Enhanced Inflammatory Potential of CD4(+) T-Cells That Lack Proteasome Immunobunit Expression, in a T-Cell Transfer-Based Colitis Model

Citation for published version:
Rasid, O, Meulenbroeks, C, Grone, A, Zaiss, D & Sijts, A 2014, 'Enhanced Inflammatory Potential of CD4(+) T-Cells That Lack Proteasome Immunobunit Expression, in a T-Cell Transfer-Based Colitis Model', PLoS ONE, vol. 9, no. 4, 95378. https://doi.org/10.1371/journal.pone.0095378

Digital Object Identifier (DOI):
10.1371/journal.pone.0095378

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
PLoS ONE

Publisher Rights Statement:
2014 Rasid et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Enhanced Inflammatory Potential of CD4⁺ T-Cells That Lack Proteasome Immunosubunit Expression, in a T-Cell Transfer-Based Colitis Model

Orhan Rasid¹, Chantal Meulenbroeks¹, Andrea Gröne², Dietmar Zaiss¹*, Alice Sijts¹*

¹ Department of Infectious Diseases and Immunology, Faculty of Veterinary Medicine, University of Utrecht, Utrecht, The Netherlands, ² Department of Pathology, Faculty of Veterinary Medicine, University of Utrecht, Utrecht, The Netherlands

Abstract

Proteasomes play a fundamental role in intracellular protein degradation and therewith regulate a variety of cellular processes. Exposure of cells to (pro)inflammatory cytokines upregulates the expression of three inducible catalytic proteasome subunits, the immunosubunits, which incorporate into newly assembled proteasome complexes and alter the catalytic activity of the cellular proteasome population. Single gene-deficient mice lacking one of the three immunosubunits are resistant to dextran sulfate sodium (DSS)-induced colitis development and, likewise, inhibition of one single immunosubunit protects mice against the development of DSS-induced colitis. The observed diminished disease susceptibility has been attributed to altered cytokine production and CD4⁺ T-cell differentiation in the absence of immunosubunits. To further test whether the catalytic activity conferred by immunosubunits plays an essential role in CD4⁺ T-cell function and to distinguish between the role of immunosubunits in effector T-cells versus inflamed tissue, we used a T-cell transfer-induced colitis model. Naïve wt or immunosubunit-deficient CD4⁺ T-cells were adoptively transferred into RAG1⁻/⁻ and immunosubunit-deficient RAG1⁻/⁻ mice and colitis development was determined six weeks later. While immunosubunit expression in recipient mice had no effect on colitis development, transferred immunosubunit-deficient T-cells were more potent in inducing colitis and produced more proinflammatory IL17 than wt T-cells. Taken together, our data show that modifications in proteasome-mediated proteolysis in T-cells, conferred by lack of immunosubunit incorporation, do not attenuate but enhance CD4⁺ T-cell-induced inflammation.

Citation: Rasid O, Meulenbroeks C, Gröne A, Zaiss D, Sijts A (2014) Enhanced Inflammatory Potential of CD4⁺ T-Cells That Lack Proteasome Immunosubunit Expression, in a T-Cell Transfer-Based Colitis Model. PLoS ONE 9(4): e95378. doi:10.1371/journal.pone.0095378

Editor: Bernhard Ryffel, French National Centre for Scientific Research, France

Received February 28, 2014; Accepted March 26, 2014; Published April 16, 2014

Copyright: © 2014 Rasid et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: The work here presented was supported by an European Federation of Immunological Sciences-Immunology Letters Short-term fellowship to OR, European Union’s Seventh Framework Programme, Grant Agreement 280873 ADITEC to AS, and an University of Utrecht stimulus grant to DZ. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: e.j.a.m.sijts@uu.nl (AS); Dietmar.Zaiss@ed.ac.uk (DZ)

Current address: Institute of Immunology and Infection Research, School of Biological Sciences, University of Edinburgh, Edinburgh, United Kingdom

Introduction

The immune system senses pathogens through pattern recognition receptors that bind specific pathogen-associated molecular patterns. Ligand binding induces a signaling cascade downstream of the receptor that activates a specific transcriptional program, allowing the immune system to respond efficiently to the invading microorganisms. The proteasome, an abundant cellular protease complex, plays an essential role in those signaling pathways, as the activation of many signaling molecules is regulated by the timely degradation of other molecules in the signaling complex. So depends the activation of the transcription factor NFκB on phosphorylation, ubiquitylation and subsequent proteasome-mediated degradation of its inhibitor IκB [1]. IκB degradation exposes a nuclear localization sequence in NFκB, allowing it to translocate to the nucleus and to initiate the expression of, amongst others, (pro)inflammatory cytokines [1–3]. Another function of proteasomes, during infection with intracellular pathogens, is the processing of pathogen-derived antigens into peptides that can be presented by MHC class I molecules on the cell surface, allowing CD8 T-cells to detect and react to the presence of intracellular pathogens (for review see [4]). Thus, proteasome activity plays an essential role at different stages of pathogen-specific immune responses.

