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M-CSF mediates TNF-induced inflammatory osteolysis

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Introduction

Inflammatory osteolysis attends disorders such as rheumatoid arthritis and psoriatic arthritis, which are among the most crippling of skeletal diseases. In this circumstance, osteoclasts erode periarticular bone, leading to joint collapse and disfigurement. The fact that large numbers of such osteoclasts appear juxtaposed to foci of synovitis suggests that the products of inflammation mediate cell recruitment.

Osteoclasts have the unique capacity to resorb bone and are derived from monocyte/macrophage precursors (1). The discovery that receptor activator of NF-κB ligand (RANKL) is the specific osteoclastogenic cytokine (2, 3) led to the development of targeted, antiresorptive therapeutic strategies (4).

Other cytokines, however, also have a significant impact on the osteoclastogenic process, not least of which is TNF-α. This molecule, which is produced in abundance in bone erosive diseases such as rheumatoid arthritis and periodontitis (5–9), profoundly accelerates the osteoclastogenic process (10). Interestingly, TNF-α alone is not sufficient to promote osteoclast precursor differentiation, but has an impact only on cells simultaneously stimulated, or primed, with RANKL (10). Thus, inflammatory osteolysis does not occur in RANK-deficient mice (11, 12).

The discovery that TNF-α is central to the bone loss attendant inflammation led to the development of agents that specifically block the cytokine and thus arrest the resorptive process (13). Anti-TNF therapy is not without complication, however, as patients are prone to infections, likely reflecting immune suppression. In addition, it appears that targeting of inflammatory cytokines such as TNF-α and IL-1 in combination is substantially more effective than suppression of only 1 (14). Thus, detailing the panoply of cytokines that mediate inflammatory osteolysis carries therapeutic implications.

Osteoclastogenesis requires participation of both osteoclast precursors, principally in the form of BM macrophages (BMMs), and BM stromal cells and their derivative osteoblasts. In general, pro-osteoclastogenic agents target BM stromal cells, which are the source of RANKL. RANKL, in turn, activates its receptor on BMMs, prompting them to assume the osteoclast phenotype. TNF-α exerts its osteoclastogenic effect by stimulating stromal cells to produce RANKL but, at high doses, also directly activates the osteoclast precursor (15).

Given that both osteoclast precursors and stromal cells are TNF-α targets, we determined their relative contributions to inflammatory osteoclastogenesis. We found that while the presence of the cytokine receptor on either cell type was sufficient to promote some degree of TNF-α-induced osteoclastogenesis, stromal cells made the greater contribution. Furthermore, TNF-α induces in vivo expression of the stromal cell product M-CSF, which maintains survival and longevity of osteoclast precursors and organizes the cytoskeleton of the mature resorptive cell (16). The fact that M-CSF plays a central role in TNF-induced osteoclastogenesis is confirmed by the capacity of an antibody directed against the M-CSF receptor, c-Fms, to completely arrest pathological osteoclastogenesis and bone resorption, whether attending inflammatory arthritis or direct injection of TNF-α.

M-CSF and its receptor, c-Fms, therefore present as candidate therapeutic targets in states of inflammatory bone erosion.

Nonstandard abbreviations used: BMM, bone marrow macrophage; IL-1Ra, IL-1 receptor antagonist; MTT, 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazoliun bromide; RANK, receptor activator of NF-κB; RANKL, RANK ligand; TNFR, TNF receptor; TRACP 5b, tartrate-resistant acid phosphatase 5b; TRAP, tartrate-resistant acid phosphatase.

