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ORIGINAL ARTICLE

Bone marrow-mesenchymal stem cells are a major source of interleukin-7 and sustain colitis by forming the niche for colitogenic CD4 memory T cells

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► Additional supplementary data are published online only. To view these files please visit the journal online (<http://dx.doi.org/10.1136/gutjnl-2012-302029>).

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Received 21 September 2012
Accepted 7 October 2012
Published Online First 9 November 2012



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► <http://dx.doi.org/10.1136/gutjnl-2012-303903>

To cite: Nemoto Y, Kanai T, Takahara M, *et al.* *Gut* 2012;**62**:1142–1152.

ABSTRACT

Objective Interleukin (IL)-7 is mainly produced in bone marrow (BM) that forms the niche for B cells. We previously demonstrated that BM also retains pathogenic memory CD4 T cells in murine models of inflammatory bowel disease (IBD). However, it remains unknown whether BM-derived IL-7 is sufficient for the development of IBD and which cells form the niche for colitogenic memory CD4 T cells in BM.

Design To address these questions, we developed mice in which IL-7 expression was specific for BM, and identified colitis-associated IL-7-expressing mesenchymal stem cells (MSC) in the BM.

Results IL-7^{-/-}×RAG-1^{-/-} mice injected with BM cells from IL-7^{+/+}×RAG-1^{-/-} mice, but not from IL-7^{-/-}×RAG-1^{-/-} mice, expressed IL-7 in BM, but not in their colon, and developed colitis when injected with CD4⁺CD45RB^{high} T cells. Cultured BM MSC stably expressed a higher level of IL-7 than that of primary BM cells. IL-7-sufficient, but not IL-7-deficient, BM MSC supported upregulation of Bcl-2 in, and homeostatic proliferation of, colitogenic memory CD4 T cells in vitro. Notably, IL-7^{-/-}×RAG-1^{-/-} mice transplanted with IL-7-sufficient, but not IL-7-deficient, BM MSC expressed IL-7 in BM, but not in their colon, and developed colitis when transplanted with CD4⁺CD45RB^{high} T cells.

Conclusions We demonstrate for the first time that BM MSC are a major source of IL-7 and play a pathological role in IBD by forming the niche for colitogenic CD4 memory T cells in BM.

INTRODUCTION

Inflammatory bowel disease (IBD) is characterised by chronic inflammation of the gastrointestinal tract. Accumulating evidence suggests that IBD is caused by an inappropriate response of the innate and acquired immune systems to commensal microbiota.¹ Even if IBD enters remission as a result of treatment, it often relapses, leading to its lifelong duration. Therefore, we hypothesised that even in remission, colitogenic memory T cells survive for a long period as 'pathogenic memory stem cells'^{2–3} in IBD patients.

Interleukin (IL)-7 is an important cytokine involved in supporting the survival of naive and memory, but not effector, CD4 T cells.^{4–6} IL-7 is secreted by stromal cells in the bone marrow (BM) and thymus, and by epithelial cells.⁷ In a series of studies, we have consistently focused on IL-7 as an

Significance of this study**What is already known on this subject?**

- IL-7 is mainly produced in BM.
- BM stromal cells forms the niche for B cells.
- We have previously reported that colitogenic memory CD4 T cells are retained in BM of IBD model mice in a IL-7-dependent manner.
- MSC have the ability to downmodulate inflammation and improve tissue repair, so their use to treat inflammatory diseases is being explored.

What are the new findings?

- IL-7^{-/-}×RAG-1^{-/-} mice injected with BM cells from IL-7^{+/+}×RAG-1^{-/-} mice, but not from IL-7^{-/-}×RAG-1^{-/-} mice, expressed IL-7 in BM, but not in the colon, and developed colitis when injected with CD4⁺CD45RB^{high} T cells.
- BM MSC produced larger amount of IL-7 than that of primary BM cells.
- IL-7-sufficient, but not IL-7-deficient, BM MSC supported upregulation of Bcl-2 in, and homeostatic proliferation of, colitogenic memory CD4 T cells in vitro.
- IL-7^{-/-}×RAG-1^{-/-} mice transplanted with IL-7-sufficient, but not IL-7-deficient, BM MSC expressed IL-7 in BM, but not in the colon, and developed colitis when transplanted with CD4⁺CD45RB^{high} T cells.

How might it impact on clinical practice in the foreseeable future?

- The present study may be a new example for changing concepts of IBD from intestinal to systemic disease, and a therapeutic approach targeting BM MSC-derived IL-7 may be feasible in the treatment of chronic immune diseases.

essential factor for the persistence of chronic T-cell-mediated colitis. We have shown that: (1) IL-7 is constitutively produced by intestinal goblet cells;⁸ (2) IL-7 transgenic mice, in which strong promoters drive systemic overexpression, develop colitis that mimics the histopathological characteristics of human IBD;⁹ (3) colitogenic CD4 effector memory T (T_{EM}) cells, which express high levels of IL-7Rα, reside in the inflamed lamina propria (LP)

of RAG-2^{-/-} mice injected with CD4⁺CD45RB^{high} T cells;¹⁰ and (4) IL-7^{-/-} × RAG-1^{-/-} mice injected with CD4⁺CD45RB^{high} T cells or colitogenic LP CD4⁺ T_{EM} cells do not develop colitis.¹¹

However, we have found that the IL-7 level of colitic intestine is less than that of normal intestine as a result of the disappearance of goblet cells.¹² Therefore, we hypothesise that colitogenic memory CD4 T cells are maintained outside the intestine as memory stem cells. Because the spleen and lymph nodes are dispensable for the development of chronic colitis,¹³ we found that BM is the main source of IL-7.^{14–15} We previously demonstrated that, in addition to a major subpopulation of T_{EM} cells, a substantial proportion of colitogenic CD4 central memory cells preferentially reside in the BM of colitic mice.^{16–17} Importantly, these resident BM CD4 memory T cells are closely associated with IL-7-producing stromal cells and retain a significant potential to induce colitis after adoptive retransfer into new SCID/RAG-2^{-/-} mice. BM CD4 memory T cells cannot induce colitis when they are transferred into IL-7^{-/-} × RAG-1^{-/-} mice, suggesting that IL-7 plays an essential role in the maintenance of CD4 memory T cells in BM.¹⁶ Using intrarectal administration of CD4 T cells, we also demonstrated that colitogenic memory CD4 T cells constantly recirculate from the LP to BM.¹⁸

However, two important questions remain: whether BM-derived IL-7 is sufficient for the maintenance of colitogenic CD4 memory T cells in the absence of IL-7 produced at other sites, and which cells in BM mainly produce IL-7 and form the niche for colitogenic memory CD4 T cells. To address these questions, we established mice in which IL-7 expression is specific to BM, and attempted to identify the IL-7-expressing cells in BM. Although it is generally accepted that mesenchymal stem cells (MSC) have the ability to downregulate inflammation, and their use to treat inflammatory diseases is being explored, we propose a new hypothesis in which BM MSC,^{19–21} a candidate for the IL-7-producing stromal cells or their progenitors in BM, play a pathological role in the maintenance of colitogenic CD4 memory T cells.

MATERIALS AND METHODS

Animals

C57BL/6 mice were purchased from Japan CLEA (Tokyo, Japan). RAG-2-deficient mice (RAG-2^{-/-}) were obtained from Taconic Laboratory (Hudson, New York, USA) and Central Laboratories for Experimental Animals (Kawasaki, Japan). RAG-1^{+/-} and IL-7^{+/-} mice on the C57BL/6 background were kindly provided by Dr Rose Zamoyska (National Institute for Medical Research, London, UK). These mice were intercrossed to generate RAG-1^{-/-} and IL-7^{-/-} × RAG-1^{-/-} littermate mice. All mice are originally derived from C57BL/6 mice. Mice were maintained under specific pathogen-free conditions in the Animal Care Facility of Tokyo Medical and Dental University. Donors and recipients were used at 6–12 weeks of age. All experiments were approved by the regional animal study committees and performed according to institutional guidelines and Home Office regulations.

See 'more information' in supplementary materials and methods (available online only) for details.

RESULTS

IL-7^{-/-} × RAG-1^{-/-} mice transplanted with BM cells from RAG-1^{-/-} mice develop colitis after adoptive transfer of CD4⁺CD45RB^{high} T cells

We first assessed whether BM-derived IL-7 is sufficient for the development of colitis in the absence of IL-7 produced at other sites. To this end, we used a model of chronic colitis induced by

the adoptive transfer of CD4⁺CD45RB^{high} T cells into RAG-1^{-/-} mice in combination with bone marrow transplantation (BMT) of donor BM cells from RAG-1^{-/-} or IL-7^{-/-} × RAG-1^{-/-} littermate mice. First, RAG-1^{-/-} and IL-7^{-/-} × RAG-1^{-/-} mice were treated with intraperitoneal busulfan and underwent total body irradiation to ablate their BM. The next day, mice were reconstituted with donor BM cells from RAG-1^{-/-} or IL-7^{-/-} × RAG-1^{-/-} mice. Mice were divided into four groups as follows (figure 1A): IL-7^{-/-} × RAG-1^{-/-} mice transplanted with RAG-1^{-/-} BM cells (IL-7^{+/-} → IL-7^{-/-}); IL-7^{-/-} × RAG-1^{-/-} mice transplanted with IL-7^{-/-} × RAG-1^{-/-} BM cells (IL-7^{-/-} → IL-7^{-/-}); RAG-1^{-/-} mice transplanted with RAG-1^{-/-} BM cells (IL-7^{+/-} → IL-7^{+/-}) and RAG-1^{-/-} mice transplanted with IL-7^{-/-} × RAG-1^{-/-} BM cells (IL-7^{-/-} → IL-7^{+/-}). Four weeks after recovery from BMT, all groups of mice were injected intraperitoneally with CD4⁺CD45RB^{high} T cells (figure 1A). As expected, IL-7^{+/-} → IL-7^{+/-} mice developed severe colitis. Interestingly, IL-7^{-/-} → IL-7^{+/-} mice also developed colitis at a level similar to that of IL-7^{+/-} → IL-7^{+/-} mice (figure 1B–E), indicating that non-hematopoietic cells, including IL-7-producing BM stromal cells and/or BM stem cells that differentiated into IL-7-producing stromal cells, could not be completely ablated by the current busulfan/irradiation protocol. In contrast, IL-7^{-/-} → IL-7^{-/-} mice did not develop colitis because of the lack of IL-7 (figure 1B–E). However, to our surprise, the clinical findings revealed that IL-7^{+/-} → IL-7^{-/-} mice injected with CD4⁺CD45RB^{high} T cells developed a wasting disease and severe colitis to a similar extent to that of control IL-7^{+/-} → IL-7^{+/-} mice (figure 1B–E), indicating that the BMT protocol led to successful transplantation of IL-7-producing BM cells in IL-7^{+/-} → IL-7^{-/-} mice.

A quantitative evaluation of T-cell expansion was performed by counting LP, spleen and BM CD4 T cells. While only a few CD4 T cells were recovered from all sites examined in IL-7^{-/-} → IL-7^{-/-} mice, approximately 100-fold higher numbers of LP, spleen and BM CD4 T cells were recovered from IL-7^{+/-} → IL-7^{-/-}, IL-7^{+/-} → IL-7^{+/-} and IL-7^{-/-} → IL-7^{+/-} mice (figure 1F). In addition, on in-vitro stimulation, LP CD4 T cells from IL-7^{+/-} → IL-7^{-/-}, IL-7^{+/-} → IL-7^{+/-} and IL-7^{-/-} → IL-7^{+/-} mice produced equal and significantly higher amounts of interferon (IFN)-γ, tumour necrosis factor (TNF)α and IL-17 than those from IL-7^{-/-} → IL-7^{-/-} mice (figure 1G). Flow cytometric analysis revealed that the CD4 T cells isolated from the LP, mesenteric lymph nodes, spleen and BM of all recipients at 8 weeks after transfer of CD4⁺CD45RB^{high} T cells had a characteristic CD69⁺IL-7Rα^{high} phenotype (see supplementary figure S1, available online only), indicating that the transferred CD4⁺CD45RB^{high} T cells differentiated into activated T_{EM} cells irrespective of the presence of IL-7. These results suggest that BM-derived IL-7 promotes the development and persistence of colitis primarily by supporting the expansion of colitogenic CD4 T_{EM} cells in the colon.