Proteasomes consist of a barrel-shaped catalytic core particle, the 20S proteasome, and one or more regulatory particles (for review see [5]). The enzymatic activity of the 20S proteasomes is exerted by three β subunits, located in the inner two rings of the 20S complex, which exhibit caspase-like (β1), trypsin-like (β2) and chymotrypsin-like activity (β5). Exposure of cells to type 1 and type 2 interferons or TNFα induces the expression of three facultative subunits, β1i/LMP2, β2i/MECL-1 and β5i/LMP7, which preferentially incorporate into newly assembled proteasome complexes and thus, when expressed, replace their constitutive homologues in the cellular proteasome population [5]. In addition, in particular cells of the hematopoietic lineage express different quantities of the three facultative subunits and, therefore, often contain so called “mixed” proteasomes, containing the constitutive and one or more inducible β subunits [5,6]. Due to altered cleavage preferences, proteasomes containing the facultative subunits (named immunoproteasomes) are more suited to generate high affinity MHC class
I ligands than constitutive proteasomes, containing the β1, β2 and β5 subunits [5,7,8]. As a consequence, pathway-specific CD8+ T-cell responses often target immunoproteasome-generated peptides [5,8,9]. Immunoproteasomes have further been shown to protect cells from interferon-induced oxidative stress, by efficient removal of aggregates of oxidant-damaged, polyubiquitylated unfolded nascent proteins [10,11] and immunoproteasome expression in the peripheral tissues was found to protect against early forms of CD8+ T-cell-mediated autoimmune diseases [7,10]. In specific, we showed that irradiated and BM reconstituted, β2i/MECL-1&β5i/LMP7-deficient recipient mice developed latent forms of CD8+ T-cell-mediated autoimmune diseases, such as insulin-dependent diabetes mellitus and diabetes insipidus [7]. This could be explained by altered MHC class I antigen processing of tissue antigens in inflamed immunosubunit-deficient tissue, in particular, since adoptive transfer of CD4+ T-cell depleted splenocytes from diseased mice conferred the disease phenotype onto RAG1−/− mice that also lacked immunosubunit expression, but not onto RAG1−/− mice that expressed the immunosubunits [7]. Alternatively, enhanced death in immunosubunit-deficient tissues following irradiation [10] may have led to presentation of tissue antigens in the draining lymph nodes and thus may have induced priming of auto-reactive CD8+ T-cells.

In hematopoetic cells, expression of the immunosubunits supports the production of many cytokines. [12–14]. Based on the latter observations, immunoproteasomes have been proposed to drive inflammatory processes, an assumption that is supported further by the anti-inflammatory effects of proteasome subunit-specific inhibitors [14]. The role of immunoproteasomes in inflammatory diseases has been investigated in further detail in different mouse models of colitis [15–17]. These studies showed that inflammatory disease was accompanied by high levels of immunosubunit expression in the inflamed tissue, with cellular infiltration and expression of inflammatory cytokines [15,16]. Inhibition of activity of the proteasome subunit LMP7/β5i or of both LMP7/β5i and β5 largely prevented DSS-induced colitis, and was associated with reduced quantities of inflammatory cytokines [14–16]. Notably, a deficiency of β5i/LMP7, in mice lacking the gene encoding this subunit, protected from DSS-induced colitis [15,16]. This was attributed to diminished processing of the transcription factor NFκB, which initiates cytokine transcription, in hematopoietic cells by Schmidt et al. [15]. Groettrup and coworkers [17], however, reported a reduced differentiation of “proinflammatory” Th1 and Th17 cells and enhanced differentiation of regulatory T-cells (Tregs) in β5i/LMP7−/− mice, suggesting that altered T-cell differentiation may explain for the ameliorating effects of β5i/LMP7 deficiency in development of DSS-induced colitis. The last authors also showed that LPS or anti-CD3 stimulated spleen cells of wt and β5i/LMP7−/− mice produce similar amounts of IL-6, IFNγ and IL-17 [14,16], arguing against a direct effect of LMP7 on the production of those cytokines. Taken together, these data establish an important regulatory role for the immunosubunit β5i/LMP7 in inflammatory disease, but the underlying molecular mechanism remains poorly understood. In addition, the protective effects of β5i/LMP7 deficiency in inflammatory disease are remarkable in light of the observed importance of immunoproteasomes in clearing potentially toxic protein aggregates in cytokine-exposed cells [10].