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BM stromal cells and osteoclast precursors contribute to TNF-induced osteoclastogenesis in vivo. We have shown that both BM stromal cells and osteoclast precursors are direct targets of TNF-α in the osteoclastic process (10, 15). The goal of our first exercise was, therefore, to determine the relative contributions of each. To this end, we turned to chimeric mice in which either WT or p55/p75 TNF receptor–deficient (TNFR–/–) BM was transplanted into irradiated recipients bearing the same or reciprocal genotype. T cells were eliminated in vivo during the course of the experiment by injection of anti-CD4 and anti-CD8 mAbs (15). Thus, WT BM transplanted into irradiated TNFR–/– (WT to KO) mice serves as a model in which osteoclast precursors but not BM stromal cells express TNFRs whereas the opposite obtains in KO to WT chimeras. WT to WT and KO to KO irradiated and transplanted animals were used as positive and negative controls, respectively.

Validating the chimeric transplantation model, BMMs isolated from WT to KO mice expressed both TNFRs in quantities similar to their WT to WT counterparts (Supplemental Figure 1; available online with this article; doi:10.1172/JCI26132DS1). Similarly, macrophages derived from KO to WT mice were identical in this regard to those of animals lacking receptors on both cell types (KO to KO).

Each group of chimeric mice was subjected to daily supracalvarial administration of increasing doses of TNF-α. The animals were sacrificed on day 5, histological sections of the calvaria were stained for tartrate-resistant acid phosphatase (TRAP) activity, and osteoclast number was determined (Figure 1). As expected, KO to KO animals failed to respond to the cytokine while WT to WT animals generated osteoclasts in a dose-dependent manner. A similarly progressive albeit more modest increase in osteoclast number occurred in mice in which TNFRs were absent in osteoclast precursors (KO to WT). The response to the cytokine was, however, substantially more blunted in chimeras lacking stromal cell TNFRs. Thus, while the presence of TNFRs on either stromal cells or osteoclast precursors was sufficient to promote some degree of osteoclastogenesis, optimal osteoclast recruitment required expression of the receptor by both cell types with the greater contribution made by stromal cells.

Results

BM stromal cells and osteoclast precursors contribute to TNF-induced osteoclastogenesis in vivo. We have shown that both BM stromal cells and osteoclast precursors are direct targets of TNF-α in the osteoclastic process (10, 15). The goal of our first exercise was, therefore, to determine the relative contributions of each. To this end, we turned to chimeric mice in which either WT or p55/p75 TNF receptor–deficient (TNFR–/–) BM was transplanted into irradiated recipients bearing the same or reciprocal genotype. T cells were eliminated in vivo during the course of the experiment by injection of anti-CD4 and anti-CD8 mAbs (15). Thus, WT BM transplanted into irradiated TNFR–/– (WT to KO) mice serves as a model in which osteoclast precursors but not BM stromal cells express TNFRs whereas the opposite obtains in KO to WT chimeras. WT to WT and KO to KO irradiated and transplanted animals were used as positive and negative controls, respectively.

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TNF-α impacts the RANK/RANKL axis. Because the RANK/RANKL axis is central to osteoclast recruitment, we asked if it is differentially impacted in the various chimeric mice (Figure 2A). Thus, we administered TNF-α or carrier for 5 days and assayed BM for both RANKL and its receptor. As we have shown, TNF-α induces RANKL gene expression in WT to WT but not in KO to KO mice (15). In keeping with their greater contribution to TNF-α–stimulated osteoclastogenesis, TNFRs on stromal cells, but not preosteoclasts, were necessary for RANKL induction by the cytokine. On the other hand, RANK mRNA levels were equivalent whether osteoclast precursors, stromal cells, or both express TNFRs. Thus, whereas RANKL induction by TNF-α required direct targeting of stromal cells, RANK mRNA expression by BMMs may have been stimulated directly (WT to KO) or indirectly (KO to WT) by the cytokine.

