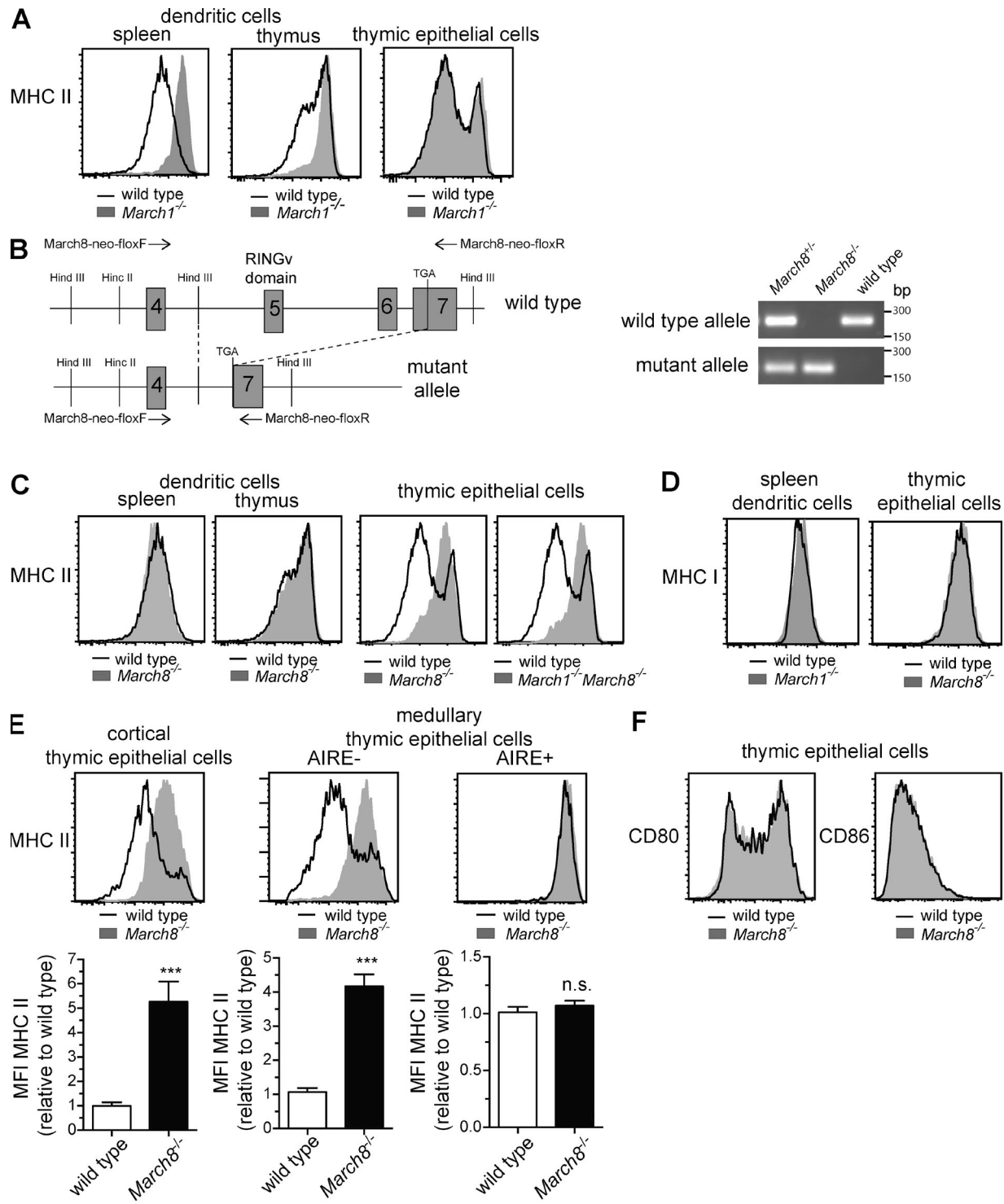
Figure 1. **MARCH 8 controls surface MHC II expression in TECs.** (A) Spleen and thymus DCs or TECs were isolated from wild-type or *March1*$^{-/-}$ mice, and surface MHC II was examined by flow cytometry. Data are representative of at least two independent experiments. (B) Diagram illustrating generation of *March8*$^{-/-}$ mice. TGA indicates a stop codon. (C) Spleen and thymus DCs or TECs were isolated from wild-type, *March8*$^{-/-}$, or *March1*$^{-/-}$ *March8*$^{-/-}$ mice, and surface MHC II was analyzed by flow cytometry. Data are representative of at least two independent experiments. (D) MHC I expression by wild-type and *March1*$^{-/-}$ DCs and *March8*$^{-/-}$ TECs. (E) MHC II expression by wild-type and *March8*$^{-/-}$ cTECs and AIRE$^-$ and AIRE$^+$ mTECs. Data are pooled from two to five independent experiments and are mean + SEM. ***, P < 0.0001, unpaired Student's *t* test. MFI, mean fluorescence intensity; n.s., not significant. (F) Expression of CD80 and CD86 by wild-type and *March8*$^{-/-}$ TECs. Data are representative of at least two independent experiments.
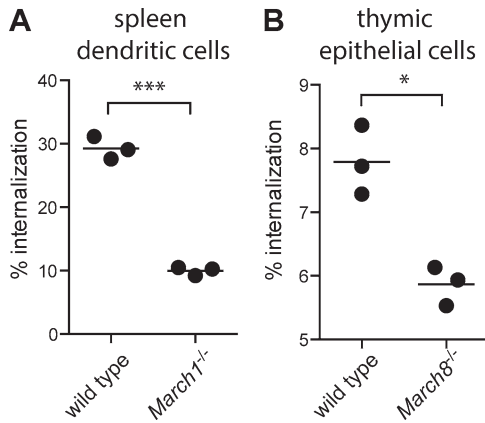
A spleen dendritic cells