To further investigate the role of proteasome immunosubunits in autoimmune, inflammatory disease, we analyzed T-cell-induced colitis development in RAG1 gene-deficient mice compared to RAG1&β2i/MECL-1&β5i/LMP7-deficient mice, in a T-cell transfer model. Using this model, we were able to distinguish between disease modifying effects of immunosubunit expression in inflamed tissue and in effector T-cells, respectively.

**Results**

β2i/MECL-1&β5i/LMP7 Deficiency does not Protect against T-cell Transfer-induced Colitis

Previous studies have shown that the absence or the inhibition of the immunosubunit β5i/LMP7 protects mice against development of DSS-induced colitis, which was attributed to diminished transcription of proinflammatory cytokines or to diminished Th1 and Th17 and enhanced Treg cell differentiation [15,17]. To determine to which extent the absence of immunosubunit expression in effector T-cells versus in inflamed tissue confers resistance to colitis development, we employed a well-established T-cell transfer-induced colitis model [18–20]. Purified naive wt or β2i/MECL-1&β5i/LMP7-deficient T-cells were transferred into RAG1-gene-deficient mice or β2i/MECL-1&β5i/LMP7 deficient mice that had been backcrossed onto the RAG1−/− background. Six weeks after cell transfer, mice were sacrificed and colitis development was determined by histological scoring (for criteria, see Materials and Methods). As expected, RAG1−/− mice transferred with wt CD4+ T-cells developed colitis (Figure 1A, Figure S1) and so did transferred RAG1−/−/β2i/MECL-1−/−/β5i/LMP7−/− mice, with similar severity as RAG1−/− mice. Surprisingly, β2i/MECL-1−/−/β5i/LMP7−/−/CD4+ T-cells also caused colitis, both in RAG1−/− and RAG1−/−/β2i/MECL-1−/−/β5i/LMP7−/− mice (Figure 1A, Figure S1). Histological scores in mice that received β2i/MECL-1&β5i/LMP7-deficient T-cells were even higher than in recipients of wt CD4+ T-cells (Figure 1B–D, Figure S1), with significant differences in the proximal colon (Figure 1B, Figure S1). Thus, neither a lack of proteasome immunosubunit expression in effector T-cells nor in the inflamed tissue conferred resistance to development of T-cell transfer-induced colitis.

To determine how colitis development in RAG1−/− mice and RAG1−/−/β2i/MECL-1−/−/β5i/LMP7−/− mice correlated with expansion of transferred, naive CD4+ T-cells, spleens of these mice were harvested and analyzed. Total numbers of splenocytes were lower in transferred RAG1−/−/β2i/MECL-1−/−/β5i/LMP7−/− mice than in transferred RAG1−/− mice (Figure 2A), consistent with the reduced spleen size and numbers of total splenocytes often observed in β2i/MECL-1&β5i/LMP7-deficient compared to wt mice (D.Z. and A.S., unpublished observations). Analysis of the splenic CD4+ T-cell populations by flow cytometry revealed no major differences in percentages of CD4+ T-cells between the different mouse groups (Figure 2B), but total numbers of CD4+ T-cells were higher in mice transferred with β2i/MECL-1&β5i/LMP7-deficient CD4+ T-cells than in recipients of wt CD4+ T-cells (Figure 2C), which was in direct correlation with the enhanced severity of inflammation in the colon (Figure 1). These data show that β2i/MECL-1&β5i/LMP7-deficiency does not impair the proliferative potential of CD4+ T-cells.

**Enhanced Induced (i)Treg Differentiation and Elevated Levels of IL17 in Colitic Mice that Received β2i/MECL-1&β5i/LMP7-deficient CD4+ T-cells**

β5i/LMP7-deficient mice are resistant to development of DSS-induced colitis, due to reduced NFκB activation or to altered CD4+ T-cell differentiation, which both may dampen the production of proinflammatory cytokines [15,17]. Intracellular staining of FoxP3 in spleen-derived CD4+ T-cells of mice with T-cell transfer-induced colitis (Figure 2D, E) showed enhanced numbers and percentages of FoxP3+FoxP3− cells, i.e. iTregs, in mice that
had received β2i/MECL-1&β5i/LMP7-deficient CD4+ T-cells. On the other hand, deficiency of β2i/MECL-1&β5i/LMP7 in recipient mice had no effect on iTreg differentiation (Figure 2D, E).