We performed highly sensitive reverse transcription PCR for the detection of IL-7 messenger RNA using samples obtained from the BM and colon. As shown in figure 1H, IL-7 mRNA was detected in the BM of IL-7^{+/-} → IL-7^{-/-}, IL-7^{+/-} → IL-7^{+/-} and IL-7^{-/-} → IL-7^{+/-} mice with colitis, but not in that of IL-7^{-/-} → IL-7^{-/-} mice without colitis. Of note, IL-7 mRNA was detected in the LP of IL-7^{+/-} → IL-7^{+/-} and IL-7^{-/-} → IL-7^{+/-} mice, but not in IL-7^{+/-} → IL-7^{-/-} or IL-7^{-/-} → IL-7^{-/-} mice regardless of the development of colitis, indicating that after BMT, IL-7^{+/-} BM cells led to the establishment of IL-7-producing stromal cells in BM. Consistent with this result, immunohistochemistry revealed that IL-7 was in the BM of IL-7^{+/-} → IL-7^{-/-}, IL-7^{+/-} → IL-7^{+/-} and IL-7^{-/-} → IL-7^{+/-} mice with colitis, but not in IL-7^{-/-} → IL-7^{-/-} mice without colitis (figure 1I). However, IL-7 protein

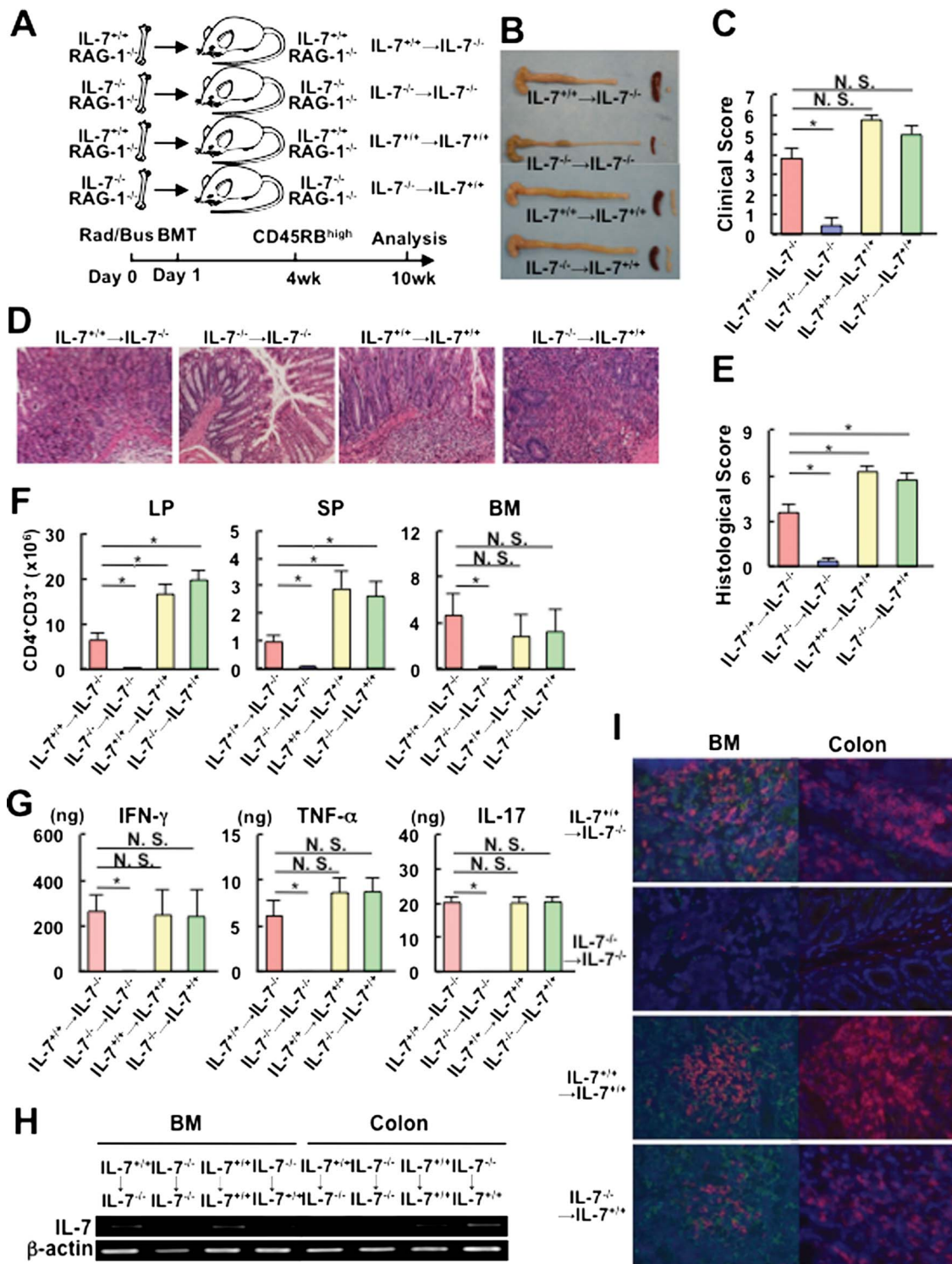
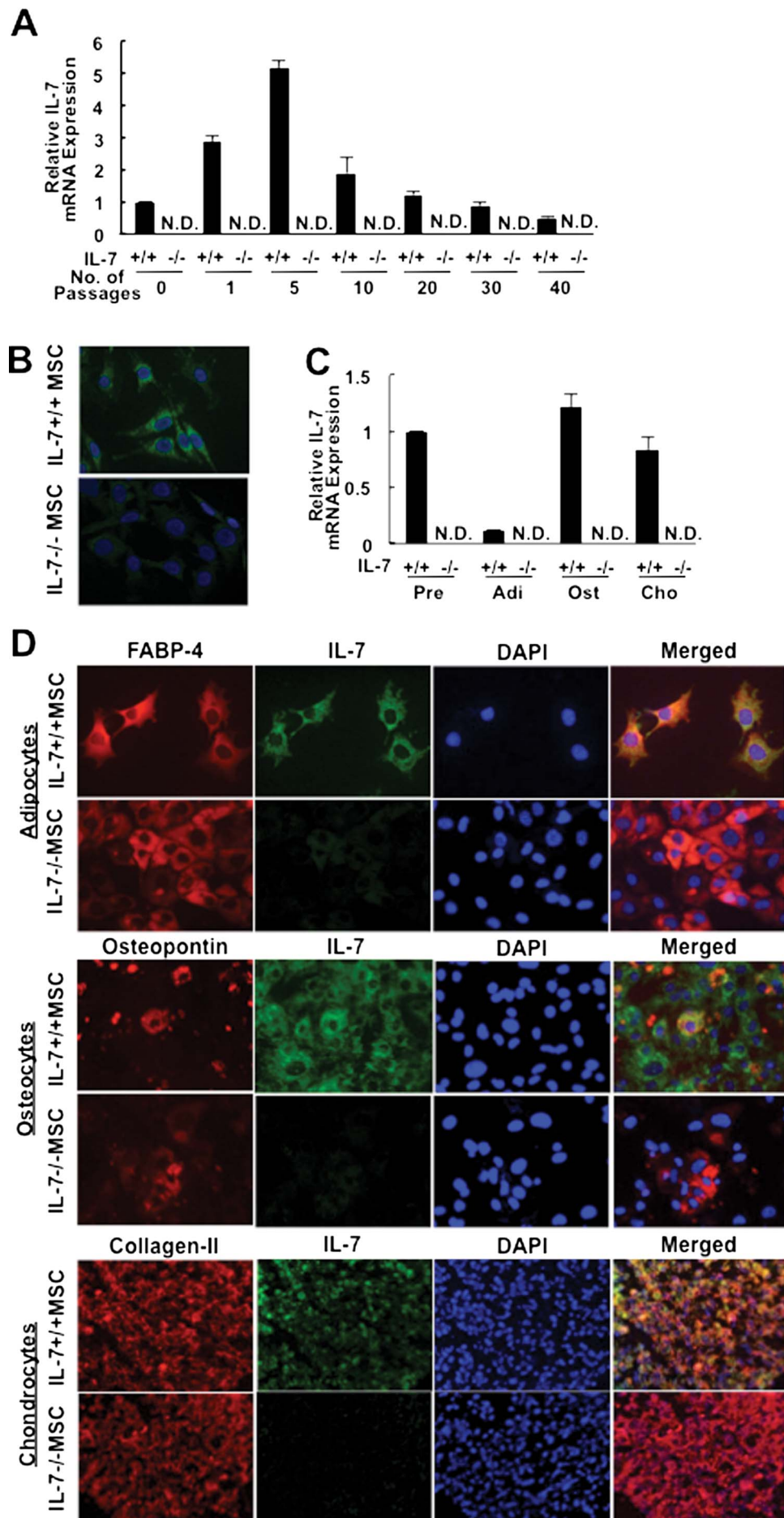


Figure 1 CD4⁺CD45RB^{high} T-cell-injected IL-7^{-/-}×RAG-1^{-/-} recipients pretransplanted with bone marrow (BM) cells from IL-7^{+/+}×RAG-1^{-/-} mice develop colitis. (A) Experimental design. Mice were divided into four groups (n=8). Each group was injected intraperitoneally with CD4⁺CD45RB^{high} T cells at 4 weeks after bone marrow transplantation. (B) Gross appearance of the colon, mesenteric lymph nodes and spleen (SP) from mice of each group at 10 weeks after cell administration. (C) Clinical scores determined at 10 weeks after administration as described in Materials and methods section. Data are shown as the mean±SEM for eight mice in each group, *p<0.01. (D) Histopathology of the distal colon of the indicated mice. Original magnification, ×200. (E) Histological scores. Data are shown as the mean±SEM for eight mice in each group, *p<0.05. (F) Absolute number of lamina propria (LP) CD3⁺CD4⁺ T cells from the colon. Data are shown as the mean±SEM. N.S., not significant, *p<0.01. (G) Cytokine production by LP CD4 T cells. LP CD4 T cells were isolated and stimulated in vitro. IFN-γ, TNF-α and IL-17 concentrations in culture supernatants were measured by ELISA. Data are shown as the mean±SEM for eight mice in each group, *p<0.05. (H) Expression of IL-7 mRNA in colonic BM and the colon from the indicated mice as detected by reverse transcription PCR. (I) Frozen sections of BM and the colon from each mouse were stained with a polyclonal anti-IL-7 antibody. Original magnification ×400.



was not detected in any group regardless of the presence of colitis by immunohistochemistry, indicating that IL-7-producing goblet cells were depleted in the inflamed mucosa of colitic mice, a phenomenon known as 'goblet depletion' in the pathology of human IBD.¹² Collectively, these data suggest that BM-derived stem cells become established in the BM after BMT and thereafter produce IL-7.

BM MSC from RAG-1^{-/-} mice express IL-7 mRNA and protein

As shown in figure 1I, IL-7-producing cells were colonised in the BM, but not in the colon of IL-7^{+/+} → IL-7^{-/-} mice even at 10 weeks after BMT, suggesting that the BM cells of RAG-1^{-/-} mice include some progenitors of IL-7-producing cells, which preferentially migrate to the BM. BM cells include not only haematopoietic stem cells, which can differentiate into granulocytes, macrophages, natural killer cells, B cells, T cells and other haematopoietic cells, but also MSC, which can differentiate into adipose tissue, cartilage, bone and other mesenchymal tissues, and both stem cells preferentially migrate to the BM after BMT.²⁰ Because it is well known that IL-7 is not secreted from haematopoietic cells, but from stromal cells in BM, we hypothesised that MSC are the progenitors of IL-7-producing cells in BM. To test this hypothesis, we cultured MSC derived from the BM of RAG-1^{-/-} and IL-7^{-/-} × RAG-1^{-/-} mice using a current standard protocol.²¹ First, IL-7 mRNA expression in cultured MSC at passages 0–40 was assessed by real-time PCR. Surprisingly, MSC derived from the BM of RAG-1^{-/-} mice (IL-7^{+/+} MSC), but not from IL-7^{-/-} × RAG-1^{-/-} mice (IL-7^{-/-} MSC), strongly expressed IL-7 mRNA at passages 1–40, which peaked at passage 5 (figure 2A). Furthermore, a substantial proportion of cultured IL-7^{+/+} MSC, but not IL-7^{-/-} MSC, expressed IL-7 protein that was detected by immunohistochemistry (figure 2B). MSC derived from both RAG-1^{-/-} and IL-7^{-/-} × RAG-1^{-/-} mice expressed MSC markers Sca-1, CD140a, CD73 and CD105, but not haematopoietic markers CD11b, Gr-1, TER119, CD3, CD45 and CD34 or endothelial markers CD146, FLK1 and VEGFR3 (see supplementary figure S2, available online only). In contrast, whole BM cells from RAG-1^{-/-} and IL-7^{-/-} × RAG-1^{-/-} mice included various types of haematopoietic cells (see supplementary figure S2, available online only). We confirmed that these cultured BM MSC had the ability to differentiate into three mesenchymal lineages: adipocytes, osteocytes and chondrocytes (figure 2D). Importantly, IL-7^{+/+} MSC and IL-7^{+/+} MSC-derived adipocytes, osteocytes and chondrocytes expressed IL-7 mRNA in sharp contrast to that of cells derived from IL-7^{-/-} mice (figure 2C). This result was also confirmed by immunohistochemistry analysis (figure 2D). We thus identified MSC not only as the progenitors of IL-7-producing cells, but also the highly IL-7-producing cells in BM.

MSC suppress activation of CD4 T cells, but support maintenance of memory CD4 T cells in vitro

Given the evidence of IL-7^{+/+} BM MSC that express high levels of IL-7, we next assessed the role of BM MSC in the

maintenance of colitogenic CD4 memory T cells in vitro. First, we attempted to confirm the hallmark character of the immunosuppressive ability of MSC.¹⁹ To this end, CD4⁺CD25⁻ T cells isolated from the spleen of wild-type mice were labelled with carboxyfluorescein diacetate succinimidyl ester (CFSE), and then co-cultured with IL-7^{+/+} or IL-7^{-/-} MSC in the presence of an anti-CD3 antibody and mitomycin-C-treated CD4 negative cells, which are used as antigen presenting cells. At 4 days after co-culture, CD4⁺CD25⁻ T cells were collected and analysed (see supplementary figure S3A, available online only). Both IL-7^{+/+} and IL-7^{-/-} MSC suppressed the proliferation of responder T cells, while those cultured without MSC proliferated extensively (see supplementary figure S3B–D, available online only).