M-CSF mediates TNF-induced osteoclastogenesis. To determine the mechanism by which TNF-α simulates RANK via a stromal cell–dependent mechanism, we turned to another stromal cell–produced osteoclastogenic cytokine, namely M-CSF, and asked if the growth factor promotes RANK mRNA expression by BMMs. In fact, like TNF-α, M-CSF induced RANK gene expression in a dose-dependent fashion (Figure 2B). Therefore, the indirect stimulatory effect of TNF-α on RANK mRNA expression may be mediated by stromal cell induction of M-CSF.
To further explore this issue, we asked if TNF-α induces M-CSF expression in vivo in a stromal cell–dependent fashion. We therefore injected TNF-α into the 4 chimeric species of mice for 5 days, after which we assessed BM M-CSF mRNA levels. TNF-α induced M-CSF mRNA in WT to WT and KO to WT but not in WT to KO or KO to KO mice (Figure 2C). Hence, the capacity of TNF-α to stimulate M-CSF gene expression requires the presence of cytokine-responsive stromal cells.

M-CSF promotes osteoclastogenesis by stimulating proliferation and survival of osteoclast precursors (17). If M-CSF represents a means by which TNF-α indirectly promotes osteoclast recruitment, one would expect absence of TNFRs on stromal cells to dampen osteoclast precursor number. In this regard, TNF-α–mediated enhancement of osteoclast precursor number required the cytokine receptor only on stromal cells, a source of M-CSF.

TNF-α enhancement of osteoclast precursor number is not mediated by IL-1. TNF-α–induced osteoclastogenesis reflects both IL-1–dependent and –independent mechanisms (18). The IL-1 mediated event, while involving BMMs, also participates in the effect of TNF-α on stromal cells and has the capacity to directly induce RANKL expression (18). This observation raises the possibility that TNF-α-stimulated M-CSF production, and thus enhancement of osteoclast precursor number, is mediated via IL-1. To address this issue, we used a VCAM-1 affinity column to isolate BM stromal cells from WT mice and those deleted of IL-1RI (18). The cells were then exposed to TNF-α or IL-1α. As seen in Figure 4, TNF-α, but not IL-1α, induced M-CSF gene expression in WT stromal cells, and the effect was not impacted by IL-1 receptor antagonist (IL-1Ra). The fact that IL-1 did not mediate TNF-α induction of M-CSF mRNA is further confirmed by the lack of impact of IL-1RI deletion. Again consistent with stimulated M-CSF synthesis, TNF-α enhancement of osteoclast precursor number in vivo was unaltered in mice lacking IL-1-α or its receptor (Figure 5).

Stromal cells or BMMs mediate optimal inflammatory osteolysis. We have shown that the presence of TNFRs solely on osteoclast precursors is sufficient to optimize bone loss in inflammatory arthritis (15). On the other hand, stromal cells are the source of TNF-α-induced M-CSF, and we therefore asked if the same occurs only if they express TNFRs. Thus, arthrogenic serum or PBS was administered to the 4 species of chimeric mice (19, 20). By 7 days, all developed cutaneous inflammation (Figure 6A). Paw swelling was also present in each, which, while identical in the 3 species of TNFR-bearing animals, was substantially less in KO to KO

Figure 2
(A) TNF-α increases RANK mRNA expression in vivo. BM was obtained from WT to WT, WT to KO, KO to WT, and KO to KO mice after 5 daily injections of TNF-α (3 μg/day) or vehicle. RNA was isolated, and RANK and RANKL mRNA expression was measured by RT-PCR. GAPDH mRNA served as loading control. (B) TNF-α and M-CSF increase RANKL mRNA expression in vitro. WT BMMs were cultured without M-CSF. After 24 hours, the cells were placed in medium containing increasing amounts of TNF-α or M-CSF. Six hours later, RNA was isolated and RANK mRNA expression was measured by RT-PCR. GAPDH mRNA served as loading control. (C) TNF-α increases M-CSF mRNA expression in vivo. BM was obtained from WT to WT, WT to KO, KO to WT, and KO to KO mice after 5 daily injections of TNF-α (3 μg/day) or vehicle. RNA was isolated, and M-CSF mRNA expression was measured by RT-PCR. GAPDH mRNA served as loading control.