B thymic epithelial cells

Figure 2. **Surface MHC II turnover is reduced in the absence of MARCH E3 ligases.** (A and B) Internalization of surface MHC II was measured for spleen DCs (A) and TECs (B). Cells were labeled with FIP-conjugated anti–MHC II antibody at 4°C (time 0). After 30 (A) or 60 (B) min of culture at 37°C, cells were removed and exposed to quencher (Q). The percentage of internalization is calculated as the FIP signal in the presence of Q (minus the signal elicited at time 0 with Q) as a percentage of the FIP signal at time 0 in the absence of Q (minus the signal elicited at time 0 with Q). Data are representative of five independent experiments (A) and two independent experiments (B) performed in triplicate. Bars represent the mean. *, P < 0.05; ***, P < 0.0001, unpaired Student's t test.

examined antigen-specific CD4+ T cell populations in the lymph nodes and spleen of naive mice. To do this, CD4+ T cells were enriched from wild-type or $March8^{-/-}$ mice using different MHC II–peptide tetramers and enumerated (Moon et al., 2007). Similar numbers of naive CD4+ T cells specific for MHC II–restricted peptides derived from I-E α chain, ribosomal protein L6 (AasF peptide), calnexin, or STM1540 proteins of *Salmonella enterica* serovar Typhimurium were detected in the two groups of mice (Fig. 3 G). Single-cell analysis of the TCR repertoire of I-E α–specific CD4+ T cells revealed no major differences in the preferences for TCRβ usage by cells isolated from wild-type and $March8^{-/-}$ mice (Fig. 3 H).

Our data shows no major perturbation in CD4+ T cell differentiation, selection, and/or maintenance of CD4+ T cells in the periphery in the absence of MARCH 8 and that elevated surface MHC II expression by cTECs and AIRE− mTECs does not significantly alter the CD4+ T cell repertoire. This is surprising because CD4+ T cell selection is critically sensitive to minor reductions in MHC II levels observed in *Cd83*-deficient mice (Kuwano et al., 2007; Tze et al., 2011). At face value, this suggests that mechanisms of CD4+ T cell selection can tolerate significant increases in MHC II levels more readily than subtle reductions. This notion is consistent with the observation that increased MHC II in thymic DCs that lack MARCH 1 does not dramatically alter CD4+ negative selection in $March1^{-/-}$ mice (Oh et al., 2013). In contrast, reduced MHC II expression alone does not appear to affect CD4+ T cell selection because mice deficient in CD83

or expressing only one MHC II allele display similarly low surface MHC II; yet, only CD83-deficient mice have a defect in CD4+ T cell selection (Kuwano et al., 2007). This suggests that altered MHC II turnover on the TEC surface, rather than reduced expression level, may be the major factor responsible for impaired CD4+ T cell selection in CD83-deficient mice. If so, counteracting the effect of the lack of CD83 on MHC II turnover in TECs should restore CD4+ T cell selection. We tested this hypothesis in the following set of experiments.