We next conducted long-term co-culture with colitogenic CD4 T_{EM} cells and MSC to assess the ability of MSC to support memory CD4 T cells (figure 3). CFSE-labelled CD4 T cells isolated from colonic LP of colitic RAG-2^{-/-} mice, which had been pre-injected with CD4⁺CD45RB^{high} T cells, were incubated with IL-7^{+/+} or IL-7^{-/-} MSC, or in conditioned medium alone (figure 3A), and CFSE was evaluated after 4 weeks of culture. The absolute number of surviving CD3⁺CD4⁺ T cells that were co-cultured with IL-7^{+/+} MSC was significantly higher than that of the other groups (figure 3B). Consistently, CD4 T cells co-cultured with IL-7^{+/+} MSC slowly divided up to five times in 4 weeks, suggesting that these cells were quiescent and divided intermittently, much like homeostatic proliferation in vivo.²² In sharp contrast, CD4 T cells co-cultured with IL-7^{-/-} MSC or cultured in medium alone did not proliferate (figure 3C). Furthermore, the expression of Bcl-2 in CD4 T cells co-cultured with IL-7^{+/+} MSC was significantly higher than that in other groups (figure 3D, E). These results indicate that IL-7^{+/+} MSC support not only homeostatic proliferation but also the survival of colitogenic CD4 T_{EM} cells in a manner dependent on IL-7-producing MSC. To exclude the possibility that these activities of IL-7^{+/+} MSC are mediated by secondary effects, rather than their production of IL-7, we performed an IL-7-blocking experiment. As shown in figure 3F–H, the ability of IL-7^{+/+} MSC to support colitogenic CD4 T_{EM} cells was almost completely abrogated by an IL-7-blocking antibody (figure 3F–H).

IL-7^{-/-} × RAG-1^{-/-} mice pretransplanted with IL-7-sufficient BM MSC develop colitis after adoptive transfer of CD4⁺CD45RB^{high} T cells

We next conducted an adoptive transfer experiment in conjunction with the transplantation of BM MSC. First, we checked whether cultured MSC could migrate to the BM, spleen and colon, because it is unknown whether these cultured MSC traffic to the same organs compared with those of freshly isolated MSC.²⁰ IL-7^{+/+} MSC were transferred to IL-7^{-/-} × RAG-1^{-/-} mice without the busulfan/irradiation protocol that was used in the previous BMT experiment. At 1, 2 and 4 weeks after the transfer, the expression of IL-7 mRNA and protein in

Figure 2 Bone marrow (BM) mesenchymal stem cells (MSC) from IL-7^{+/+} × RAG-1^{-/-} mice express IL-7 mRNA and protein. (A) Expression of IL-7 mRNA in IL-7^{+/+} and IL-7^{-/-} MSC at various passages and in freshly isolated BM cells from RAG-1^{-/-} (IL-7^{+/+} BM cells) and IL-7^{-/-} × RAG-1^{-/-} (IL-7^{-/-} BM cells) mice were determined by real-time PCR. Data are relative mRNA expression levels in MSC at each passage compared with that in IL-7^{+/+} BM cells. (B) Adherent monolayer of cultured MSC stained with a polyclonal anti-IL-7 antibody. Original magnification ×400. (C) Real-time PCR was performed to check the expression of IL-7 mRNA in differentiated tissues derived from IL-7^{+/+} and IL-7^{-/-} MSC. Data are relative mRNA expression levels in each differentiated cell type compared with that in IL-7^{+/+} pre-MSC. (D) Adherent monolayer of differentiated tissues derived from IL-7^{+/+} and IL-7^{-/-} MSC were stained with anti-FABP-4, anti-osteopontin, anti-collagen-II (all red) and anti-IL-7 (green) antibodies and DAPI (blue). Original magnification ×400.

the BM, spleen and colon of recipient mice was determined (figure 4A). As shown in figure 4B and C, at each time point, IL-7 mRNA and protein was detected in the BM, but not in the spleen or colon.

Given the evidence of IL-7-producing MSC that migrate to the BM, 1×10^6 IL-7^{+/+} or IL-7^{-/-} MSC were transplanted into IL-7^{-/-} × RAG-1^{-/-} mice. At 4 weeks after transplantation, CD4⁺CD45RB^{high} T cells were injected into the pretransplanted mice (figure 5A). At 6 weeks after transfer, the colon from IL-7^{+/+} MSC-transplanted mice, but not that from IL-7^{-/-} MSC-transplanted mice, was enlarged and had a greatly thickened wall (data not shown). Overall, the assessment of colitis by

clinical scoring showed a clear difference between mice that received IL-7^{+/+} or IL-7^{-/-} MSC (figure 5B). This result was confirmed by histological examination of multiple colon sections (figure 5C, D). The absolute number of CD3⁺CD4⁺ T cells recovered from the BM, spleen and LP of IL-7^{+/+} MSC-transplanted mice was significantly higher than that from IL-7^{-/-} MSC-transplanted mice (figure 5E). Flow cytometric analysis revealed that CD4 T cells isolated from the BM, spleen and LP of IL-7^{+/+} MSC-transplanted mice at 6 weeks after transfer of CD4⁺CD45RB^{high} T cells had a characteristic CD44⁺CD62L⁻CD69⁺IL-7Rα^{high} effector memory phenotype (see supplementary figure S4, available online only). Furthermore, on in-vitro stimulation, LP CD4 T cells from IL-7^{+/+} MSC-transplanted mice produced significantly higher amounts of IFN-γ, TNFα and IL-17 than those from IL-7^{-/-} MSC-transplanted mice (figure 5F). More importantly, IL-7 mRNA and protein were detected in the BM, but not the colon, of IL-7^{+/+} MSC-transplanted mice, and not in either the BM or colon of IL-7^{-/-} MSC-transplanted mice (figure 5G, H). We further compared the number of MSC transplanted into this colitis model, and found that transplantation of 1×10^6 MSC, but not 1×10^5 or 1×10^4 MSC, induced colitis in terms of the clinical score, histology, absolute number of recovered LP CD4 T cells, and cytokine expression (see supplementary figure S5A–H, available online only). This result suggested that insufficient numbers of MSC appropriately migrated to induce colitis because of the loss of their homing receptors during culture.

In addition to the above results, BM MSC have been identified as progenitors of mesenchymal tissues because they can migrate to injured tissues to repair them.²¹ Therefore, transplantation of BM MSC for tissue repair has been proposed based on their stem cell qualities observed in animal models of IBD. In fact, Duijvestein *et al*²³ recently reported the feasibility of autologous BM MSC for the treatment of patients with refractory Crohn's disease. Moreover, recent studies suggest that MSC play a second role in inducing peripheral tolerance by

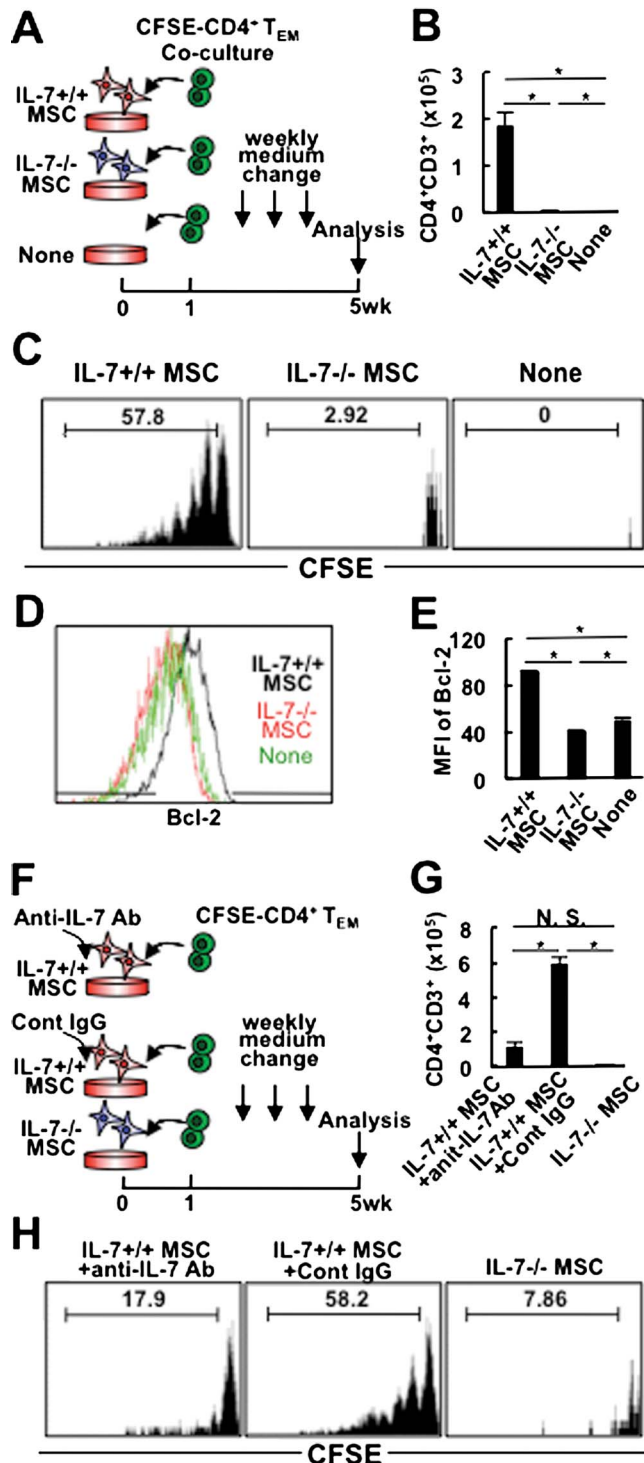
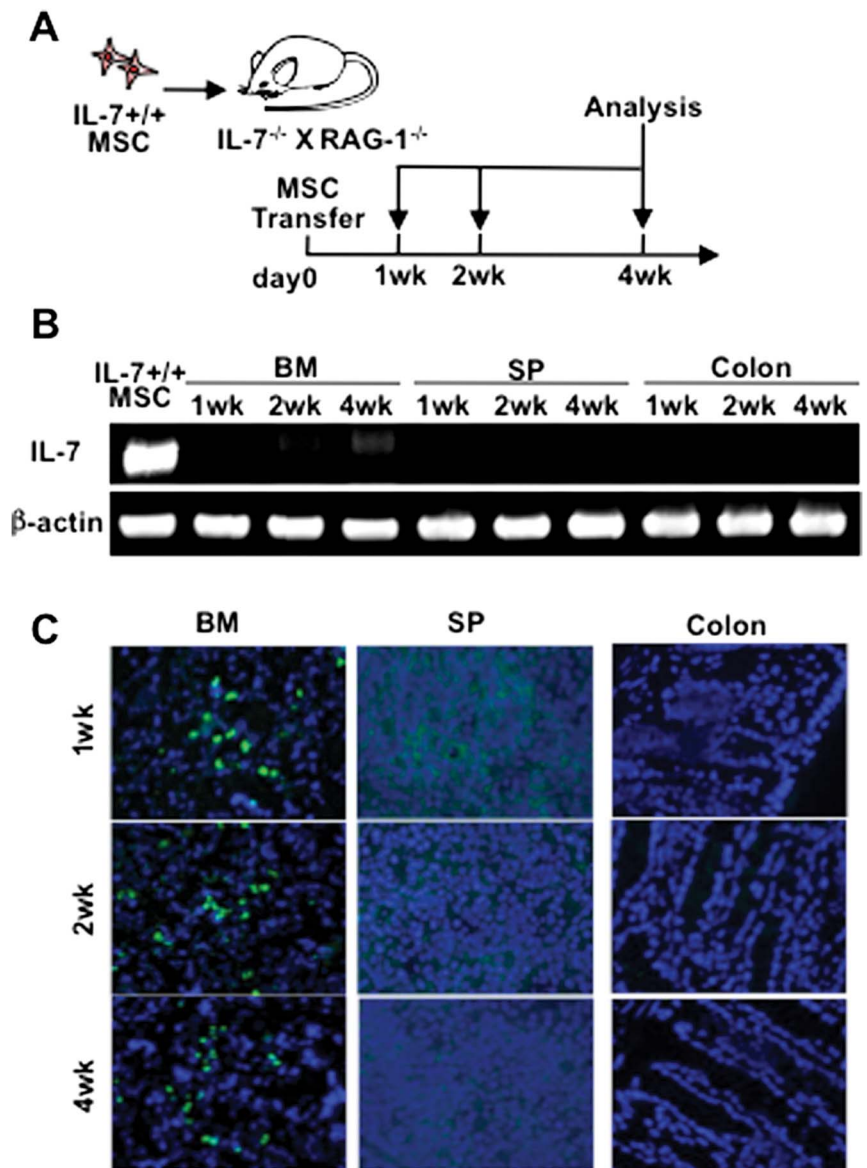


Figure 3 IL-7^{+/+}, but not IL-7^{-/-}, mesenchymal stem cells (MSC) induce extensive proliferation of colitogenic CD4 T cells in vitro. (A) Experimental design. Colitogenic memory CD4 T cells were isolated from colonic lamina propria (LP) of colitic RAG-2^{-/-} mice re-injected with CD4⁺CD45RB^{high} T cells, and labelled with CFSE. CFSE-labelled colitogenic memory CD4 T cells (1×10^6) were then co-cultured with IL-7^{+/+} or IL-7^{-/-} MSC. CFSE-labelled memory CD4 T cells were incubated in conditioned medium as a negative control. (B) Cell counts of recovered CD3⁺CD4⁺ cells were performed by flow cytometry. Data are shown as the mean±SEM of six samples in each group, *p<0.05. (C) After 4 weeks of co-culture, CFSE in memory CD4 T cells was evaluated by flow cytometry. Representative data of six samples are shown. (D) Intracellular staining of Bcl-2 in colitogenic CD4 T_{EM} cells in each group. Colitogenic CD4 T_{EM} cells were co-cultured with IL-7^{+/+} or IL-7^{-/-} MSC, or incubated in conditioned medium alone. (E) Mean fluorescence intensity of Bcl-2 in CD3⁺CD4⁺ cells in each group. Data are shown as the mean±SEM. (F) Experimental design. Colitogenic memory CD4 T cells were isolated from colonic LP of colitic RAG-2^{-/-} mice pre-injected with CD4⁺CD45RB^{high} T cells, and labelled with CFSE. CFSE-labelled colitogenic memory CD4 T cells (1×10^6) were co-cultured with IL-7^{+/+} MSC in medium containing a polyclonal anti-IL-7 antibody or isotype control IgG. CFSE-labelled memory CD4 T cells were co-cultured with IL-7^{-/-} MSC as a negative control. (G) Cell counts of recovered CD3⁺CD4⁺ cells were performed by flow cytometry. Data are shown as the mean±SEM of three samples in each group, *p<0.05. (H) After 4 weeks of co-culture, CFSE in memory CD4 T cells was detected by flow cytometry. Representative data for six samples are shown.