Figure 3
TNF-α–mediated increase in osteoclast precursor number in vivo requires cytokine-responsive stromal cells. The percentage of osteoclast precursors in BM recovered from WT to WT, WT to KO, KO to WT, and KO to KO mice after 5 daily injections of TNF-α (3 μg/day) or vehicle was determined by FACS, using FITC-conjugated anti-CD11b mAb (solid line) and FITC-conjugated isotype mAb (dotted line).
mice (Figure 6B). Whereas periarthritic inflammation was extensive in the WT to WT, WT to KO, and KO to WT serum-injected mice, it was sparse in those devoid of TNFRs (Figure 6C). Importantly, inflammatory osteolysis, as manifested by the percentage of bone surface juxtaposed to osteoclasts, was indistinguishable in arthritic mice whether TNFRs were present on stromal cells, preosteoclasts, or both (Figure 6, D and E). In contrast, no significant osteoclastogenesis obtained in serum-injected KO to KO mice or any species administered PBS. Finally, osteoclast precursor number, represented by CD11B expression, was also enhanced to similar degrees in the BM of the 3 TNFR-bearing chimeras (Figure 7). These observations are in keeping with the hypothesis that, in the context of severe inflammation, TNF-α, IL-1α, and IL-1Rα alone or in combination for 24 hours. M-CSF mRNA in equal amounts of total RNA was determined by RT-PCR. GAPDH mRNA served as loading control.

Blockade of M-CSF–induced signaling prevents inflammatory osteolysis. The data presented thus far raise the possibility that M-CSF plays a central role in states of TNF-α–induced osteolysis, including inflammatory arthritis. To explore the clinical implications of this issue, we turned to a mAb generated against the M-CSF receptor, c-Fms (21). To determine its efficacy, we added increasing amounts of the antibody to cultures of WT BMMs in the presence of M-CSF (KO to WT) or acting in concert with constitutive levels of the latter cytokine (WT to KO).

Figure 5

TNF-α–mediated increase in osteoclast precursor number in vivo is IL-1 independent. The percentage of osteoclast precursors in BM recovered from WT, IL-1RI−/−, and IL-1α−/− mice after 5 daily injections of TNF-α (3 μg/day) or vehicle was determined by FACS using FITC-conjugated anti-CD11b mAb (filled profiles) and FITC-conjugated isotype mAb (open profiles).

resorptive cells juxtaposed to virtually the entire inflamed bone surface (Figure 9, C and D). On the other hand, antibody-treated mice exhibited a total arrest of arthritis-induced osteoclastogenesis despite persistence of profound inflammation.