CD83 regulation of MARCH 8 activity is critical for CD4+ T selection

CD83 has been proposed to sequester the E3 ligase that ubiquitinates MHC II in TECs (Tze et al., 2011). In the absence of CD83, the ligase would over-ubiquitinate MHC II, causing increased internalization and reduced surface expression of the molecule. MARCH 1 was proposed as the ligase involved, but as we show here, the ligase that regulates MHC II turnover and surface expression in TECs is MARCH 8, not MARCH 1. Therefore, we examined whether MARCH 8 was responsible for the reduction in TEC MHC II expression and impaired CD4+ T cell selection in mice lacking functional CD83.

$Cd83^{anu/anu}$ is an ENU (N-ethyl-N-nitrosourea) mutant mouse strain defective in CD83 and, consequently, CD4+ T cell selection (Tze et al., 2011). Analysis of TECs isolated from $Cd83^{anu/anu}$ mice showed that cTECs and mTECs expressed lower MHC II levels than their wild-type counterparts (Fig. 4 A), as would be expected if the role of CD83 were to reduce the activity of MARCH 8. Deletion of *March8* rescued MHC II levels in $March8^{-/-} \times Cd83^{anu/anu}$ mice, with TECs isolated from these mice displaying high MHC II levels similar to those observed in MARCH 8–deficient TECs (Fig. 4 A). Therefore, the mechanism responsible for the impact of CD83 on MHC II expression in TECs is the impairment of MARCH 8 activity. This is further illustrated with analysis of CD4+ T cell development in these mice. Removal of MARCH 8 in mice lacking functional CD83 restored the number of blood CD4+ T cells (Fig. 4 B), CD4+ SP thymocytes (Fig. 4 C), and splenic CD4+ T cells (Fig. 4 D) to wild-type levels.