Figure 4 Time course analysis of IL-7 expression in the bone marrow (BM), spleen and colon of IL-7^{-/-} × RAG-1^{-/-} mice pre-injected with IL-7^{+/+} mesenchymal stem cells (MSC). (A) Experimental design. IL-7^{-/-} × RAG-1^{-/-} mice were injected intravenously with IL-7^{+/+} MSC. At 1, 2 and 4 weeks after the transfer, the BM, spleen (SP) and colon of the mice were collected and checked for the expression of IL-7. (B) IL-7 mRNA expression in the BM, spleen and colon at each time point as assessed by quantitative reverse transcription PCR. (C) IL-7 protein expression in the BM, spleen and colon at each time point as assessed by immunohistochemistry. IL-7 (green) and DAPI (blue).



inhibiting the release of proinflammatory cytokines and interacting with various kinds of immune cells.¹⁹ Therefore, we checked whether our cultured MSC could suppress colitis when they were transferred together with CD4⁺CD45RB^{high} T cells to RAG-2^{-/-} mice as a preventive protocol. Mice were divided into four groups as follows: RAG-1^{-/-} mice injected with CD4⁺CD45RB^{high} T cells and IL-7^{+/+} MSC (IL-7^{+/+} MSC); RAG-1^{-/-} mice injected with CD4⁺CD45RB^{high} T cells and IL-7^{-/-} MSC (IL-7^{-/-} MSC); RAG-1^{-/-} mice injected with CD4⁺CD45RB^{high} T cells (RB^{high}) as a positive control; and RAG-1^{-/-} mice injected with CD4⁺CD45RB^{high} T cells and CD4⁺CD25⁺ T cells (RB^{high}+T_{reg}) as a negative control (figure 6A). Both IL-7^{+/+} MSC and IL-7^{-/-} MSC groups developed a wasting disease and colitis with a thickened colon and splenomegaly to the same extent as that in the RB^{high} group, while the RB^{high}+T_{reg}-negative control group gained weight and did not develop colitis (figure 6B–F). A large number of LP CD4 T cells was recovered from IL-7^{+/+} MSC, IL-7^{-/-} MSC, and RB^{high} groups, while only a small number of LP CD4 T cells was recovered from the RB^{high}+T_{reg} group (figure 6G). As shown in figure 6H, on in-vitro stimulation, LP CD4 T cells from IL-7^{+/+}

MSC, IL-7^{-/-} MSC and RB^{high} groups produced equal and significantly higher amounts of IFN- γ , TNF α and IL-17 than those by the RB^{high}+T_{reg} group. These data indicated that, at least in our present in-vivo model, neither IL-7^{+/+} MSC nor IL-7^{-/-} MSC could suppress the development of colitis, even when they were transferred in combination with CD4⁺CD45RB^{high} T cells. Although we performed multiple injections of IL-7^{+/+} and IL-7^{-/-} MSC to suppress colitis and evaluate a therapeutic effect, colitis could not be suppressed in terms of clinical and histological scores, the number of infiltrated LP CD4 T cells and cytokine production (see supplementary figure S6A–G, available online only).

DISCUSSION

BM MSC have previously been identified as progenitors of mesenchymal tissues by migrating to injured tissues to repair them,^{19–21} and transplantation of BM MSC for tissue repair has been proposed based on their stem cell qualities. Moreover, recent studies suggest that cultured MSC play a second role in the induction of peripheral tolerance by inhibiting the release of proinflammatory cytokines and interacting with various kinds of

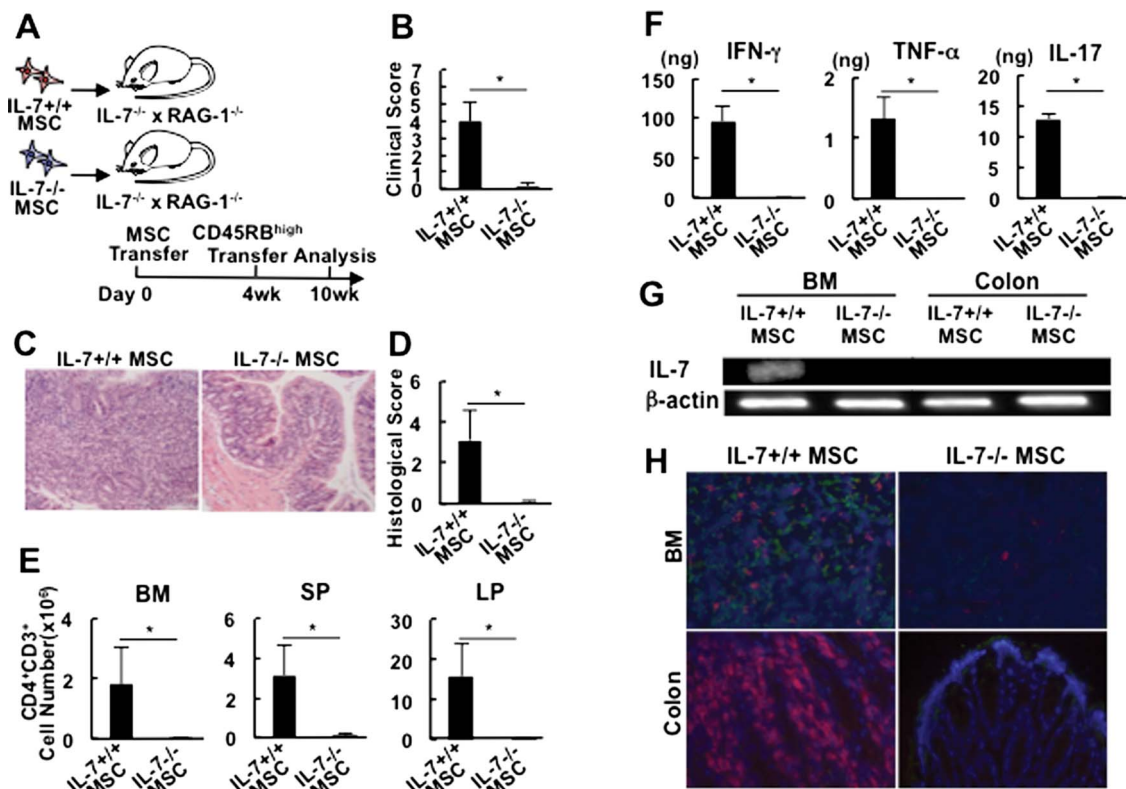


Figure 5 CD4⁺CD45RB^{high} T-cell-injected IL-7^{-/-} × RAG-1^{-/-} mice pretransplanted with IL-7^{+/+}, but not IL-7^{-/-}, mesenchymal stem cells (MSC) develop colitis. (A) Experimental design. Mice were divided into two groups (n=5). Each group was injected intraperitoneally with CD4⁺CD45RB^{high} T cells at 4 weeks after MSC transfer. (B) Clinical scores. Data are shown as the mean ± SEM for five mice in each group, *p<0.05. (C) Histological results for the colons of each group. Original magnification ×200. (D) Histological scores. Data are shown as the mean ± SEM for five mice in each group, *p<0.05. (E) Absolute number of lamina propria (LP) CD3⁺CD4⁺ T cells from the colon at 10 weeks after transfer. Data are shown as the mean ± SEM. N.S. not significant, *p<0.01. (F) Cytokine production by LP CD4 T cells stimulated in vitro. IFN-γ, TNFα and IL-17 concentrations in culture supernatants were measured by ELISA. Data are shown as the mean ± SEM for five mice in each group, *p<0.05. (G) Expression of IL-7 mRNA in the bone marrow (BM) and LP of IL-7^{+/+} MSC- or IL-7^{-/-} MSC-transplanted mice as measured by reverse transcription PCR. (H) Expression of IL-7 protein in the BM and LP of each group of mice as detected by immunohistochemistry.

immune cells. However, the present study clearly shows that: (1) BM MSC produce IL-7; (2) MSC have the potential to support the proliferation and survival of colitogenic CD4 T_{EM} cells; and notably (3) transplantation of BM MSC into IL-7^{-/-} × RAG-1^{-/-} mice induces colitis when the mice are later injected with CD4⁺CD45RB^{high} T cells; and (4) IL-7 expression is maintained in the BM of IL-7^{-/-} × RAG-1^{-/-} mice transplanted with BM MSC. The present study thus suggests the possible participation of IL-7-producing BM MSC as niche cells to maintain colitogenic CD4 memory T cells. Although it is possible that IL-7 produced in BM leads to levels of circulating IL-7 that support local (intracolonic) expansion of T-cell populations, rather than facilitating the formation of a niche in BM for these cells, we previously demonstrated that intrarectally administered colitogenic CD4 T cells surprisingly egress to the colon, migrate to BM.¹⁸ In addition, we have reported that IL-7^{-/-} × RAG-1^{-/-} host mice combined with colitic RAG-2^{-/-} donor mice as a parabiosis develop colitis without IL-7 expression in any organ.¹² Therefore, we concluded that colitogenic memory CD4 T cells as 'memory stem cells' may be supported in some specific niche, such as BM, in which IL-7 is abundant even when in the acute phase of colitis.

Because we used IL-7 as a marker of MSC in this setting, it is possible that transferred MSC can spread to many tissues including inflamed colonic mucosa to become differentiated cells but lose expression of IL-7. However, it remains unknown why IL-7

was not detected in the inflamed colon of IL-7^{-/-} × RAG-1^{-/-} mice after transfer of IL-7^{+/+} MSC with CD4⁺CD45RB^{high} T cells, although MSC-derived adipocytes that expressed IL-7 could not be detected (figure 2C,D). Nevertheless, it is noteworthy that IL-7 production by the transferred MSC was maintained only in the BM regardless of their differentiation status. Therefore, we propose that, in addition to the two major roles previously reported, namely tissue repair^{19–21} and immune suppression,^{19, 20} BM MSC-derived IL-7 is positively involved in the perpetuation of chronic inflammatory diseases by forming the niche for pathogenic CD4 memory T cells in BM (figure 7). Although many differences exist between our colitis model induced by a lymphopenic driver, other murine models, such as dextran sodium sulfate-induced acute colitis model, and human IBD, we propose a pathological role of IL-7-producing MSC at least in our model. Furthermore, the present study supports a conceptual change of IBD from an intestinal to a systemic disease, and suggests therapeutic approaches that target BM MSC-derived IL-7 for the treatment of IBD.