In keeping with the clinical implications of these observations, the increase in bone resorptive activity induced by inflammatory arthritis was completely prevented in antibody-treated animals (Figure 9E). Despite a small but significant decrease in serum tartrate-resistant acid phosphatase 5b (TRACP 5b) levels in arthritic mice receiving anti–c-Fms as compared with naive animals, the antibody appeared to exert a substantially greater impact on inflammation-induced than physiological osteoclastogenesis, as TRAP-expressing cells within the tibial metaphysis appeared to be abundant in each circumstance (Figure 9F). Although TNF-α is a dominant mediator, the osteoclastogenesis of inflammatory arthritis is the product of a number of cytokines. Therefore, as a final exercise, we asked if arrest of M-CSF signaling specifically affects TNF-α–stimulated bone resorption. WT mice were administered supracalvarial TNF-α daily, with or without anti–c-Fms mAb. Once again, control animals received only PBS. By 5 days, TNF-α alone induced a marked osteoclastogenic response, which was completely prevented by c-Fms mAb (Figure 10, A and B). Similar to animals with inflammatory arthritis, this arrest of TNF-α–induced osteoclastogenesis was paralleled by blunting of in vivo bone resorption manifested by TRACP 5b serum to a level even lower than that of controls (Figure 10C). Again reflecting the relative sensitivity of osteoclast recruitment as compared with precursor number to anti–c-Fms, the antibody only nominally affected the number of CD11B cells...
Figure 6
Stromal cells or BMMs mediate optimal inflammatory osteolysis. Mice in each chimeric group were injected with arthrogenic serum derived from K/BxN mice. (A) Appearance of paws of representative mice at day 7 after injection with arthrogenic serum (+) or PBS (−). (B) Paw thickness measured daily for 10 days for each group of chimeric mice injected with arthrogenic serum (+) or PBS (−). (C) H&E-stained histological sections of ankles at day 7 showing severe inflammation (**) in arthrogenic serum-treated (+) WT to WT, WT to KO, and KO to WT mice compared with the relatively mild changes occurring in similarly treated KO to KO animals. Minus sign indicates those injected with PBS. (D) TRAP-stained histological sections of ankles of serum-injected or serum-noninjected WT to WT, WT to KO, KO to WT, and KO to KO mice at day 7. (E) Histomorphometric quantitation of the percentage of bone surface covered by osteoclasts (OC) in ankles of PBS-treated (−) or arthrogenic serum–treated (+) WT to WT, WT to KO, KO to WT, and KO to KO mice. *P < 0.001 arthrogenic serum– vs. PBS-treated mice. n = 4 mice per group. Magnification, ×40.
in TNF-α–treated mice (70.7% ± 0.6% vs. 90.2% ± 2.0% of isolated BM cells) (Figure 10D).

**Discussion**

Rheumatoid arthritis is a complicated condition, as a host of cytokines produced by a variety of cells contributes to its pathogenesis. While RANKL and IL-1 are important participants in development of focal bone erosions, which eventuate in joint collapse, TNF-α is the principal and rate-limiting culprit, as its blockade dampens both the inflammatory and osteoclastogenic components of the disease (13). On the other hand, blockade of TNF-α alone is insufficient to optimize arrest of inflammatory joint disease, as coordinate treatment with IL-1Ra is more effective (14). Added to the potential complications attending TNF-α inhibition, these observations underscore the importance of identifying new therapeutic candidates in this disease, a goal which can be achieved only by gaining insight into the means by which TNF-α impacts its target cells.

Inflammatory osteoclastogenesis represents a complex relationship between macrophages and mesenchymal stromal cells, including those in BM and synovium. Each produce, and are targets of, inflammatory cytokines such as TNF-α, which enhances osteoclastogenesis by interacting both families of cells (15, 18). The cytokine stimulates stromal cells to synthesize RANKL and IL-1. TNF-α also directly prompts macrophages to differentiate into osteoclasts when exposed to constitutive levels of the key osteoclastogenic cytokine, i.e., RANKL (10). Thus, our first exercise was to determine the relative contributions of stromal cells and macrophages to TNF-α-induced osteoclastogenesis. Because this undertaking required isolating the contribution of each in vivo, we turned to mice chimeric for TNFRs in the BM and stromal compartment and found that, while both were required for optimal TNF-α-induced osteoclastogenesis, stromal cells had the greater impact. This pronounced contribution of stromal cells to the osteoclastogenic process involved stimulated production of RANKL. Alternatively, TNF-α–induced RANK mRNA levels in osteoclast precursors were similar whether TNFRs were present on macrophages, stromal cells, or both. Thus, enhanced RANK expression does not account for the dominant role played by stromal cells in TNF-α-stimulated osteoclast recruitment.

RANKL and IL-1 are produced by stromal cells under the influence of TNF-α, but the importance of these cells as indi-

![Figure 7](image-url)  
Stromal cells or BMMs mediate optimal inflammation-induced osteoclast precursor number. The percentage of osteoclast precursors in BM recovered from WT to WT, WT to KO, KO to WT, and KO to KO mice 7 days after injections of arthrogenic serum or vehicle was determined by FACS using FITC-conjugated anti-CD11b mAb (thick lines) and FITC-conjugated isotype mAb (thin lines).