Analysis of cytokine expression in TCR-activated splenic T-cells by RT-PCR demonstrated enhanced quantities of IL17 mRNA in recipients of β2i/MECL-1&β5i/LMP7-deficient CD4+ T-cells (Figure 3A), while expression levels of IFNγ, IL10 and TNFα did not differ between the different mouse groups (Figure 3B–D). Thus, both iTregs and IL17-producing cells were more frequent in spleens of colitic mice that had been transferred with β2i/MECL-1&β5i/LMP7-deficient CD4+ T-cells than in mice that had received wt CD4+ T-cells.

**Discussion**

Previous studies have shown that proteasome immunosubunits may modify host susceptibility to autoimmune and inflammatory diseases at multiple levels, i.e. by altering MHC class I antigen processing in inflamed tissues, by modulating the ability of cells to cope with cell stress and by modulating signal transduction and transcriptional programs in cells, leading to modified T-cell differentiation [7,10,15,17]. We have used a murine model of T-
Immunosubunit-Deficient T-Cells Drive Inflammation

Figure 3. Cytokine expression in mice with T-cell transfer-induced colitis. Splenocytes of mice with T-cell transfer-induced colitis were stimulated with anti-CD3 mAb for 4 hrs. mRNA was extracted and cytokine expression was quantified by RT-PCR. Expression of (A) IL17a, (B) IFNγ, (C) IL10, and (D) TNFα relative to 18S rRNA is shown for individual mice per experimental group. Bars represent mean±SEM (n = 3–6). *p<0.05. Data are representative of two independent experiments.

doi:10.1371/journal.pone.0095378.g003

cell transfer-induced colitis to further examine the role of the proteasome immunosubunits in inflammatory diseases. We show that naïve CD4+ T-cells of mice that lack the two immunosubunits β2i/MECL-1&β5i/LMP7 cause colitis upon transfer into RAG1+/- mice, which is more severe than colitis induced by transfer of naïve wt CD4+ T-cells. Enhanced colitis scores were associated with enhanced numbers of total splenic CD4+ T-cells, enhanced frequencies and numbers of iTregs and enhanced IL17 expression. Previous studies in humans and DSS-treated mice showed that not only immune cells but also inflamed colon tissue expressed the proteasome immunosubunits [16,21]. In our experiments, the severity of T-cell transfer-induced colitis did not differ between Rag1+/- mice and RAG1+/- mice that had been backcrossed onto an RAG1+/- background (Figure 1), arguing against a role for immunosubunit expression in the inflamed gut in colitis development. This is consistent with prior observations, which showed that transplantation of wt bone marrow rendered β5i/LMP7-deficient mice susceptible to development of DSS-induced colitis [15]. Thus, in the T-cell transfer model, β2i/MECL-1&β5i/LMP7-deficiency in transferred, naïve CD4+ T-cells enhances colitis development in RAG1+/- mice, whereas immunosubunit-deficiency in the targeted gut does not have any effect on colitis development.

Studies by different groups have demonstrated that proteasomes play an important role in cytokine production and that modulation of proteasome subunit composition may alter cytokine production. For example, dendritic cells of LMP2-deficient mice produce less IFNα, IL-6, IL-1β and TNFα following influenza virus infection than wt dendritic cells [12]. This defect was attributed to the formation of mixed proteasomes, containing the immunosubunits β2i/MECL-1 and β5i/LMP7 and the constitutive subunit β1/8, which may diminish transcription of these cytokines by delaying NFκB processing in those cells. A diminished transcription of the same cytokines, IL17 and IL23 was detected also during DSS-induced colitis in β5i/LMP7-deficient, in β1i/1MP2-deficient and in β2i/MECL-1-deficient mice, as well as in mice treated with selective inhibitors targeting the β5i/LMP7 and β5 subunits or the β5i/LMP7 subunit only [15,16]. This was accompanied by a reduced activation of NFκB, in β5i/LMP7-deficient cells [15] and reduced Th1 and Th17 but enhanced Treg cell differentiation of CD4+ T-cells in the lamina propria of β5i LMP7-deficient/inhibitor-treated mice with mild forms of DSS-induced colitis [15–17]. Following T-cell transfer into RAG2+/- mice, Kalim et al. [17] further observed a diminished Th1 and Th17 and enhanced Treg cell differentiation in recipients of β5i/LMP7-deficient CD4+ T-cells, suggesting that differences in T-cell differentiation explain for the relative resistance of inhibitor-treated or β5i/LMP7-deficient mice to development of DSS-induced colitis.