From a clinical viewpoint, we have previously demonstrated that IL-7 protein in the serum of patients with ulcerative colitis (UC) is higher than that in healthy controls.²⁴ Furthermore, IL7R has previously been identified as one of the disease susceptibility genes of UC.²⁵ Therefore, it may be interesting to compare the IL-7 levels in BM, especially in BM MSC, between IBD patients and healthy controls to determine whether BM

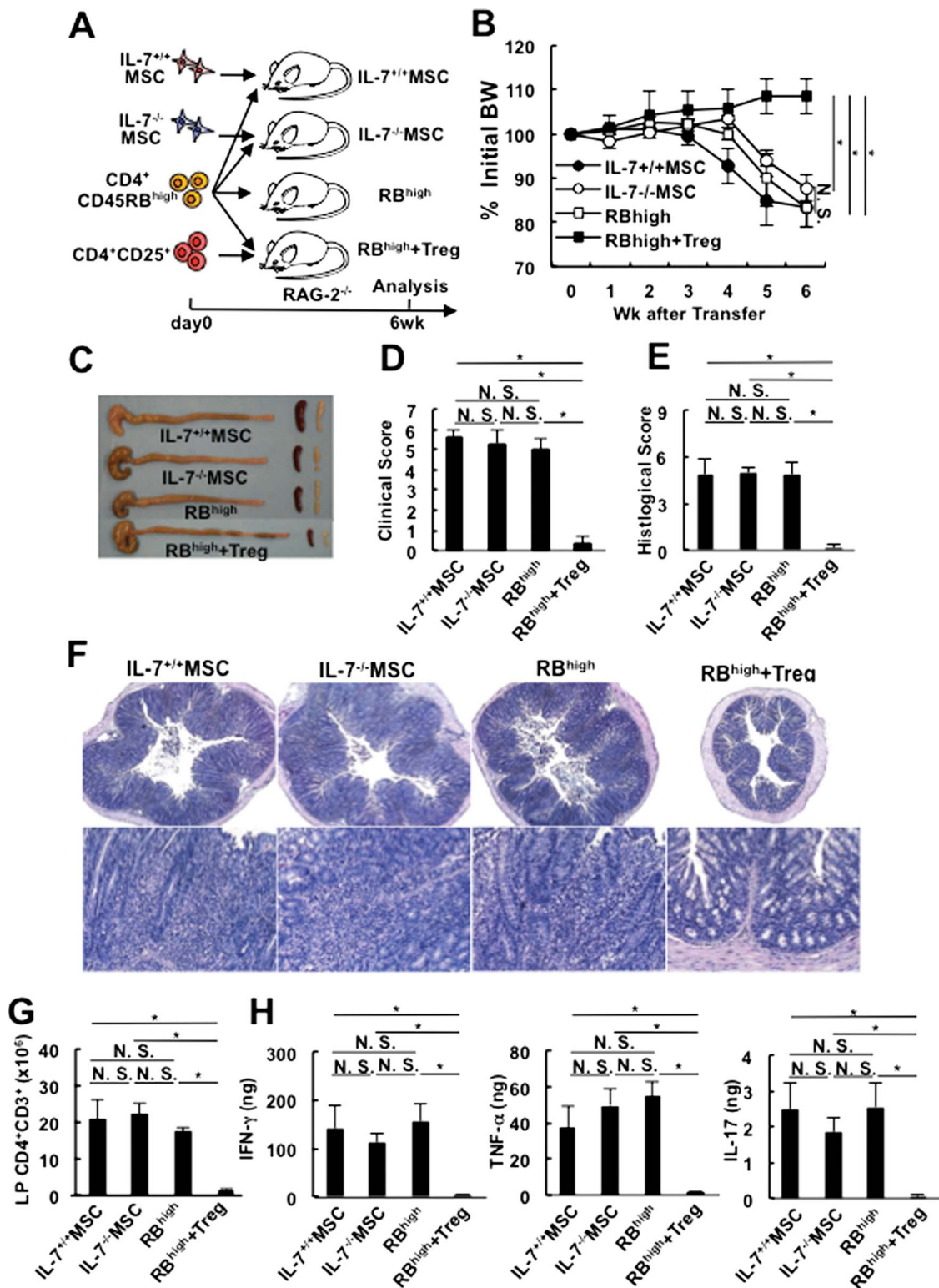
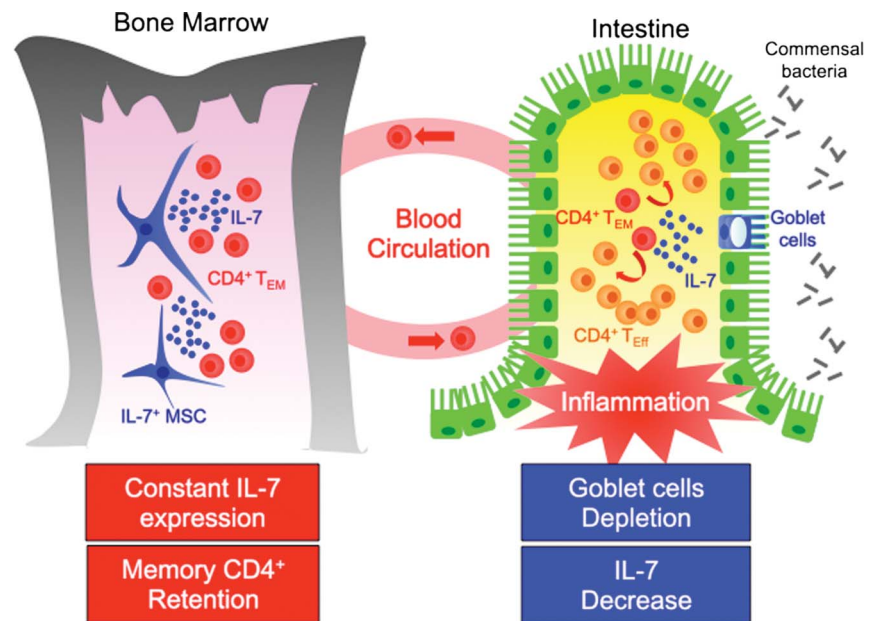


Figure 6 CD4⁺CD45RB^{high} T-cell-injected RAG-1^{-/-} recipients pre-injected with either IL-7^{+/+} or IL-7^{-/-} mesenchymal stem cells (MSC) develop colitis. (A) Experimental design. Mice were divided into four groups as follows: RAG-1^{-/-} mice that were pre-injected with CD4⁺CD45RB^{high} T cells and IL-7^{+/+} MSC (n=3, IL-7^{+/+} MSC); RAG-1^{-/-} mice that were pre-injected with CD4⁺CD45RB^{high} T cells and IL-7^{-/-} MSC (n=3, IL-7^{-/-} MSC); RAG-1^{-/-} mice that were pre-injected with CD4⁺CD45RB^{high} T cells (n=3, RB^{high} cells); and RAG-1^{-/-} mice that were pre-injected with CD4⁺CD45RB^{high} T cells and CD4⁺CD25⁺ T cells (n=3, RB^{high}+Treg cells). (B) Percentage of the initial body weight (BW) of each group. Data are shown as the mean±SEM for three mice in each group, *p<0.05. (C) Representative gross appearance of the spleen, mesenteric lymph nodes and colon of each group. (D) Clinical scores. Data are shown as the mean±SEM for three mice in each group, *p<0.05. (E) Histological scores. Data are shown as the mean±SEM for three mice in each group, *p<0.05. (F) Histopathology of the distal colon of the indicated mice at 6 weeks after transfer. Original magnification, ×40 upper panel and ×200 lower panel. (G) Absolute number of lamina propria (LP) CD3⁺CD4⁺ T cells from the colon at 6 weeks after transfer. Data are shown as the mean±SEM. N.S. not significant, *p<0.01. (H) Cytokine production by LP CD4 T cells. LP CD4 T cells were isolated at 6 weeks after transfer and stimulated with anti-CD3 and anti-CD28 antibodies for 48 h. IFN-γ, TNF-α and IL-17 concentrations in culture supernatants were measured by ELISA. Data are shown as the mean±SEM for three mice in each group, *p<0.05.

Figure 7 Model for the maintenance of colitogenic CD4 T_{EM} cells by bone marrow (BM) mesenchymal stem cell (MSC)-derived IL-7. BM MSC-derived IL-7 plays a role in the maintenance of colitogenic CD4 T_{EM} cells, and may be a clinical target for the treatment of inflammatory bowel diseases.



MSC are responsible for IL-7 production in the pathogenesis of human UC, and a strategy targeting IL-7 might be a feasible clinical approach for the treatment of UC. Furthermore, the current approach for the induction of remission (the acute stage of the disease) using autologous or allogeneic MSC in patients with intractable UC would be considered based on the present finding that MSC may play a pathological role in the maintenance of colitogenic memory T cells (remission stage). However, we would like to emphasise that the present results are consistent with the current concept of using MSC to treat human IBD in ongoing clinical trials, because we also confirmed that our cultured MSC suppressed the proliferation of CD4 T cells in the short-term culture system. Finally, it should be emphasised that the strategy of IL-7 blockade is at an immature stage at this time, because IL-7 is essential not only for colitogenic CD4 T cells but also protective memory CD4 T cells such as regulatory T cells. Therefore, further investigation in this field is warranted.

Overall, in support of previous evidence that BM is a reservoir organ for CD4 memory T cells, we demonstrated for the first time that BM MSC express IL-7 and comprise the key population that forms the niche for colitogenic memory CD4 T cells and causes the persistence of chronic colitis.

Acknowledgements The authors are grateful to R. Zamoyska for providing the mice used in this study.

Contributors YN helped to design the study, performed experiments, analysed the data, and wrote the paper; TK conceived and designed the study, analysed the data, and wrote the paper; MT performed experiments; SO, TN, RO and KT helped to design the study and MW supervised the study.

Funding This study was supported in part by grants-in-aid for scientific research, scientific research on priority areas, exploratory research and creative scientific research from the Japanese Ministry of Education, Culture, Sports, Science and Technology; the Japanese Ministry of Health, Labour and Welfare; the Japan Medical Association; the Foundation for Advancement of International Science; the Terumo Life Science Foundation; the Ohya Health Foundation; the Yakult Bio-Science Foundation; the Research Fund of the Mitsukoshi Health and Welfare Foundation; and the Japan Intractable Disease Research Foundation.

Competing interests None.

Provenance and peer review Not commissioned; externally peer reviewed.

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Revised manuscript # gutjnl-2012-302029

SUPPLEMENTAL INFORMATION

Bone marrow mesenchymal stem cells are major source of IL-7 and sustain colitis by forming the niche for colitogenic CD4⁺ memory T cells

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Supplemental Material and Methods

Generation of MSC. To purify MSC from BM of RAG-1^{-/-}, IL-7^{-/-} × RAG1^{-/-}, we used the Stemcell Technologies (Vancouver, Canada) MesenCult® system as previously described (1). BM cells from compact bone from each group were harvested, and 2.5×10^7 BM cells in 5 ml complete MesenCult® medium, made up of 40 ml MesenCult® MSC basal medium and 10 ml MSC stimulatory supplements, were cultured in a 12 cm dish at 37 °C in 5% CO₂. After 1 wk, nonadherent cells were aspirated and fresh complete MesenCult® medium was added. Thereafter, a half-volume change of complete MesenCult® medium was performed at weekly intervals. Once cells were 80% confluent, they were passaged with trypsin-EDTA. We used MSC after at least the seventh passage, when Sca-1 expression was high and any hematopoietic marker expression

was low. In addition, we did not use MSC after the fortieth passage for *in vitro* or *in vivo* study, because IL-7 expression in IL-7^{+/+} MSC decreased gradually after this time, possibly as a result of gene silencing (Fig. 2A).

Coculture of colitogenic memory CD4⁺ T cells with IL-7^{+/+} or IL-7^{-/-} MSC.

To investigate whether IL-7^{+/+} MSC are sufficient for the maintenance of colitogenic memory CD4⁺ T cells *in vitro*, we performed the following experiment. LP CD4⁺ T cells were obtained from the colon of colitic RAG-2^{-/-} mice previously injected with CD4⁺CD45RB^{high} T cells. These cells were incubated and labeled with CFSE as previously described (2), and 1 × 10⁶ CFSE-labeled colitogenic memory CD4⁺ T cells were cocultured with 80% confluent IL-7^{+/+} or IL-7^{-/-} MSC in complete MesenCult® medium. CFSE-labeled memory CD4⁺ T cells were incubated alone in complete MesenCult® medium as a negative control. Half-volume medium changes were carefully performed in each group so as not to aspirate any cells, and 4 wk later, CFSE expression was checked by flow cytometry.

Intracellular staining of Bcl-2 of the colitogenic CD4⁺ T_{EM} cells cocultured with IL-7^{+/+} or IL-7^{-/-} MSC. To clarify further the mechanism of maintenance of colitogenic memory CD4⁺ T cells by IL-7^{+/+} MSC, we checked the expression of Bcl-2 in the CD4⁺ T_{EM} cells cocultured with IL-7^{+/+} or IL-7^{-/-} MSC. Colitogenic CD4⁺ T_{EM} cells were obtained and cocultured as described above. Two days later, staining of intracellular Bcl-2 in the recovered cells was performed and analyzed by flow cytometry. For the IL-7 blocking experiment, 1 × 10⁶ CFSE-labeled colitogenic memory CD4⁺ T cells were cocultured with 80% confluent IL-7^{+/+} MSC in complete MesenCult® medium that included 10 µg/ml of anti-IL-7 polyclonal antibody (R&D Systems) or the same concentration of control IgG.

CFSE-labeled memory CD4⁺ T cells were incubated with 80% confluent IL-7^{+/+} MSC as a negative control. Half-volume medium changes with complete medium including anti-IL-7 antibody or control IgG or with medium alone were carefully performed in each group so as not to aspirate any cells, and 4 wk later, CFSE expression was checked by flow cytometry.

