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Interleukin-27 inhibits ectopic lymphoid-like structure development in early inflammatory arthritis

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Ectopic lymphoid-like structures (ELSs) reminiscent of secondary lymphoid organs often develop at sites of chronic inflammation where they contribute to immune-mediated pathology. Through evaluation of synovial tissues from rheumatoid arthritis (RA) patients, we now show that low interleukin-27 (IL-27) expression corresponds with an increased incidence of ELS and gene signatures associated with their development and activity. The presence of synovial ELS was also noted in mice deficient in the IL-27 receptor (IL-27R) after the onset of inflammatory arthritis. Here, pathology was associated with increased synovial expression of pro-inflammatory cytokines, homeostatic chemokines, and transcriptional regulators linked with lymphoid neogenesis. In both clinical and experimental RA, synovial ELS coincided with the heightened local expression of cytokines and transcription factors of the Th17 and T follicular helper (Tfh) cell lineages, and included podoplanin-expressing T cells within lymphoid aggregates. IL-27 inhibited the differentiation of podoplanin-expressing Th17 cells, and an increased number of these cells were observed in IL-27R-deficient mice with inflammatory arthritis. Thus, IL-27 appears to negatively regulate ELS development in RA through control of effector T cells. These studies open new opportunities for patient stratification and treatment.

Rheumatoid arthritis (RA) is characterized by an immune-mediated destruction of joint tissue caused by chronic inflammation of the synovium (Manzo et al., 2010). Synovitis in RA is highly heterogeneous and is classified according to specific histological features (Klimiuk et al., 1997; Pitzalis et al., 2013). In RA, synovial histopathology is defined as fibroblast– (or pauci immune), diffuse-, or lymphoid-rich. The latter is characterized as lymphoid follicle-like structures ranging from T and B cell aggregates to highly organized structures comprising follicular DC (fDC) networks reminiscent of germinal centers (GCs). These structures are present in ∼40% of RA patients (Manzo et al., 2010; Pitzalis et al., 2013) and are associated with severe disease, T cell priming, and autoantibody production (Takemura et al., 2001; Rosengren et al., 2008; Humby et al., 2009). Although circulating rheumatoid factor (RF) and anticitrullinated protein antibodies (ACPA) correlate with disease severity (Avouac et al., 2006), these clinical markers unreliably predict synovial pathology.

IL-27 is a regulator of adaptive immunity and limits T cell–driven pathology by restricting IL-2 activity and the expansion of IL-17–secreting T helper 17 (Th17) cells (Villarino et al., 2003; Owaki et al., 2006; Stumhofer et al., 2006). Recently, Th17 cells were shown to enhance ectopic lymphoid-like structure (ELS) formation in inflamed tissues (Peters et al., 2011; Rangel-Moreno et al., 2011). Indeed, 2015 Jones et al. This article is distributed under the terms of an Attribution–Noncommercial–Share Alike-No Mirror Sites license for the first six months after the publication date (see http://www.rupress.org/terms). After six months it is available under a Creative Commons License (Attribution–Noncommercial–Share Alike 3.0 United States license, as described at http://creativecommons.org/licenses/by-nc-sa/3.0/).
Th17 cell plasticity permits the acquisition of Tfh-like effector characteristics that support ELS expansion and GC reactions (Lu et al., 2011; Peters et al., 2011; Hirota et al., 2013). In models of inflammatory arthritis, IL-27 blocks Th17-associated joint pathology (Niedbala et al., 2008; Pickens et al., 2011) and inhibits osteoclastogenesis to restrict bone erosion (Kalliolias et al., 2010). While elevated synovial and serum IL-27 levels have been observed in RA (Wong et al., 2010; Tanida et al., 2011), no study has considered the impact of IL-27 on synovial histopathology. Here, we show that IL-27 control of CD4 T cell responses prevents the development of synovial ELS.

RESULTS AND DISCUSSION

Synovial ELSs in RA contain IL-27R+ lymphocytic aggregates

The IL-27 receptor comprises a heterodimeric complex of IL-27R (WSX-1) and gp130, the β-signaling receptor of the IL-6 cytokine family. To evaluate how IL-27R expression relates to local joint pathology, RA synovia were graded histologically for the presence or absence of ELS (Fig. 1 A and Fig. S1). Tissue with grade-3 (G3) ELS aggregates comprising CD3+, CD20+, and CD21+ cells (ELS+) were compared with biopsies displaying diffuse lymphocytic infiltrates (ELS−). To validate our cellular characterization, expression of key homeostatic chemokines, cytokines, and molecular signatures of ELS were evaluated (Timmer et al., 2007; Humby et al., 2009). Consistent with the presence of lymphoid follicles, heightened CXCL13, CCL19, and CXCR5 expression was observed in ELS+ patient biopsies (Fig. 1 B). Elevated transcripts for activation-induced cytidine deaminase (AID), an enzyme involved in somatic hypermutation and class switching, was also observed (Fig. 1 B). Consistent with the presence of CD21+ fDC networks detected by immunohistochemistry
IL-27–deficient mice display severe inflammatory arthritis