In agreement with Kalim et al. [17], we observe an enhanced differentiation of naïve immunosubunit-deficient CD4+ T-cells into iTregs in adoptively transferred RAG1+/- mice. However, we also find that these iTregs fail to protect the transferred mice against colitis development. Thus, recipients of β2i/MECL-1&β5i/LMP7-deficient T-cells develop colitis six weeks after T-cell transfer, with even higher histological scores and higher quantities of IL17a in the spleens than detected in recipients of wt CD4+ T-cells, despite enhanced numbers and frequencies of iTregs. On the other hand, FACS-purified Tregs derived from β2i/MECL-1&β5i/LMP7-deficient, immunocompetent mice suppress CD4+ T-cell-induced colitis upon cotransfer (not shown), indicating that β2i/MECL-1&β5i/LMP7-deficiency does not disable Treg function. Interestingly, in a recent publication, Basler et al. [22] showed that both β5i/LMP7-deficient and wt mice develop experimental autoimmune encephalitis (EAE) following immunization with the MOG35–55 peptide. Disease intensity did not significantly differ between mouse groups in this study, but was found to be more intense in β5i/LMP7-deficient mice by Seifert et al. [10], using the same model. As Th17 cells play a central role in the onset and maintenance of EAE, these studies indicate that an exchange of β5i/LMP7 for β5 in T-cells does not diminish T-cell-induced inflammatory disease. Moreover, specific inhibition of β5i/LMP7 ameliorated peptide-immunization-induced EAE in wt mice, while specific inhibition of the constitutive proteasome subunit β5 ameliorated EAE in LMP7-deficient mice [22],
indicating that the enzymatic activity of the β5/β5i proteasome active site subunit is critical for CD4+ T-cell function. Taken together, we conclude that the exchange of β5i/LMP7 for β5 in T cells does not abolish but may modulate CD4+ T-cell-mediated disease, with aggravating effects on inflammation in case of T-cell transfer-induced colitis.

While our data show that immunosubunit-deficiency does not ameliorate T-cell transfer-induced colitis, immunosubunit-deficient mice are protected from DSS-induced colitis [15–17]. Although unlikely, it cannot be ruled out that this discrepancy between effects in the two models may be explained by the use of different immunosubunit deficient mice in these studies. While resistance to DSS-induced colitis was observed in single immunosubunit-deficient mice, lacking either β2i/MECL-1 or β5i/LMP7 [15–17], we used β2i/MECL-1 & β5i/LMP7-deficient T-cells to determine the effects of immunosubunit deficiency in development of T-cell transfer colitis. Thus we cannot exclude that specific proteasome subtypes [23,24], present in single immunosubunit-deficient cells but lacking in double immunosubunit-deficient cells, or the other way around, are responsible for the discrepancy between effects of immunosubunit deficiency in colitis induction in the two models. A more likely explanation however lies in the involvement of different immune effector cells in DSS-induced compared to T-cell transfer-induced colitis and perhaps the differing roles of NFκB activation in these cell types. In DSS-induced colitis, inflammation is driven primarily by leukocytes of the innate immune system, such as monocyte-derived macrophages, which are dependent on NFκB activation for cytokine expression. Thus, delayed NFκB processing may modify the cytokine environment in DSS-treated mice and thereby prevent the onset of lead to modest inflammation at most. In T-cell transfer-induced colitis, inflammation is mediated by activated CD4+ T-cells. In T cells, NFκB activation plays a role only during priming, since CD28-mediated costimulatory signals are dependent on the NFκB pathway but once primed, T-cells secrete cytokines mainly upon antigen-induced TCR stimulation. As discussed above, β5i/LMP7-deficient T cells are activated in inflammatory disease models (as well as infection models) and secrete cytokines upon TCR engagement with quantities comparable to those secreted by wt T cells [14,16], thus a possibly delayed NFκB activation does not impair their function.

Taken together, we conclude that immunosubunit deficiency may influence disease processes in different ways, depending on the etiology of disease. Our data argue against any direct attenuating effects on inflammatory CD4+ T-cells but, in contrary, show that β2i/MECL-1 & β5i/LMP7-deficiency enhances CD4+ T-cell-mediated inflammation in T-cell transfer-induced colitis.

Materials and Methods

Mice

C57BL/6 (B6), B6 RAG-1<−/−> or B6 RAG-1−/− β5i/LMP7−/− mice [24] were used for induction of colitis. All experiments were performed with age-matched mice.