MSC suppression assay *in vitro*

First, IL-7^{+/+} MSC and IL-7^{-/-} MSC were cultured in respective well. The next day, CFSE-labeled CD4⁺CD25⁻ cells, anti-CD3 antibody and Mitomycin-C treated CD4⁻ cells, which are used as antigen presenting cells, were added. Well of CD4⁺CD25⁻ cells, anti-CD3 antibody and CD4⁻ cells were used as positive control. Well of CD4⁺CD25⁻ cells and CD4⁻ cells without anti CD3 antibody was used as negative control. Four days after the co-culture started, expression of CFSE on CD4⁺CD25⁻ cells in each well was detected by flow cytometer. n=3

BMT and induction of colitis. To assess the specific necessity for BM-derived IL-7 in the development and persistence of colitis, we performed an adoptive transfer experiment in combination with BMT using RAG-1^{-/-} and IL-7^{-/-} × RAG-1^{-/-} littermate recipients (Fig. 1A). Mice first were administered 10 mg/kg busulfan (Sigma-Aldrich) intraperitoneally, and thereafter they underwent whole-body irradiation with a total of 5 Gy to ablate their BM. On the next day, mice were reconstituted with 5×10^6 donor BM cells via a single tail vein injection and were used for adoptive transfer experiments after 4 wk recovery. For the adoptive transfer, CD4⁺ T cells were first isolated from spleens of C57BL/6 mice using the anti-CD4 (L3T4)-MACS system (Miltenyi Biotec, Auburn, CA) according to the manufacturer's instructions. Enriched CD4⁺ T cells (96–97% pure, as estimated by flow cytometry [FACS Calibur, Becton

Dickinson, Sunnyvale, CA]) were then labeled with PE-conjugated anti-mouse CD4 (RM4-5; BD Pharmingen, San Diego, CA) and FITC-conjugated anti-CD45RB (16A; BD Pharmingen). CD4⁺CD45RB^{high} T cells were isolated using a FACS Aria cell sorter (Becton Dickinson). This population was > 98.0% pure on reanalysis. Mice were divided into four groups as follows: Group 1, IL-7^{-/-} × RAG-1^{-/-} mice (n = 8) that had been transplanted with male RAG-1^{-/-} BM cells and subsequently injected with CD4⁺CD45RB^{high} T cells; Group 2, IL-7^{-/-} × RAG-1^{-/-} mice (n = 8) that had been transplanted with IL-7^{-/-} × RAG-1^{-/-} BM cells and subsequently injected with CD4⁺CD45RB^{high} T cells; Group 3, RAG-1^{-/-} mice (n = 8) that had been transplanted with RAG-1^{-/-} BM cells and subsequently injected with 3 × 10⁵ CD4⁺CD45RB^{high} T cells; and Group 4, RAG-1^{-/-} mice (n = 8) that had been transplanted with IL-7^{-/-} × RAG-1^{-/-} BM cells and subsequently injected with CD4⁺CD45RB^{high} T cells.

All mice were observed for clinical signs such as hunched posture, piloerection, diarrhea, and blood in the stool. At autopsy, mice were assessed by a clinical score (3) that is the sum of three parameters: hunching and wasting, 0 or 1; colon thickening, 0–3 (0, no colon thickening; 1, mild thickening; 2, moderate thickening; 3, extensive thickening); and stool consistency, 0–3 (0, normal beaded stool; 1, soft stool; 2, diarrhea; 3, bloody stool) (4).

MSC transfer and time course detection of IL-7. IL-7^{+/+} MSC (1 × 10⁶) were transferred to IL-7^{-/-} × RAG-1^{-/-} mice via a single tail vein injection. One, 2, and 4 wk after the transfer, mice (n = 3) were sacrificed, and the expression of IL-7 mRNA in the BM, SP and colon was checked by RT-PCR, while IL-7 protein was checked by immunohistochemistry.

MSC transfer and induction of colitis. To assess the importance of MSC as the main source of IL-7 for the persistence of chronic colitis, we performed the following *in vivo* experiment. MSC were cultured and purified as described above. Mice were then injected with 1×10^6 IL-7^{+/+} or IL-7^{-/-} MSC via a single tail vein injection and were used for adoptive transfer experiments after 3 wk. Mice were divided into two groups as follows: Group 1, IL-7^{-/-} × RAG-1^{-/-} mice (n = 5) that had been transplanted with IL-7^{+/+} MSC and subsequently injected with CD4⁺CD45RB^{high} T cells; Group 2, IL-7^{-/-} × RAG-1^{-/-} mice (n = 5) that had been transplanted with IL-7^{+/+} MSC and subsequently injected with CD4⁺CD45RB^{high} T cells. All mice were observed for clinical signs and assessed for a clinical score as described above.

Simultaneous transfer of MSC and CD4⁺CD45RB^{high} T cells to RAG-2^{-/-} mice. We checked whether our cultured MSC could suppress colitis when they were transferred to RAG-2^{-/-} mice simultaneously with CD4⁺CD45RB^{high} T cells. Mice were divided into four groups as follows. Group 1: RAG-2^{-/-} mice were injected with 1×10^6 IL-7^{+/+} MSC via a single tail vein injection and simultaneously injected intraperitoneally with 3×10^5 CD4⁺CD45RB^{high} T cells (n = 3). Group 2: RAG-2^{-/-} mice were injected with 1×10^6 IL-7^{-/-} MSC via a single tail vein injection and simultaneously injected intraperitoneally with 3×10^5 CD4⁺CD45RB^{high} T cells (n = 3). Group 3: RAG-2^{-/-} mice were injected intraperitoneally with 3×10^5 CD4⁺CD45RB^{high} T cells alone (n = 3). Group 4: RAG-2^{-/-} mice were injected intraperitoneally with 3×10^5 CD4⁺CD45RB^{high} T cells and 3×10^5 CD4⁺CD25⁺ T cells (n = 3). All mice were observed for clinical signs and were assessed for a clinical score as described above.

Adoptive transfer of different numbers of IL-7^{+/+} MSC in CD4⁺CD45RB^{high} T cells transfer. 1x10⁶ (Gr. 1), 1x10⁵ (Gr. 2) or 1x10⁴ (Gr. 3) IL-7^{+/+} MSC were transferred to IL-7^{-/-} x RAG-1^{-/-} mice via a single tail vein injection. Four weeks after MSC transfer, each mouse was transferred with 3 x 10⁵ CD4⁺CD45RB^{high} T cells sorted from splenocyte of C57BL/6 mice intraperitoneally. Fourteen weeks after MSC transfer, mice were sacrificed and analyzed. n=5 in each group.

Multiple injection of MSC in CD4⁺CD45RB^{high} T cells transfer colitis. 3 x 10⁵ CD4⁺CD45RB^{high} T cells were transferred into RAG-2^{-/-} mice intraperitoneally. At the same time, 1 x 10⁶ IL-7^{+/+} MSC (IL-7^{+/+} MSC) and 1 x 10⁶ IL-7^{-/-} MSC (IL-7^{+/+} MSC) were transferred intravenously. In addition, they were also transferred 1 and 2 weeks after the RB^{high} T cells injection. As positive control, CD4⁺CD45RB^{high} T cells alone were transferred into RAG-2^{-/-} mice (RB^{high}). As negative control, 3 x 10⁵ CD4⁺CD25⁺ regulatory T cells were co-transferred with CD4⁺CD45RB^{high} T cells into RAG-2^{-/-} mice (RB^{high} + Treg). n=5 in each group. Six weeks after MSC transfer mice were sacrificed and analyzed.

MSC differentiation assay. IL-7^{+/+} MSC and IL-7^{-/-} MSC were induced to differentiate to adipocytes, osteocytes and chondrocytes using the Mouse Mesenchymal Stem Cell Functional Identification Kit® (R&D Systems). After differentiation, adherent cells were stained with anti-FABP-4 antibody for adipocytes, anti-osteopontin antibody for osteocytes and anti-collagen-II antibody for chondrocytes, together with polyclonal anti-IL-7 antibody in multicolor immunohistochemistry. Differentiated cells were also collected using trypsin-EDTA, RNA was purified and RT-PCR was performed to check the expression of IL-7 mRNA.

Histological examination. Tissue samples were fixed in PBS containing 6% neutral-buffered formalin. Paraffin-embedded sections (5 mm) were stained with H&E. Three tissue samples from the proximal, middle, and distal parts of the colon were prepared. The sections were analyzed without prior knowledge of the type of T cell reconstitution or treatment. The area most affected was graded by the number and severity of lesions. The mean degree of inflammation in the colon was calculated using a modification of a previously described scoring system (4), as follows. Mucosal damage: 0, normal; 1, 3–10 intraepithelial leukocytes (IEL)/high power field (HPF) and focal damage; 2, >10 IEL/HPF and rare crypt abscesses; 3, >10 IEL/HPF, multiple crypt abscesses and erosion/ulceration. Submucosal damage: 0, normal or widely scattered leukocytes; 1, focal aggregates of leukocytes; 2, diffuse leukocyte infiltration with expansion of submucosa; 3, diffuse leukocyte infiltration. Muscularis damage: 0, normal or widely scattered leukocytes; 1, widely scattered leukocyte aggregates between muscle layers; 2, leukocyte infiltration with focal effacement of the muscularis; 3, extensive leukocyte infiltration with transmural effacement of the muscularis.

Tissue preparation. Single cell suspensions were prepared from SP, MLN, LP, and BM as previously described (2). To isolate LP CD4⁺ T cells, the entire length of colon was opened longitudinally, washed with PBS, and cut into small pieces. The dissected mucosa was incubated with Ca²⁺-, Mg²⁺-free Hanks' balanced salts solution containing 1 mM DTT (Sigma-Aldrich) for 45 min to remove mucus and then treated with 3.0 mg/ml collagenase (Roche Diagnostics GmbH, Germany) and 0.01% DNase (Worthington Biomedical Co., Freehold, NJ) for 2 h. The cells were pelleted twice through a 40% isotonic

Percoll solution and then subjected to Ficoll–Hypaque density gradient centrifugation (40%/75%). Enriched LP CD4⁺ T cells were obtained by positive selection using anti-CD4 (L3T4) MACS magnetic beads. The resultant cells analyzed by flow cytometry contained > 95% CD4⁺ cells. BM cells were obtained by flushing two femurs with cold RPMI-1640.

RT–PCR. Total RNA was isolated by using Nucleospin® (MACHERY-NAGEL). Aliquots of 0.5 mg of total RNA were used for complementary DNA synthesis in 20 mL of reaction volume by using QuantiTect Reverse Transcription Kit® (QIAGEN). One microliter of reverse transcription product was amplified with 0.25 U of rTaq DNA polymerase (Toyobo) in a 50 μ l reaction. Sense and antisense primers and the cycle numbers for the amplification of each gene were as follows: IL-7, forward 5'–GCCTGTCACATCATCTGAGTGCC–3' and reverse 5'–CAGGAGGCATCCAGGAACTTCTG–3' (35 cycles); glyceraldehyde-3-phosphate dehydrogenase (G3PDH) forward 5'–TGAAGGTCGGTGTGAACGGATTTGGC–3' and reverse 5'–CATGTAGGCCATGAGGTCCACCAC–3' (30 cycles). The amplification for each gene was logarithmic under these conditions. PCR products were separated on 1.8% agarose gels, stained with ethidium bromide, and visualized with a Lumi-Imager F1 (Roche Diagnostics).

Real time PCR. Total RNA was isolated by using Nucleospin® (MACHERY-NAGEL). Aliquots of 0.5 mg of total RNA were used for complementary DNA synthesis in 20 mL of reaction volume by using QuantiTect Reverse Transcription Kit® (QIAGEN). To validate gene expression changes, quantitative RT-PCR analysis was performed by Applied Biosystems 7500 using validated TaqMan Gene Expression Assays (Applied Biosystems). The

TaqMan probes and primers for mouse IL-7 (assay identification number Mm01295805_m1) was Assay-on-Demand gene expression products (Applied Biosystems). The mouse b-actin gene was used as endogenous control (catalog number 4352933E; Applied Biosystems). The thermal cycler conditions were as follows: hold for 10min at 95°C, followed a cycle of 95°C for 15s and 60°C for 1min for 50 cycles. Amplification data were analyzed with an Applied Biosystems Sequence Detection Software version 1.3, and the relative mRNA amounts and range were determined by comparative CT method. Briefly, we normalized each set of samples using the difference in threshold cycles (CT) between the sample gene and housekeeping gene (b-actin): $\Delta CT = (CT_{\text{sample}} - CT_{\text{b-actin}})$. Relative mRNA levels were calculated by the expression $2^{-\Delta\Delta CT}$ where $\Delta\Delta CT = \Delta CT_{\text{sample}} - \Delta CT_{\text{standard}}$. We used IL-7^{+/+} BMC as standard in figure 2A. We used IL-7^{+/+} pre MSC as standard in figure 2D. We used donor IL-7^{+/+} MSC as standard in supplemental figure 5H.

Immunohistochemistry. Consecutive colon cryostat sections (5 mm) were fixed and stained with anti-CD4 mAb (BD Pharmingen) or biotin-conjugated polyclonal anti-IL-7 antibody (R&D Systems). Alexa Fluor® 584 goat anti-rat IgG or Alexa Fluor® 488 streptavidin (Molecular Probes) was used as secondary reagent. All microscopy was carried out on a BioZERO BZ8000 (Keyence, Tokyo).

Cytokine ELISA. To measure cytokine production, 1×10^5 LP CD4⁺ T cells were cultured in 200 μ l culture medium at 37 °C in a humidified atmosphere containing 5% CO₂ in 96-well plates (Costar, Cambridge, MA) precoated overnight at 4 °C with 5 mg/ml hamster anti-mouse CD3e mAb (145-2C11, BD Pharmingen) and hamster 2 mg/ml anti-mouse CD28 mAb (37.51, BD

Pharmingen) in PBS. Culture supernatants were removed after 48 h and assayed for cytokine production. Cytokine concentrations were assayed by specific ELISA according to the manufacturer's recommendation (R&D Systems).