In summary, we have identified MARCH 8 as the major E3 ubiquitin ligase responsible for controlling MHC II trafficking in TECs. Moreover, we demonstrate that MARCH 8 activity is regulated by CD83, with critical consequences for CD4+ T cell selection. The mechanism by which CD83 specifically controls MARCH 8 is unknown but may involve physical interaction between their transmembrane domains (Tze et al., 2011). Finally, we unequivocally demonstrate distinct cell-intrinsic roles for MARCH 1 and MARCH 8 in DCs and TECs, respectively. The teleological reason for the differential use of these two closely related ligases is not entirely clear. One possibility is that the ability of MARCH 1 to ubiquitinate additional molecules in DCs, such as CD86, would be deleterious in TECs. MARCH 8 does not affect CD86 expression (Fig. 1 F), so there are subtle differences in
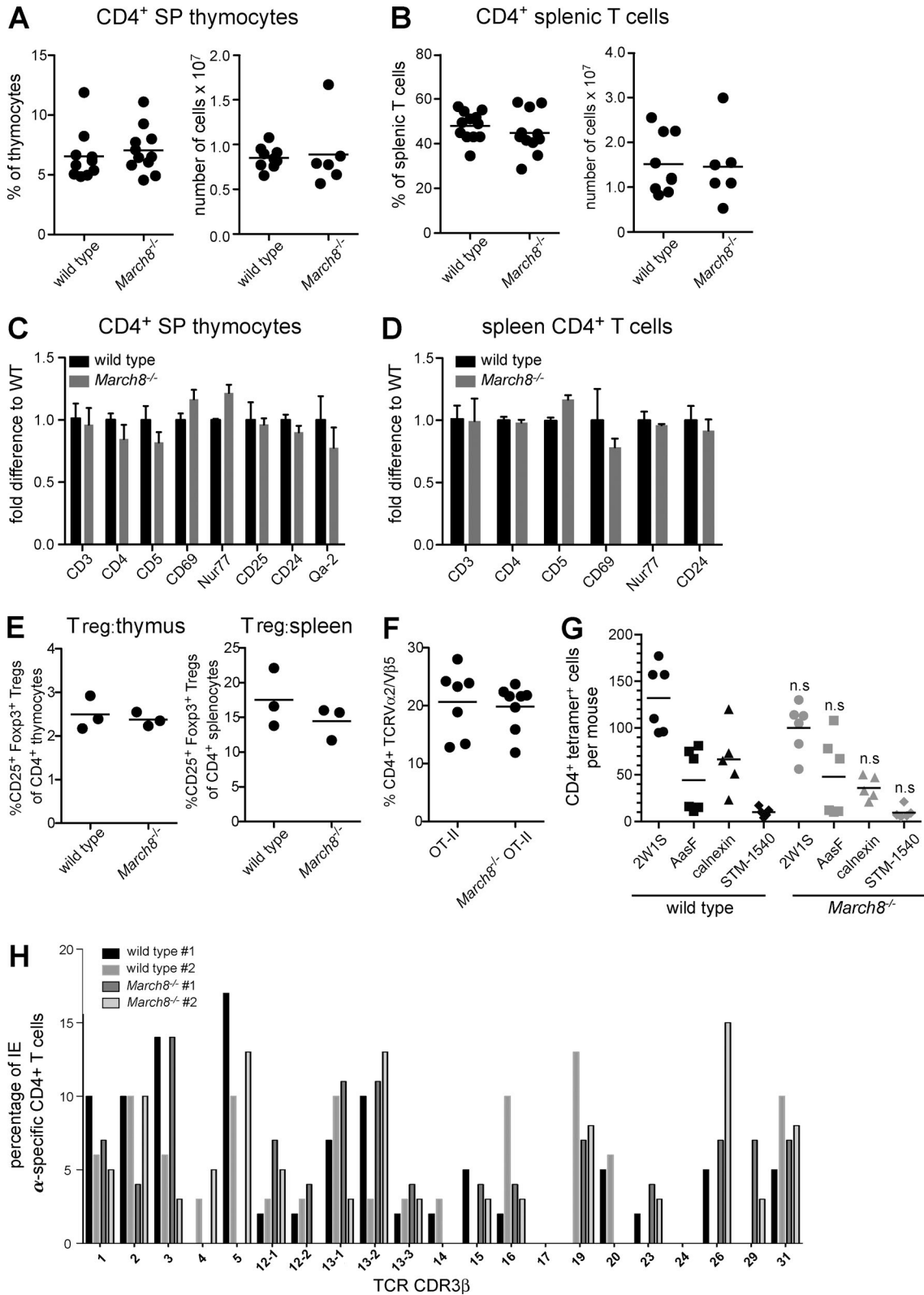
Figure 3. **The absence of MARCH 8 does not significantly alter the CD4⁺ T cell repertoire.** (A and B) Frequency and number of CD4⁺ CD3⁺ thymocytes (A) or splenic CD4⁺ T cells (B) from wild-type or *March8⁻/⁻* mice. The graphs display data pooled from a minimum of three independent experiments with symbols representing individual mice. Bars designate the mean. (C and D) Summary of the fold difference in geometric mean fluorescence intensity for

the substrate specificity of the two ligases that may underpin specialized roles in distinct antigen-presenting cell types. Our results do not exclude another possibility, namely that MARCH 8 ubiquitinates another receptor that, if not ubiquitinated, can compensate for the lack of CD83. However, replacement of the Lys residue that becomes ubiquitinated in the MHC II β chain with an Arg is sufficient to compensate for the effect of CD83 deficiency (see von Rohrscheidt et al. in this issue), an observation that discards this possibility.

It will be interesting to examine whether the specialization of MARCH 1 and 8, and indeed other members of the MARCH family, extends to other antigen-presenting cell types. The substrate specificity of each MARCH may be mediated by differential transmembrane region interactions (Bartee et al., 2004) or by the participation of distinct accessory proteins involved in MARCH function (e.g., the E2 ligases and/or deubiquitinating enzymes). These specializations may affect not just which substrates are ubiquitinated, but also the type of ubiquitin chains incorporated into the same substrate in different cell types, as has been shown to be the case for MHC II in DCs and B cells (Ma et al., 2012). Differential use of ubiquitination machinery opens the prospects of exerting fine control of MHC II antigen presentation in specific cell types with important consequences for the manipulation of immune outcomes.