Ethics Statement

All animal experiments were carried out in strict accordance with the Dutch Animal Experimentation Act and EU directives 86/609/CEE and 2010/63/EU related to the protection of vertebrate animals used for experimental or other scientific purposes. The experimental protocols were approved by the Committee on Animal Experiments of the University of Utrecht (DEC 2012.II.02.029) and performed in the Central Laboratory Animal Research Facility of the University of Utrecht, which has AAALAC (Association for Assessment and Accreditation of Laboratory Animal Care) accreditation.

T-cell Transfer Colitis Model

To induce colitis, CD4+ CD45RBhi cells were FASC-purified from the spleens of B6 wt and B6 β2i/MECL-1<−/−> or B6 RAG-1−/− β5i/LMP7−/− donor mice, using a BD Influx™ (BD Biosciences). A total of 4×106 CD4+CD45RBhi cells were injected intraperitoneally (i.p.) in 200 µl PBS into B6 RAG-1<−/− or B6 RAG-1−/− β5i/LMP7−/− β2i/MECL-1−/− recipient mice. Mice were monitored for 6 weeks for clinical signs and body weight and then sacrificed. Colonos were flushed with 10% formalin to remove feces, fixed and stored in 70% ethanol for H&E histopathology. Colitis development was evaluated by histology by two independent experts in a blinded fashion, with minor modifications from the protocol described in [20]. In brief, inflammatory infiltrates, depletion of goblet cells and epithelial hyperplasia were scored as specified in Table 1. Scores for specific colon sections represent the sum of scores for these different criteria. The overall histological score per mouse colon is the average of individual scores for the proximal, mid and distal colon segments.

Flow Cytometry and T-cell Stimulation

Spleens were passed through a 70 µm cell strainer to prepare single cell suspensions, and erythrocytes were lysed by treatment with ammonium chloride. Cells for T-cell transfer were stained with anti-CD4 mAb (RM4-5, eBioscience) in the presence of Fc-block, enriched using a BD Influx™ (BD Biosciences) and then were stained with anti-CD45RB (16A, BD Pharmingen) and anti-CD25 (PC61, eBioscience) mAbs and resorted to obtain a CD4+CD45RBhiCD25+ population that was used for induction of colitis. To analyze spleens of T-cell transferred mice, total cell counts in single cell suspensions were determined and cell samples were stained for CD4+ cell surface and intracellular FoxP3 expression (clone FJK-16S, eBioscience) according to manufacturer’s instructions. Cells were measured on a FACSCantoII (BD Biosciences) and analyzed with FlowJo software (Tree Star). To determine cytokine expression, splenocytes were stimulated with or without anti-CD3 mAb (145.2C11, BD Pharmingen, 2 µg/ml) for 4 h, pelleted and then stored at −20°C in TRIzol reagent (Invitrogen, Breda, NL) prior to RNA purification.

Quantitative PCR

RNA was extracted from TRIzol stored samples as instructed (Invitrogen, Breda, NL) and quantified using a Nanodrop ND-1000 (Thermo Scientific, Ethen-Leur, NL). 1 µg of total RNA was reverse transcribed into cDNA synthesis using an iScript cDNA Synthesis Kit (Bio-Rad Laboratories, Veenendaal, NL). TaqMan® Gene Expression Assays (Applied Biosystems, Austin, TX, USA) were used for qRT-PCR amplification and expression of the following genes was assessed: IL17, IFNγ, TNFα and IL10. Relative expression of target genes was calculated using the Pfaffl method with 18S rRNA as a reference gene.

Statistical Analysis

Statistical analyses were performed with GraphPad Prism 4.00 (Graphpad Software, San Diego, CA) using Mann–Whitney U test (+) to compare results between experimental groups. Significant results are at P<0.05.
Table 1. Histological scoring of T-cell transfer colitis.

| Score | Criteria |
|-------|----------|
| 0     | No infiltration of mononuclear cells |
| 1     | Focal infiltration of mononuclear cells in the lamina propria |
| 2     | Multiple foci of mononuclear cells in the lamina propria |
| 3     | Multifocal infiltration distending the lamina propria and/or few cells in the submucosa |
| 4     | Evident infiltration in the lamina propria and submucosa, distending the submucosal space |
| 5     | Severe transmural infiltration of mononuclear cells |