![Figure 8](image-url)  
Anti–c-Fms antibody arrests osteoclastogenesis in vitro. (A) BMMs from WT mice were cultured with increasing amounts of anti–c-Fms mAb in the presence of 100 ng/ml M-CSF. After 3 days, the number of viable cells was measured using the MTT assay. MTT absorbance was determined at an OD of 570 nm. (B) The same number of BMMs were cultured in the presence of M-CSF (100 ng/ml) and RANKL (50 ng/ml) with increasing amounts of anti–c-Fms mAb for 3 days. The cells were stained for TRAP activity to identify osteoclasts. Magnification, ×400. (C) Number of osteoclasts generated in wells containing various amounts of anti–c-Fms antibody. *P < 0.001 vs. 0 ng/ml.
The development of models of inflammatory arthritis in the context of TNFR chimeric mice enables us to attribute various components of the disease, including synovitis and periarticular osteolysis, to TNF-α induced M-CSF gene expression in vivo and did so only in the presence of stromal cell–residing TNFRs. The capacity of TNF-α to increase osteoclast precursor numbers, in vivo, is in keeping with the proproliferative and prosurvival properties of abundant M-CSF.

IL-1, whose expression by BMMs and stromal cells is also enhanced by TNF-α, mediates approximately 50% of the osteoclastogenic capacity of TNF-α (18). IL-1, however, does not participate in TNF-induced M-CSF production. Specifically, arrest of IL-1 signaling by either IL-1Ra or deletion of the functional IL-1 receptor has no effect on the capacity of TNF-α to promote M-CSF production or to increase osteoclast precursor number in vitro and in vivo. Thus, M-CSF appears to be a mediator of that component of TNF-stimulated osteoclastogenesis occurring in an IL-1–independent manner.

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The fact that TNF-α as rheumatoid arthritis, the cytokine’s effect is maximized by targetting of osteoclasts by increasing their precursor pool, the majority of which does not become bone resorptive polykaryons, but host defense mononuclear phagocytes. Thus, the coincident immunosuppressive effect of inhibiting macrophage proliferation and survival as a means of arresting inflammatory periarticular erosion is a potential limitation of M-CSF blockade. On the other hand, anti-c-Fms mAb prevents RANKL and M-CSF–induced osteoclast formation at a concentration at least 1 order of magnitude less than its capacity to decrease cell number in vitro. This observation raises the possibility that, in the context of inflammatory osteolysis, osteoclast recruitment is more sensitive to M-CSF inhibition than is macrophage proliferation and/or survival. In fact, mice treated with carrier or anti-c-Fms mAb developed equivalent periarticular inflammation while those receiving the antibody were completely free of pathological osteoclastogenesis and bone resorption. This observation reflects to a substantial degree arrest of TNF-α signaling, as similar results obtained in TNF-α-injected mice also receiving anti-c-Fms mAb. Like arthritic animals, those directly receiving TNF-α experienced complete arrest of osteoclastogenesis but only a modest decrease in macrophage number. Interestingly, nonpathological osteoclastogenesis located distant from the inflamed joint was robust in each case. While the enhanced sensitivity to c-Fms arrest of pathological, as compared with physiological, osteoclastogenesis remains unexplained, it may reflect participation of redundant cytokines. For example, the osteopetrosis and arrested osteoclastogenesis of the M-CSF–deficient op/op mouse resolves with age due to expression of VEGF (30), GM-CSF, and/or IL-3 (31). While speculative, the possibility remains that these 2 cytokines substitute for M-CSF in a physiological setting of osteoclast recruitment.