Flow cytometry. To detect the surface expression of a variety of molecules, isolated splenocytes, BM, or LP mononuclear cells were preincubated with an Fc γ R-blocking mAb (CD16/32; 2.4G2, BD Pharmingen) for 20 min followed by incubation with specific FITC-, PE-, PerCP-, APC- or biotin-labeled antibodies for 30 min on ice. FITC- or PE or APC-conjugated Sca1 (D7), Biotin-conjugated anti-mouse IL-7R α (A7R34), APC-conjugated anti-mouse PDGFR α (APA5), APC-conjugated anti-mouse PDGFR β (APB5), PE-conjugated anti-mouse CD105 (MJ7/18), PE-conjugated anti-mouse CD146 (P1H12), PE-conjugated anti-mouse FLK1 (Avas12a1) and biotin-conjugated anti-mouse VEGFR3 (AFL4) were obtained from eBioscience (San Diego, CA). The following mAbs were obtained from BD Pharmingen: FITC- or PerCP-conjugated anti-mouse CD3 (RM4–5), FITC-, PE-, PerCP- or APC-conjugated anti-mouse CD4 (16A), PE-conjugated CD11b (M1/70), FITC-conjugated Gr-1 (RB6-8C5), FITC-conjugated TER119 (TER119), FITC-conjugated CD45 (30-F11), FITC-conjugated CD34 (RAM34), FITC- or APC-conjugated anti-mouse CD45RB (IM7), PE-conjugated anti-mouse CD44 (PC61), FITC-conjugated anti-mouse CD62L (H1.2F3), FITC-conjugated anti-mouse CD69 (A20), PE-conjugated anti-mouse CD73 (TY23). Biotinylated antibodies were detected with PE–streptavidin (BD Pharmingen). Standard two-, three-, or four-color flow cytometric analyses were performed using a FACS Calibur flow cytometer and

CellQuest software. Background fluorescence was assessed by staining with control irrelevant isotype-matched mAbs.

Statistical analysis. We examined the normality of the distribution of results in each group. If results from either group were not normally distributed, we assessed the difference between any two groups using the Mann–Whitney *U*-test. If results from both groups were normally distributed, we assessed the variance of the population to which each group belonged using the *F*-test. When the populations were homoscedastic, we assessed the difference between two groups using Student's *t*-test. In the absence of homoscedasticity, we assessed the difference using Welch's *t*-test. We used Statcell software for all statistical analyses. Results are expressed as the mean \pm SEM. Differences were considered significant when $P < 0.05$.

Supplemental Figure Legends

Supplemental Figure 1

Expression of IL-7R α and CD69 on LP CD4⁺ T cells by FACS.

BM, SP, MLN, and LP CD3⁺CD4⁺ T cells from IL-7^{+/+}→IL-7^{-/-}, IL-7^{+/+}→IL-7^{-/-}, IL-7^{+/+}→IL-7^{+/+} or IL-7^{-/-}→IL-7^{+/+} mice were isolated at 6 wk after transfer, and the expression of IL-7R α and CD69 was determined by flow cytometry.

Supplemental Figure 2

Phenotypic characterization of cultured MSC and freshly isolated bone marrow cells from IL-7^{+/+} x RAG-1^{-/-} or IL-7^{-/-} x RAG-1^{-/-} mice

Hematopoietic markers, CD11b, Gr-1, TER119, CD3, CD45, CD34, endothelial markers, CD146, CD309, VEGFR and MSC markers, Sca-1, CD140a, CD140b, CD73, CD105 on cultured MSC and freshly isolated bone marrow cells from IL-7^{+/+} x RAG-1^{-/-} or IL-7^{-/-} x RAG-1^{-/-} mice were checked by flow cytometry. MSC were used after more than 7th passage. Representatives of 5 separate samples in each group.

Supplemental Figure 3

Both IL-7^{+/+} MSC and IL-7^{-/-} MSC suppressed proliferation of activated CD4⁺ T cells *in vitro*

(A) Experimental design. First, IL-7^{+/+} MSC (Gr. 1) and IL-7^{-/-} MSC (Gr. 1) were cultured in respective well. The next day, CFSE-labeled CD4⁺CD25⁻ cells, anti-CD3 antibody and Mitomycin-C treated CD4⁻ cells, which are used as antigen presenting cells, were added. Well of CD4⁺CD25⁻ cells, anti-CD3 antibody and CD4⁻ cells were used as positive control (Gr. 3). Well of CD4⁺CD25⁻ cells and CD4⁻ cells without anti CD3 antibody was used as negative control (Gr. 4). Four days after the co-culture started, expression of CFSE on CD4⁺CD25⁻ cells in each well was detected by flow cytometer. n=3 **(B)** Expression of CFSE on collected CD4⁺CD25⁻ cells in each well. Representative results of three separate samples in each group. **(C)** The number of collected CD4⁺CD3⁺ cells in each well. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.01$. **(D)** Percentage of divided cells was calculated by the result of CFSE expression. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.01$.

Supplemental Figure 4

Phenotype of CD4⁺ T cells isolated from BM, SP, and LP of IL-7^{+/+} MSC mice and IL-7^{-/-} MSC mice 7 wk after transfer of CD4⁺CD45RB^{high} T cells

Expression of IL-7R α , CD69, CD44 and CD62L on the CD3⁺CD4⁺ gated cells in BM, SP, and LP was checked by flow cytometry. Representative results of five separate samples in each group.

Supplemental Figure 5

Different numbers of IL-7^{+/+} MSC were transferred into IL-7^{-/-} x RAG-1^{-/-} mice 4 weeks before CD4⁺CD45RB^{high} T cells transfer.

(A) 1x10⁶ (Gr. 1), 1x10⁵ (Gr. 2) or 1x10⁴ (Gr. 3) IL-7^{+/+} MSC were transferred to IL-7^{-/-} x RAG-1^{-/-} mice. Four weeks after the transfer, each mouse was transferred with CD4⁺CD45RB^{high} T cells. Ten weeks after, mice were sacrificed and analyzed. n=5 in each group. (B) Gross appearance of the colon, MLN and SP from mice of each group at 14 wk after MSC administration. (C) Clinical scores determined at 14 wk after MSC administration as described in Materials and Methods. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.01$. (D) Histopathology of colon of the indicated mice 14 wk after MSC transfer. Original magnification $\times 200$. (E) Histological scores. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.05$. (F) Absolute cell number of LP CD3⁺CD4⁺ T cells from colon 14 wk after MSC transfer. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.01$. (G) Cytokine production by LP CD4⁺ T cells. LP CD4⁺ T cells were isolated 14 wk after MSC transfer and stimulated *in vitro*. IFN- γ , TNF- α , and IL-17 concentrations in culture supernatants were measured by ELISA. Data are shown as the mean \pm SEM *

N.S., not significant. $P < 0.05$. **(H)** Relative expression of IL-7 mRNA in the BM or colon from the indicated mice was determined by Real time-PCR. Data are shown as the mean \pm SEM *

Supplemental Figure 6

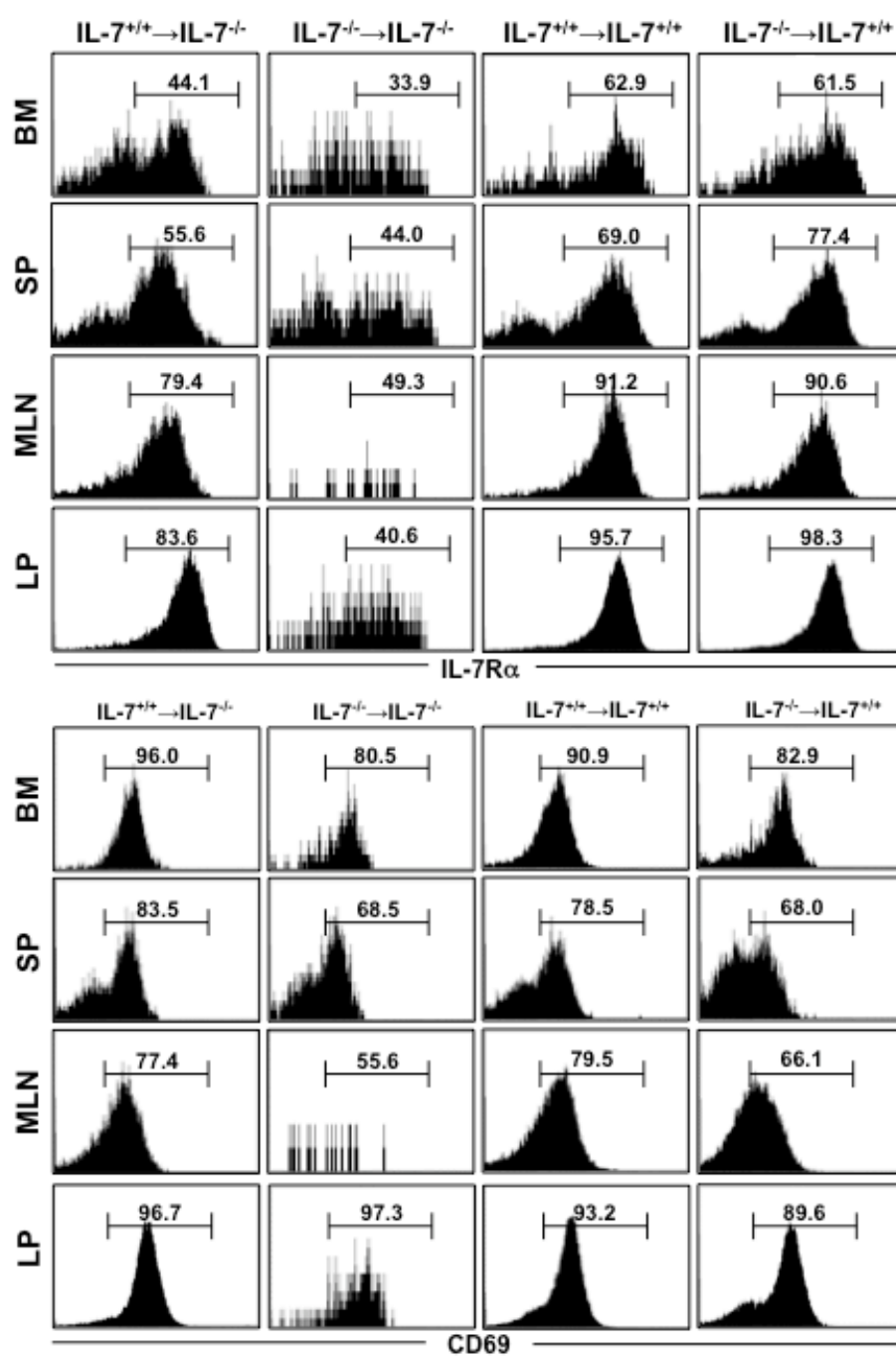
Multiple injection of MSC could not suppressed CD4⁺CD45RB^{high} T cells transfer colitis

(A) CD4⁺CD45RB^{high} T cells were transferred into RAG-2^{-/-} mice. At the same time, IL-7^{+/+} MSC (IL-7^{+/+} MSC) and IL-7^{-/-} MSC (IL-7^{+/-} MSC) were transferred intravenously. In addition, they were also transferred 1 and 2 weeks after the RB^{high} T cells injection. As positive control, CD4⁺CD45RB^{high} T cells alone were transferred into RAG-2^{-/-} mice (RB^{high}). As negative control, CD4⁺CD25⁺ regulatory T cells were co-transferred with CD4⁺CD45RB^{high} T cells into RAG-2^{-/-} mice (RB^{high} + Treg). n=5 in each group. **(B)** Gross appearance of the colon, MLN and SP from mice of each group at 6 wk after MSC administration. **(C)** Clinical scores determined at 14 wk after MSC administration as described in Materials and Methods. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.01$. **(D)** Histological scores. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.05$. **(E)** Histopathology of colon of the indicated mice 6 wk after MSC transfer. Original magnification $\times 200$. **(F)** Absolute cell number of LP CD3⁺CD4⁺ T cells from colon 6 wk after MSC transfer. Data are shown as the mean \pm SEM. N.S., not significant. * $P < 0.01$. **(G)** Cytokine production by LP CD4⁺ T cells. LP CD4⁺ T cells were isolated 6 wk after MSC transfer and stimulated *in vitro*. IFN- γ , TNF- α , and IL-17

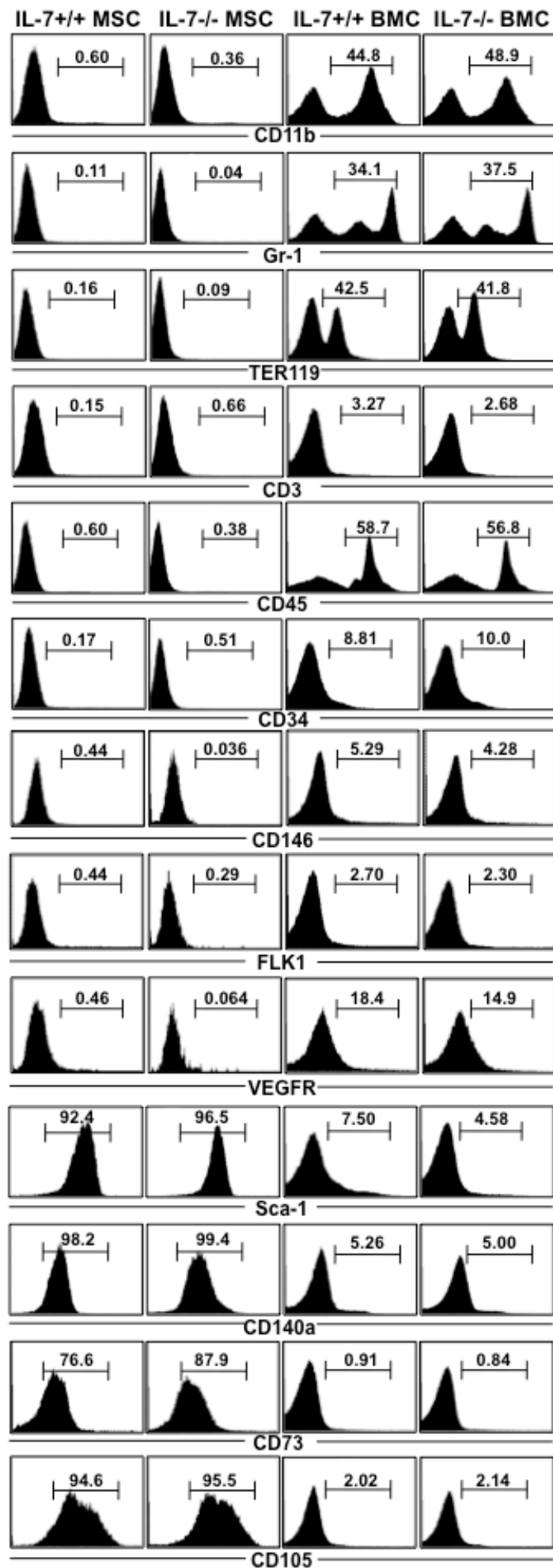
concentrations in culture supernatants were measured by ELISA. Data are shown as the mean \pm SEM * N.S., not significant. $P < 0.05$.