Depletion of goblet cells

| Score | Criteria |
|-------|----------|
| 0     | No loss of goblet cells |
| 1     | Focal loss of goblet cells |
| 2     | Multifocal loss of goblet cells, but with areas with normal appearance |
| 3     | General diminished numbers of goblet cells |
| 4     | Depletion of goblet cells |

Epithelial hyperplasia

| Score | Criteria |
|-------|----------|
| 0     | Normal epithelium |
| 1     | Few areas of mild hyperplasia |
| 2     | Mild epithelial hyperplasia |
| 3     | Severe hyperplasia with crowding of epithelial crypts |

Depletion of goblet cells

| Score | Criteria |
|-------|----------|
| 0     | No loss of goblet cells |
| 1     | Focal loss of goblet cells |
| 2     | Multifocal loss of goblet cells, but with areas with normal appearance |
| 3     | General diminished numbers of goblet cells |
| 4     | Depletion of goblet cells |

Inflammatory infiltrate

| Score | Criteria |
|-------|----------|
| 0     | No infiltration of mononuclear cells |
| 1     | Focal infiltration of mononuclear cells in the lamina propria |
| 2     | Multiple foci of mononuclear cells in the lamina propria |
| 3     | Multifocal infiltration distending the lamina propria and/or few cells in the submucosa |
| 4     | Evident infiltration in the lamina propria and submucosa, distending the submucosal space |
| 5     | Severe transmural infiltration of mononuclear cells |

Supporting Information

Figure S1 Representative histological colon sections. Flow cytometry-sorted naive CD4+ T-cells of B6 (WT) or β2i/MECL-1-/-β5i/LMP7-/- (IS-/-) mice were transferred into RAG1-/- or RAG1-/-β2i/MECL-1-/-β5i/LMP7-/- (IS-/- x RAG1-/-) mice and colitis development was determined 6 weeks later by histological scoring of H&E stained tissue samples [see Materials & Methods]. Pictures were taken at 40x magnification. (A) Infiltrate in the lamina propria and submucosa with multifocal loss of goblet cells and mild epithelial hyperplasia; (B) Infiltrate in the lamina propria and submucosa with focal loss of goblet cells and mild epithelial hyperplasia; (C) Multifocal infiltration in the lamina propria with diminished number of goblet cells and mild epithelial hyperplasia; (D) Evident infiltration distending submucosal plaque with depletion of goblet cells and severe epithelial hyperplasia with crowding of mucosal crypts; (E) Transmural infiltration with depletion of goblet cells and severe hyperplasia; (F) Evident infiltration with loss of goblet cells and severe epithelial hyperplasia; (G) Evident infiltration with multifocal loss of goblet cells and few areas of epithelial hyperplasia; (H) Multifocal infiltration in the lamina propria and loss of goblet cells with severe hyperplasia and crowding of crypts; (I) Multiple foci of inflammatory infiltrate and loss of goblet cells and mild hyperplasia; (J) Transmural infiltration with diminished goblet cells and mild hyperplasia; (K) Evident infiltration with depletion of goblet cells and severe hyperplasia; (L) Evident infiltrate in the lamina propria and submucosa with diminished goblet cells and hyperplasia. Data are representative of two independent experiments.

Author Contributions

Conceived and designed the experiments: OR CM AG DZ. Performed the experiments: OR CM DZ. Analyzed the data: OR CM AG DZ. Wrote the paper: OR DZ AS.