Thus, M-CSF joins the panoply of cytokines involved in the pathogenesis of inflammatory osteolysis. Although this study represents short-term arrest of M-CSF signaling initiated at induction of the arthritic process, the profundity of its effect on osteoclasts as compared with macrophages enhances its therapeutic appeal. The potential of M-CSF inhibition as a means of treating rheumatoid arthritis is underscored by the development of c-Fms–selective small molecules (32) and the capacity of the tyrosine kinase inhibitor drug Imatinib to target the receptor (33). Given the significant complications encountered with other forms of anticytokine therapy, however, the therapeutic targeting of M-CSF must be approached with caution (34).

Methods

Mice. C57BL/6 mice deleted of genes coding for both TNFR type 1 and TNFR type 2 on a C57BL/6 background were generated as described (15). C57BL/6 WT mice were purchased from the Jackson Laboratory. Animals were housed in the animal care unit of the Department of Pathology, Washington University School of Medicine, and were maintained according to the guidelines of the Association for Assessment of Laboratory Animal Care. All animal experimentation was approved by the Animal Studies Committee of Washington University School of Medicine.

Reagents. The following mAbs were obtained from BD Biosciences: purified rat anti-mouse VCAM-1 (no. 553330), purified rat anti-mouse CD3 molecule complex (no. 555273), FITC-conjugated rat anti-mouse CD11b (no. 553310), purified hamster anti-mouse TNFR1 (no. 559915), PE-conjugated hamster anti-mouse TNFR2 (no. 550086), and isotype control antibodies.
Goat anti-rat IgG microbeads for immunopurification were obtained from Miltenyi Biotec. Recombinant murine TNF-α was prepared in our laboratory as described (15). Recombinant human M-CSF was generously provided by Daved H. Fremond (Washington University, St. Louis, Missouri, USA). Murine RANKL was expressed in our laboratory as described (15).

**BM transplantation.** Mice were killed by CO2 gas, and femoral BM cells were flushed with culture medium as described (35). VCA-M1 and CD3-positive cells were depleted from BM by negative selection using MACS goat anti-rat IgG Microbeads (Miltenyi Biotec) as described (15). One day after administration of 10 Gy of total body γ-irradiation, we injected 1 x 10^9 CD3 and VCA-M1-depleted BM cells in 100 μl PBS into 4- to 6-week-old male mice via tail vein.

In vivo T cell depletion. Female ICR-SCID mice (Taconic) were primed by intraperitoneal injection of 0.5 ml of incomplete Freund’s adjuvant. After 7 days, the mice received intraperitoneal injections of 5 x 10^6 YTS cells, which secrete anti-CD4 antibodies, or H3S cells, which secrete anti-CD8 antibodies (kindly provided by Osami Kanagawa, Washington University, St. Louis, Missouri, USA). One to 2 weeks later, ascses was recovered, incubated at 37°C for 1 hour, and transferred to 4°C overnight. Cells and oil were removed by centrifugation, and ascites was stored at –80°C C. Mice were administered 4 weekly injections of 30 μl of anti-CD4 and anti-CD8 ascses to assure arrest of T cell generation in vivo (15).

**FACS analysis.** To assess the number of osteoclast precursors, freshly isolated BM cells were incubated in NaN3 (0.1%) plus FBS-PBS (FBS, 1%) for 30 minutes with FITC-conjugated rat anti-mouse CD11b mAb. The samples were diluted with the same solution and analyzed by FACS for CD11b-expressing cells. To evaluate BM engraftment, BMMMs were incubated for 30 minutes with anti-TNFFR1 mAb and then for 30 minutes with FITC-conjugated anti-IgG mAb. They were then washed and diluted with NaN3 plus FBS. A second aliquot of BM cells was incubated for 30 minutes with PE-labeled anti-TNFFR2 mAb. TNFR1 and TNFR2 expression were analyzed by FACS.