MATERIALS AND METHODS

Mice

C57BL/6, $March1^{-/-}$ (Matsuki et al., 2007), $March8^{-/-}$, OT-II, and $Cd83^{anu/anu}$ (Tze et al., 2011) mice were bred and maintained in specific pathogen–free conditions at the Bio21 Molecular Science and Biotechnology Institute. In brief, $March8^{-/-}$ mice were generated by the insertion of loxp sites flanking exon 5 that encodes the RING-variant domain. Mice were crossed with CAG-Cre mice to delete exon 5 by Cre-mediated recombination (Matsuki et al., 2007). Analysis was undertaken with mice aged 8–10 wk. Experiments were performed in accordance with the Institutional Animal Care and Use Committee guidelines of the University of Melbourne.

Isolation of DCs

Organs were finely chopped and digested with 140 μg/ml DNase I (Roche) and 1 mg/ml collagenase type III (Worthington Biochemical Corporation). Cell clusters were further dissociated by treatment with 10 mM EDTA. Light-density cells were isolated by centrifugation over a Nycodenz gradient (1.077 g/cm³; Axis-Shield) at 1,700 g and incubated with rat anti–mouse antibodies against CD3 (KT3-1.1), Thy1-1 (T24/31.7), CD45R (RA36B2), and erythrocyte (TER119; all produced at the Walter and Eliza Hall Institute [WEHI] antibody facility), followed by depletion with goat anti–rat IgG–coated magnetic beads (QIAGEN). The resulting cell preparations were determined by flow cytometry to be of 70–85% purity for CD11c⁺ cells. Thymic DCs were identified as CD45⁺ CD11c⁺ cells in single-cell suspensions generated by the digestion of thymuses in 0.1% DNase I (Sigma-Aldrich) and 0.5 U/ml Liberase (Roche).

Isolation of TECs

To enrich TECs for flow cytometry, cells were prepared as previously described (Jain and Gray, 2014). In brief, single thymuses were finely chopped, and cell suspensions were gently agitated to deplete thymocytes. Tissue fragments were digested with 0.1% DNase I (Sigma-Aldrich) and 0.5 U/ml Liberase (Roche). Cell suspensions were stained with antibodies specific for MHC II, CD45, CD326 (epithelial cell adhesion molecule), Ly51 (all BioLegend), and UEA-1 (Vector Laboratories) before analysis with a flow cytometer (LSRFortessa; BD).

MHC II turnover assay

Fluorescence internalization probe (FIP)–azide (5′ Cy5-TCAGTTCAGGACCCTCGGCT-N₃ 3′) and quencher (Q; 5′-AGCCGAGGGTCCTGAACTGA-BHQ2 3′) were purchased from Integrated DNA Technologies. Anti–MHC II antibody (clone M5114) was functionalized with Click-IT succinimidyl ester DIBO alkyne (Thermo Fisher Scientific) by incubating with a 10-fold molar excess of succinimidyl ester DIBO alkyne for 2 h at 4°C. Functionalized antibody was purified using a Zeba spin desalting column (Thermo Fisher Scientific) and incubated with a twofold molecular excess of FIP-azide at 4°C overnight. FIP-labeled antibody was purified using a 30-kD Amicon filter (EMD Millipore), and the degree of functionalization was measured with a spectrophotometer (1000 UV-Vis; NanoDrop). SHIP internalization assays were performed by staining cells on ice for 30 min with FIP-Cy5–conjugated anti–MHC II antibody in the presence of anti-CD16/32 antibody (BioLegend) to block nonspecific binding to Fc receptors. Staining was followed by two washes and incubation of FIP-anti–MHC II–bound cells in complete RPMI 1640 at 37°C and