References

1. Alkalay I, Yaron A, Hatzshai A, Orian A, Ciechanover A, et al. (1995) Stimulation-dependent I kappa B alpha phosphorylation marks the NF-kappa B inhibitor for degradation via the ubiquitin-proteasome pathway. Proc Natl Acad Sci U S A 92: 10599–10603.
2. Palombella VJ, Goldberg AL, Maniatis T (1994) Ubiquitin-dependent polyubiquitination and degradation of NF-kappa B1 protein and the activation of NF-kappa B. Cell 78: 773–785.
3. Traenckner EB, Baeuerle PA (1994) B-alpha that is still bound to NF-kappa B. EMBO J 13: 5433–5441.
4. Zaiss DM, Bekker CP, Grone A, Lie BA, Sijts AJ (2011) Proteasome immunosubunit-deficient T-cells drive inflammation. J Exp Med 187: 97–104.
5. Zaiss DM, de Graaf N, Sijs AJ (2008) The proteasome immunosubunit multicatalytic endopeptidase complex-like 1 is a T-cell-intrinsic factor influencing homeostatic expansion. Infect Immun 76: 1207–1213.
6. Zaiss DM, Bech-Otschir D, Voigt A, et al. (2010) Mice completely lacking immunoproteasomes show major changes in antigen presentation. Nat Immunol 13: 129–135.
7. Zaiss DM, Bekker CP, Grone A, Lie BA, Sijs AJ (2011) Proteasome immunosubunits protect against the development of CD8 T cell-mediated autoimmune diseases. J Immunol 187: 2302–2309.
8. Zaiss DM, Bialy LP, Elstein F, Boch-Otschir D, Voigt A, et al. (2010) Immunoproteasomes preserve protein homeostasis upon interferon-induced oxidative stress. Cell 142: 613–624.
9. Pickerling AM, Koop AL, Troh CY, Ermak G, Grune T, et al. (2010) The immunoproteasome, the 20S proteasome and the PA28alphabeta proteasome regulator are oxidative-stress-adaptive proteolytic complexes. Biochem J 432: 585–594.
12. Hensley SE, Zanker D, Dolan BP, David A, Hickman HD, et al. (2010) Unexpected role for the immunoproteasome subunit LMP2 in antiviral humoral and innate immune responses. J Immunol 184: 4115–4122.
13. Qureshi N, Morrison DC, Reis J (2012) Proteasome protease mediated regulation of cytokine induction and inflammation. Biochim Biophys Acta 1823: 2087–2093.
14. Muchamuel T, Basler M, Aujay MA, Suzuki E, Kalim KW, et al. (2009) A selective inhibitor of the immunoproteasome subunit LMP7 blocks cytokine production and attenuates progression of experimental arthritis. Nat Med 15: 781–787.
15. Schmidt N, Gonzalez E, Visekruna A, Kuhl AA, Loddenkemper C, et al. (2010) Targeting the proteasome: partial inhibition of the proteasome by bortezomib or deletion of the immunosubunit LMP7 attenuates experimental colitis. Gut 59: i96–i96.
16. Basler M, Dajee M, Moll C, Groettrup M, Kirk CJ (2010) Prevention of experimental colitis by a selective inhibitor of the immunoproteasome. J Immunol 185: 634–641.
17. Kalim KW, Basler M, Kirk CJ, Groettrup M (2012) Immunoproteasome subunit LMP7 deficiency and inhibition suppresses Th1 and Th17 but enhances regulatory T cell differentiation. J Immunol 189: 4182–4193.
18. Powrie F, Leach MW, Mauze S, Menon S, Caddle LB, et al. (1994) Inhibition of Th1 responses prevents inflammatory bowel disease in scid mice reconstituted with CD45RBhi CD4+ T cells. Immunity 1: 553–562.
19. Coombes JL, Robinson NJ, Maloy KJ, Uhlig HH, Powrie F (2005) Regulatory T cells and intestinal homeostasis. Immunol Rev 204: 184–194.
20. Zaiss DM, van Loosdregt J, Gorlani A, Bekker CP, Gröne A, et al. (2013) Amphiregulin enhances regulatory T cell-suppressive function via the epidermal growth factor receptor. Immunity 30: 275–284.
21. Visekruna A, Joeris T, Seidel D, Kroesen A, Loddenkemper C, et al. (2006) Proteasome-mediated degradation of IkappaBalpha and processing of p105 in Crohn disease and ulcerative colitis. J Clin Invest 116: 3195–3203.
22. Basler M, Munch S, Mochamuel T, Moll C, Jiang J, et al. (2014) Inhibition of the immunoproteasome ameliorates experimental autoimmune encephalomyelitis. EMBO Mol Med 6: 226–238.
23. Dahlmann B, Ruppert T, Kloeziel PM, Kuehn L (2001) Subtypes of 20S proteasomes from skeletal muscle. Biochimia 85: 293–299.
24. Joeris T, Schmidt N, Ermert D, Krienke P, Visekruna A, et al. (2012) The proteasome system in infection: Impact of β5 and LMP7 on composition, maturation and quantity of active proteasome complexes. PLoS One 7(6): e39827. Doi:10.1371/journal.pone.0039827.
25. Caudill CM, Jayarapu K, Elenich L, Monaco JJ, Colbert RA, et al. (2006) T cells lacking immunoproteasome subunits MECL-1 and LMP7 hyperproliferate in response to polyclonal mitogens. J Immunol 176: 4075–82.
26. van Helden MJ, de Graaf N, Bekker CP, Boog CJ, Zais DM, et al. (2011) Immunoproteasome-deficiency has no effects on NK cell education, but confers lymphocytes into targets for NK cells in infected wild-type mice. PLoS One 6(8): e23769. doi:10.1371/journal.pone.0023769.