Supplemental Reference

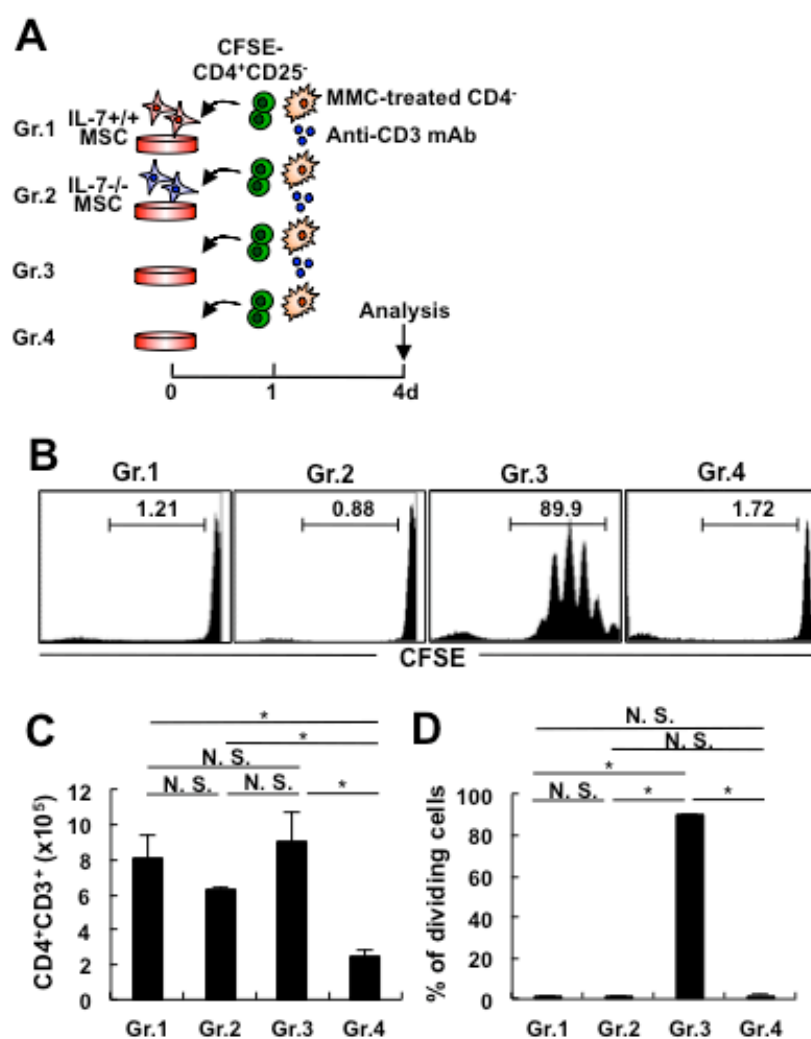
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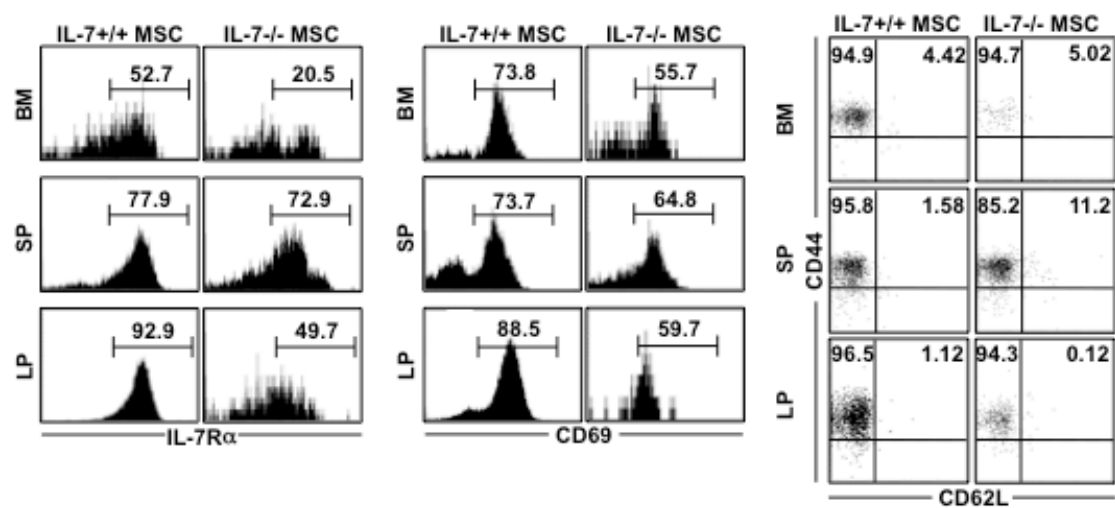


Supplemental Fig.1
Nemoto

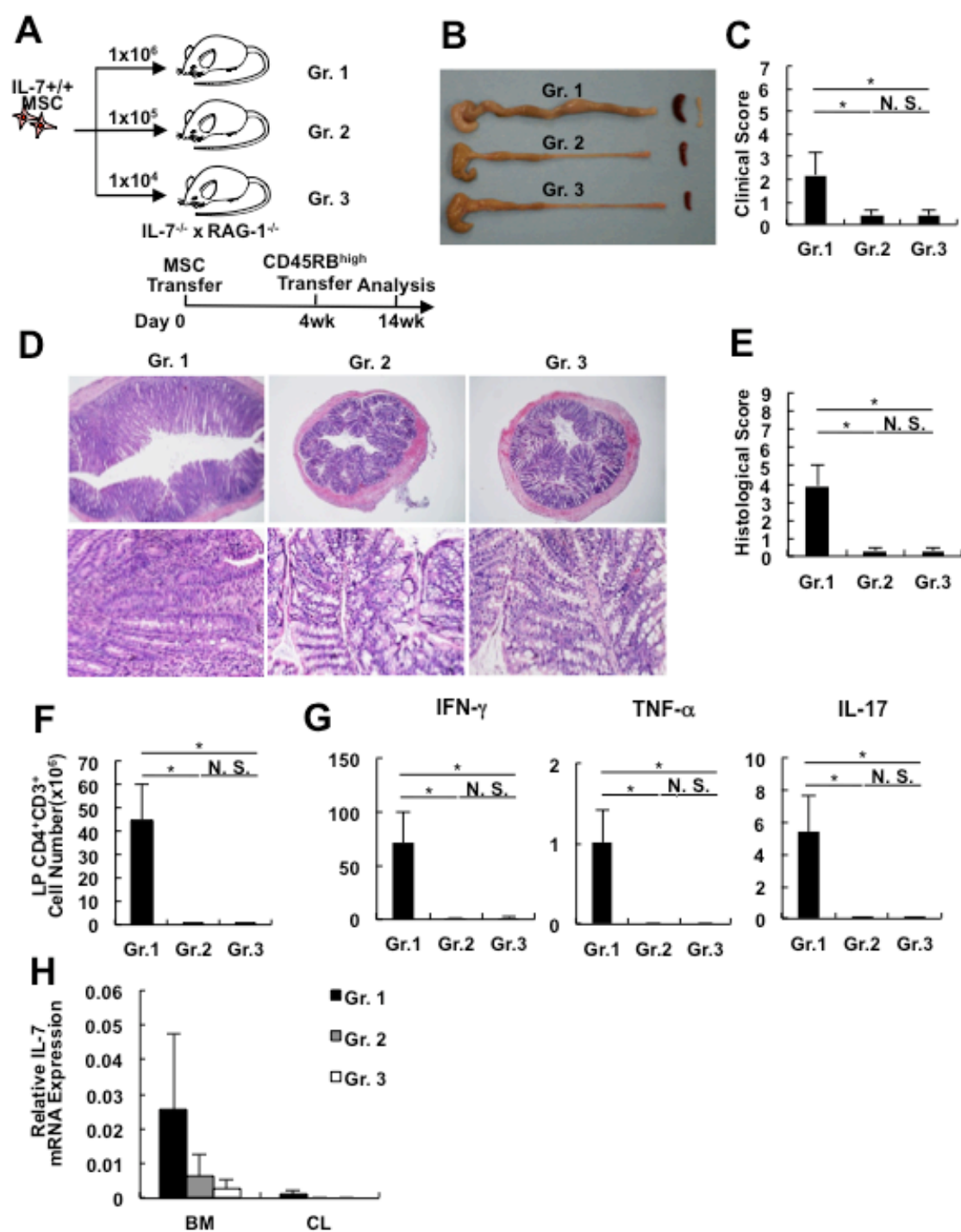


Supplemental Fig.2
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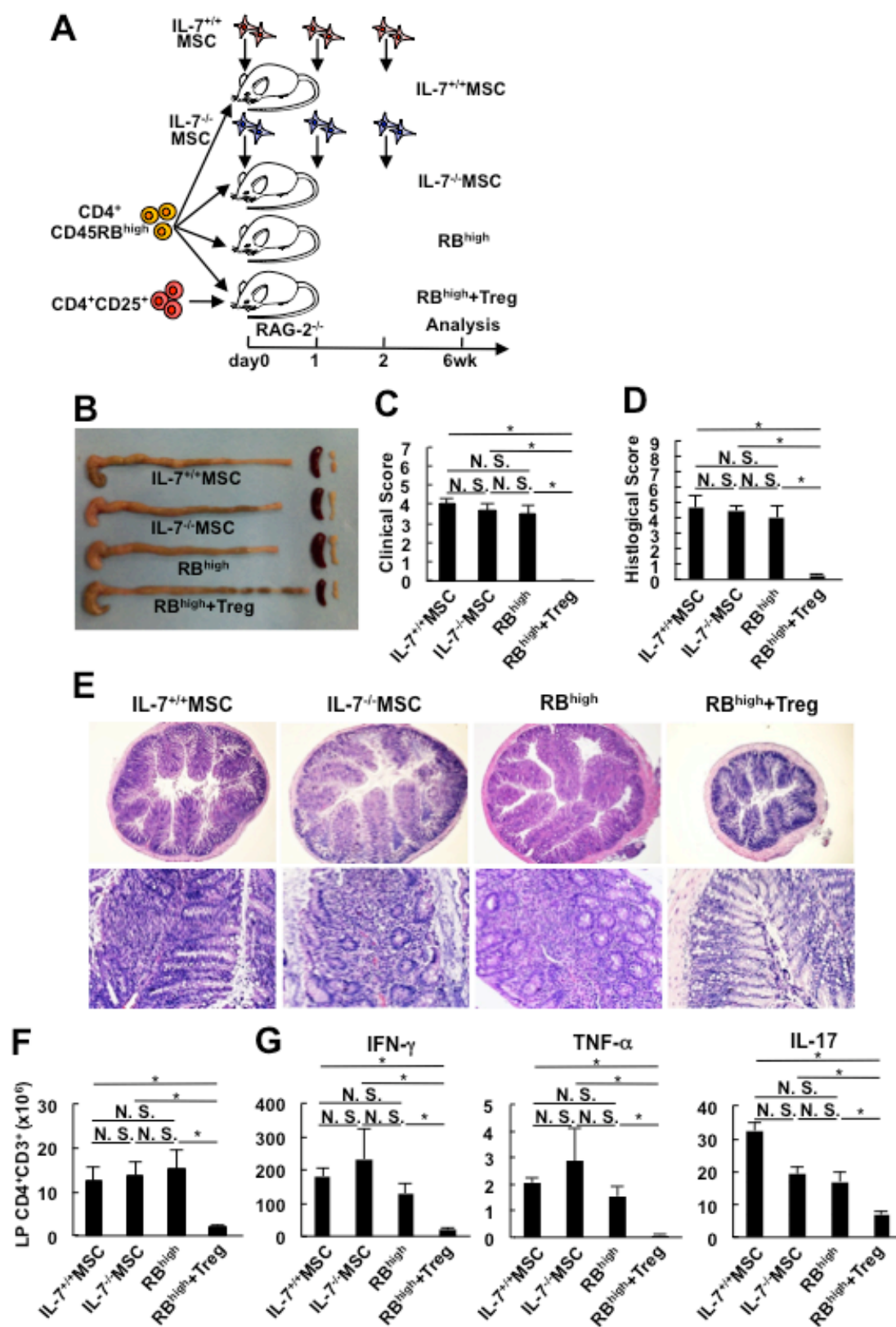




Supplemental Fig.4
Nemoto



Supplemental Fig.5
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Supplemental Fig.6
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