T cell markers expressed by cells isolated from wild-type and $March8^{-/-}$ mice: CD4⁺ SP thymocytes (C) or CD4⁺ splenic T cells (D). Graphs display mean + SD and represent data from three individual mice for each marker. (E) Percentage of CD25⁺ FoxP3⁺ T reg cells for CD4⁺ SP thymocytes and CD4⁺ splenic T cells for wild-type and $March8^{-/-}$ mice. (F) Frequency of CD4⁺ OT-II (TCR Vα2/Vβ5⁺) T cells in blood lymphocytes for wild-type and $March8^{-/-}$ mice. (G) Number of naive CD4⁺ tetramer⁺ progenitors in the spleen and lymph node of wild-type and $March8^{-/-}$ mice. Data are pooled from two independent experiments. n.s., not significantly different relative to wild-type, Mann-Whitney U test. (E–G) Each symbol represents an individual mouse. Bars designate the mean. (H) Single I-Eα wild-type or $March8^{-/-}$ CD4⁺ T cells were isolated, and the TCRβ usage was determined by multiplex single-cell reverse transcription and PCR amplification of TCR CDR3ε regions. Analysis was performed for two individual mice of each genotype.
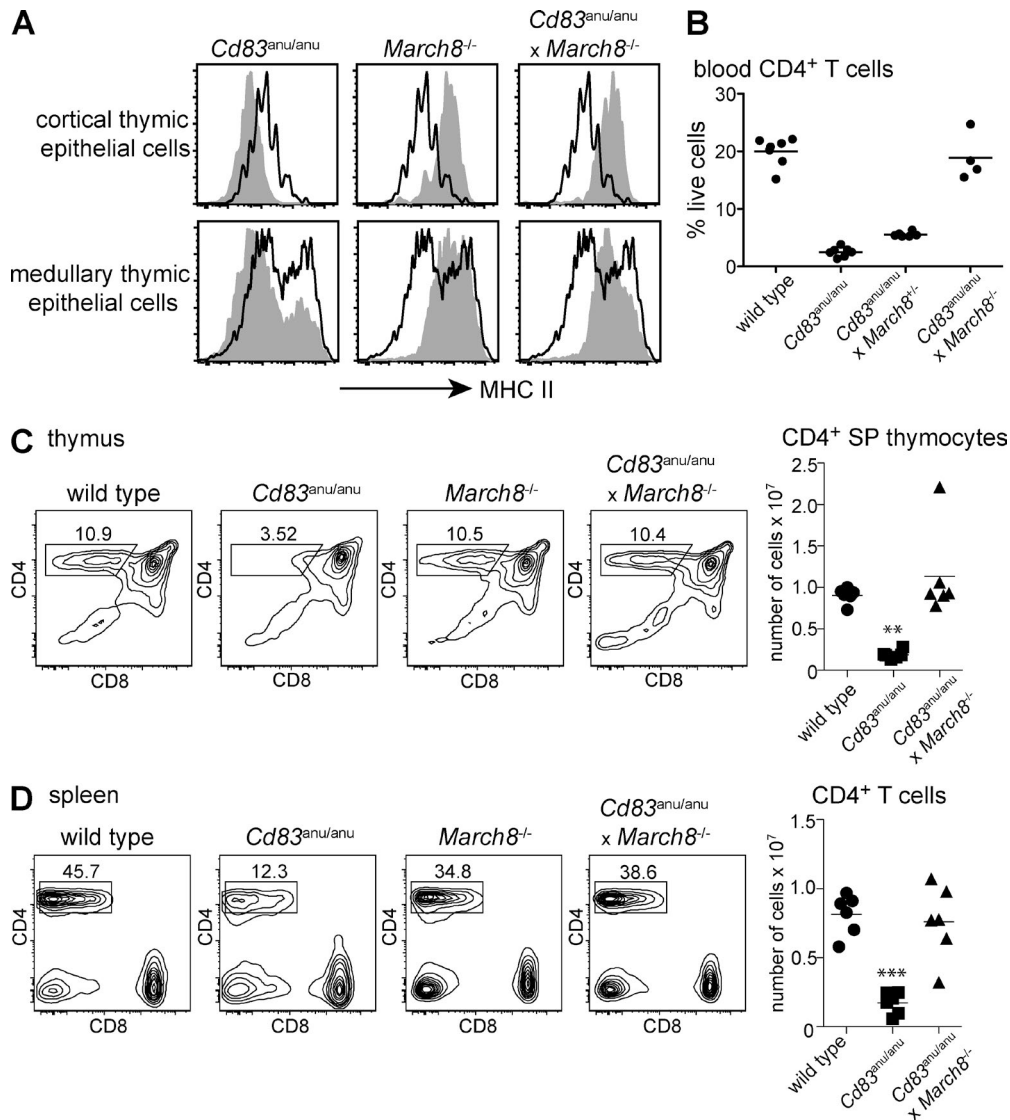
Figure 4. CD83 regulation of MARCH 8 activity is critical for CD4+ T cell selection. (A) MHC II expression on cTECs and mTECs from *Cd83*$^{anu/anu}$, *March8*$^{-/-}$, and *Cd83*$^{anu/anu}$ × *March8*$^{-/-}$ mice. Histograms are representative of two independent experiments. (B) Frequency of CD4+ T cells in peripheral blood lymphocytes of wild-type, *Cd83*$^{anu/anu}$, *March8*$^{-/-}$, and *Cd83*$^{anu/anu}$ × *March8*$^{-/-}$ mice. Each symbol represents an individual mouse. (C) Thymic CD4 versus CD8 profiles in CD3+ thymocytes of CD83$^{anu/anu}$, *March8*$^{-/-}$, and *Cd83*$^{anu/anu}$ × *March8*$^{-/-}$ mice. (D) Spleen CD4 versus CD8 profiles in CD3+ splenic T cells of *Cd83*$^{anu/anu}$, *March8*$^{-/-}$, and *Cd83*$^{anu/anu}$ × *March8*$^{-/-}$ mice. (C and D) The graphs display data from two independent experiments. Each symbol represents an individual mouse. Bars indicate the mean. **, P < 0.01; ***, P < 0.001, one-way ANOVA followed by Tukey's multiple comparison test.