To consider the impact of IL-27 on inflammatory arthritis, disease activity was monitored in WT and Il27ra−/− mice after the onset of antigen-induced arthritis (AIA; Nowell et al., 2009), Il27ra−/− mice displayed exacerbated joint pathology, as indicated by increases in leukocyte infiltration, synovial exudate, hypertrophy, and hallmarks of cartilage and bone erosion (Fig. 2, A–C). By day 35 (d35) of AIA, WT and Il27ra−/− mice displayed extensive cartilage degradation. However, an increased incidence of focal bone erosions was seen in Il27ra−/− mice (Fig. 2, A and C). These findings reveal a protective role for IL-27 in AIA and support the ability of IL-27 to inhibit RANKL–dependent and -independent osteoclastogenic bone erosion (Niedbala et al., 2008; Kalliolas et al., 2010; Pickens et al., 2011). Increased arthritis severity in Il27ra−/− mice was also linked with heightened adaptive immune responses. Specifically, Il27ra−/− mice showed elevated antigen (mBSA)–specific serum IgG titers (Fig. 2 D), increased Th17 cell numbers in draining LNs (Fig. 2 E), and a concomitant increase in serum IL-17 levels early after disease onset (Fig. 2 F).

Exacerbated synovitis in IL-27R deficiency is linked with ELS development

Based on IL-27 bioactivity and the pattern of IL-27R expression in human synovial biopsies, we next assessed the impact of IL-27R deficiency on the pattern of synovitis. Il27ra−/− mice with AIA showed heightened synovial T cell infiltration and the presence of discrete CD3+ aggregates throughout the synovium (Fig. 3 A). Whereas a small proportion of mice presented with small aggregates at d3 after AIA (not depicted), by d10 all Il27ra−/− mice developed multiple lymphoid aggregates (7.1 ± 0.8 per synovial section and 12.8 × 104 ± 1.7 μm2 in size; Fig. 3, A and B). WT mice developed a more diffuse pattern of synovial inflammation and showed significantly fewer lymphoid aggregates. When present, these were both smaller in size and less organized (1.9 ± 0.4 per synovial section and 1.6 × 104 ± 0.5 μm2 in size; Fig. 3 B). Although the inflated synovium of Il27ra−/− mice showed a paucity of B220+ cells, IHC staining for B cells colocalized with the defined CD3+–rich aggregates (Fig. 3 C). However, the degree of B cell involvement often varied between aggregates (e.g., compare Fig. 3 C and Fig. 5 A). Although...
F4/80\(^+\) myeloid cells were largely restricted to areas surrounding the lymphoid rich zones (Fig. 3 C). IHC detected the transcriptional regulator of Tfh cells and GC B cells, Bcl-6, and the DC marker CD21 within their composition (Fig. 3, D and E). Thus, lymphoid aggregates in the inflamed synovium of \(\text{Il27ra}^{-/-}\) mice resemble ELS.

To explore the initiation of ELS formation, we examined synovial expression of cytokines (IL6, IL21, LTB, and VEGF), homeostatic chemokines (CXCL12, CXCL13, CCL19, and CCL21), and transcriptional regulators (B6 and PRDM1) linked with ectopic lymphoid neogenesis at d3 of AIA (Fig. 3 F; Manzo et al., 2005, 2010; Barone et al., 2008). Consistent with the presence of Bcl-6\(^+\) lymphoid aggregates in \(\text{Il27ra}^{-/-}\) mice, qPCR analysis showed increased synovial expression of B6 as compared with WT controls. No difference in IL6, IL21, LTB, VEGF, CXCL12, or PRDM1 was seen between WT and \(\text{Il27ra}^{-/-}\) mice (Fig. 3 F). Increased B6 expression was, however, accompanied by enhanced CXCL13 and CCL21 expression (Fig. 3 F), which steers the spatial organization of lymphoid cells within ELS (Luther et al., 2000; Chen et al., 2002). In contrast, synovial CCL19 expression was reduced in \(\text{Il27ra}^{-/-}\) mice. Although CCL19 and CCL21 share a common chemokine receptor (CCR7), they have a differential impact on composition and cellular organization of ELS (Luther et al., 2002; Haynes et al., 2007). Thus, relative differences in CCL19 and CCL21 expression within the inflamed synovium of \(\text{Il27ra}^{-/-}\) mice may promote the CD3-rich nature of the observed ELS. By d10 of AIA, once ELSs were formed, expression of CXCL13 and CCL21 were comparable between WT and \(\text{Il27ra}^{-/-}\) mice (Fig. 4 A). However, at this later time point, increased expression of the lymphoecogenic cytokines LTA and LTB (LTa and LTB) was observed in \(\text{Il27ra}^{-/-}\) mice (Fig. 4 A). Similarly, synovial PRDM1 (Blimp1) expression, which supports B cell differentiation into antibody-secreting plasma cells, was also heightened in \(\text{Il27ra}^{-/-}\) mice at d10 (Fig. 4 A). These data are consistent with increased PRDM1 expression in ectopic GCs after cytomegalovirus infection of salivary glands (Grewal et al., 2011). Thus,
IL-27 regulates synovial ELS through inhibition of homeostatic chemokines, lymphoid cytokines, and transcriptional regulators involved in lymphoid neogenesis.