**RNA preparation and RT-PCR analysis.** Total RNA from BM cells was isolated by RNeasy mini kit (QiAGEN). For RT-PCR analysis, cDNA was synthesized from 1 μg of total RNA using reverse transcriptase and oligo-DT primers in a volume of 20 μl. PCR was performed with a cDNA reaction mixture using PCR supermix (Invitrogen Corp.) and appropriate primers in a volume of 50 μl. The following primers were used: GAPDH, 5'-ACCTGGT-CAGGCTCATTTCC-3' and 5'-TGACCGCAACCTTTATGATGAC-3', RANK, mouse RANK PCR Primer Pair (R&D Systems); RANKL, human/mouse TRANCE/TNFSF11 PCR Primer Pair (R&D Systems); and M-CSF, 5'-GACCTGCGGAGATGGC-3' and 5'-GGTGGTTTGAAGGTACCAAGG-3'. Samples were transferred to a programmable thermal cycler (Hybaid; Thermal Electron Corporation) preheated to 94°C. Each cycle consisted of a denaturation step at 94°C for 45 seconds, an annealing step at 55°C for 45 seconds, and an extension step at 72°C for 45 seconds for RANKL, RANK, and GAPDH and a denaturation step at 94°C for 1 minute, an annealing step at 58°C for 1 minute, and an extension step at 72°C for 1 minute for M-CSF. We separated 10-μl aliquots of PCR products by electrophoresis on a 2.0% agarose gel.

Serum transfer arthritis. KRN-TCR transgenic mice on a C57Bl/6 background were kindly provided by D. Mathis and C. Benoist (Howard University School of Medicine, Boston, Massachusetts, USA). K/BxN mice, which spontaneously develop severe inflammatory arthritis (18) and whose serum immunoglobulin is arthrogenic in a T cell–independent manner (15), in mouse strains other than KRN, were generated by breeding KRN-TCR with nonobese diabetic mice (Taconic). Serum was obtained from 6- to 12-week-old K/BxN mice, pooled, and stored in aliquots at –70°C. T cell-depleted WT to WT, WT to KO, KO to WT, and KO to KO mice were injected once intraperitoneal with 200 μl of serum or PBS. Paw thickness was measured with a caliper daily for 10 days. A second group of animals was sacrificed at day 7 for histology and FACS analysis. Paws were stripped of soft tissue, and bones and joints were subjected to histological examination and evaluation of numbers of CD11b-positive cells.

**Administration of anti–c-Fms antibody.** AFS98, a rat monoclonal, anti-murine c-Fms antibody (IgG2a) that inhibits M-CSF–dependent colony formation and cell growth by blocking the binding of M-CSF to its receptor, has been described (21). The AFS98 hybridoma was kindly supplied by Shin-ichi Nishikawa (Graduate School of Medicine, Kyoto University Medical School, Kyoto, Japan). The clone was maintained in HyQ-CCM medium (HyClone), and the antibody was purified using Protein G (Sigma-Aldrich). We administered intraperitoneally 500 μm of AFS98 in 500 μl of PBS or PBS alone every day for 7 days to arthritic or TNF-injected mice.

**Macrophage proliferation assay.** BMMs from WT mice were cultured with several doses of AFS98 mAb in the presence of 100 ng/ml M-CSF. After 3 days, the number of viable cells was measured using the MTT (3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyterazolium bromide; Sigma-Aldrich) assay. In brief, 10 μl MTT (5 mg/ml) was added to 100 μl culture medium in each well and incubated at 37°C for 4 hours. We added 150 μl 0.04N HCl in isopropanol to each well to stop the reaction, and MTT absorbance was determined at OD of 570 nm.

Serum TRACP 5b assay. Serum was obtained 7 days after injection of arthrogenic serum or following 5 days of daily TNF-α administration. TRACP 5b levels were determined according to the protocol of the MouseTRAP Assay kit (IDS).

**Histological analysis.** Osteoclast number was determined using the Osteometer System version 2.2 (Osteometrics Corp.).

**Statistics.** All data are expressed as mean ± SD. Statistical significance was calculated by 2-tailed Student’s t-test.

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