10% CO_2. Cells were removed at specific time points and placed on ice. Cells were washed, phenotyped for surface markers, and resuspended in media containing propidium iodide with or without 1 mM Q. Cells were analyzed using a flow cytometer (LSRFortessa). Data were analyzed with FlowJo software (Tree Star).

T cell analysis of spleen and thymus
Spleen or thymus single-cell suspensions were depleted of red blood cells and stained with antibodies specific for CD3 (KT3-1.1; WEHI antibody facility) and CD4 (RM4-4) and CD8α (53-6.7; both BioLegend). For Foxp3+ T reg cell anal-

ysis, samples were stained with CD25 (PC61; WEHI antibody facility), fixed, and permeabilized with transcription factor staining buffer (eBioscience) and stained with anti-FoxP3 (FJK-16s; eBioscience) according to the manufacturer's instructions. Samples were analyzed on a flow cytometer (LSR-Fortessa) and FlowJo software.

Enumeration and isolation of naive epitope–specific CD4+ T cells
Tetramer-based magnetic enrichment was used for the identification and isolation of naive epitope-specific CD4+ T cells, as has been described previously (Moon et al., 2007). In brief,

single-cell suspensions of pooled spleen and major LNs (auxiliary, brachial, cervical, inguinal, and mesenteric) from individual mice were stained with PE– or allophycocyanin-labeled I-A^{b}2W1S, I-A^{b}Cal, I-A^{b}AasF, and I-A^{b}STM-1540 MHC II tetramers (provided by M. Jenkins, University of Minnesota, Minneapolis, MN; Nelson et al., 2015), washed, and labeled with anti–PE-mAb– and anti–allophycocyanin-mAb–conjugated magnetic microbeads, and tetramer-bound cells were enriched over a magnetic LS column (Miltenyi Biotec). Enriched cells were then stained with Fixable Live/Dead Aqua-Blue Viability dye (Thermo Fisher Scientific) and a panel of conjugated mAbs to identify epitope-specific cells (CD4, CD3ε, CD11c, CD11b, F4/80, B220, NK1.1, and CD8α). The entire enriched sample was acquired on an LSRII flow cytometer with FACSDiva software (BD), and data were analyzed with FlowJo software.

TCR CDR3β usage

Individual I-E α–specific CD4$^+$ T cells were sorted into wells of a 96-well plate using a flow cytometer (FACSAria; BD). Single-cell reverse transcription and nested, multiplexed PCR amplification of TCR CDR3β regions were performed. Second-round PCR products were purified and used as a template in sequencing reactions with internal *TRBC* antisense primers, as previously described (Dash et al., 2011). TCR gene segments were assigned using the International ImMunoGeneTics database (Lefranc, 2001).

Online supplemental material

Fig. S1 shows flow cytometry gating strategy. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20160312/DC1.

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