**IL-27 Inhibits Effector T Cells Linked with ELS Formation**

Recent studies have highlighted novel roles for effector T cell subsets, such as Th17 and Tfh cells, in ectopic lymphoid neogenesis and the control of GC reactions (Lu et al., 2011; Peters et al., 2011; Rangel-Moreno et al., 2011; Hirota et al., 2013). Thus, cytokines linked with either T cell differentiation or plasticity of effector T cells into Th-like phenotypes may regulate ELS involvement in chronic disease (Lu et al., 2011; Peters et al., 2011; Hirota et al., 2013). As IL-27 inhibits effector Th17 responses, we considered the expression of Th17 and Tfh cell markers within Th-like phenotypes. At d10 of AIA, formation of ELS in Il27ra−/− mice was associated with increases in Il17a and the Tfh markers Bcl6 and Il21 (Fig. 4 B). No differences in Il10 and Il7 were observed between WT and Il27ra−/− mice.

The transcription factor STAT3 regulates Th17 and Tfh cell responses and is linked with lymphoid neogenesis and GC activities. In experimental arthritis, gp130-mediated STAT3 signaling exacerbates pathology (Atsumi et al., 2002; Nowell et al., 2009), and synovial tissues containing lymphoid follicles show enhanced STAT3 activity (Sawa et al., 2006; Timmer et al., 2007). IHC of infiltrating synovial leukocytes for tyrosine phosphorylated (pY)-STAT3 in Il27ra−/− mice revealed a high degree of STAT3 activity (Fig. 4 C). However, pY-STAT3 staining localized with diffuse infiltrates throughout the synovium and was not confined to ELS. Thus, localized STAT3 activity is an unreliable indicator of ELS and is consistent with the broader roles of STAT3 in governing chronic inflammation (Atsumi et al., 2002; Sawa et al., 2006; Nowell et al., 2009).

Recent studies have identified effector Th17 cells with Th-like properties that express the glycoprotein podoplanin (Pdp; gp38; Peters et al., 2011; Hirota et al., 2013). These cells contribute to ELS development in autoimmunity and GC reactions (Peters et al., 2011; Hirota et al., 2013; Miyamoto et al., 2013). Because Il27ra−/− mice show heightened peripheral Th17 responses (Fig. 2, E and F) and the local expression of Th17/Tfh markers during AIA (Figs. 3, D and E, and 4 B), we examined if synovial ELS development was linked to infiltrating Pdp-expressing T cells. Synovial tissue from AIA-challenged Il27ra−/− mice showed increased Th17 cells (Fig. 5 A). Although Pdp+ cells were enriched at ELS, staining was also seen in other areas (e.g., synovial lining). Indeed, synovial Pdpn expression remained comparable in WT and Il27ra−/− mice (Fig. 5 B). Whereas draining LNs from Il27ra−/− mice with AIA showed no increase in the total number of CD4+Pdp+ T cells (Fig. 5 C), an increased number of Pdp+ Th17 cells were detected (Fig. 5 D).
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To determine if IL-27 could suppress Pdp+ Th17 cell development, naïve CD4 T cells were cultured under Th17-polarizing conditions and expression of IL-17 and Pdp was assessed by flow cytometry (Fig. 5, E and F). Although IL-27 had a modest impact on the number of total CD4 cells expressing Pdp, IL-27 preferentially inhibited the expansion of Pdp+IL-17+ CD4 cells (Fig. 5, E and F). Subsequent IF studies of the inflamed synovium of Il27ra−/− mice revealed a colocalization of Pdp and CD3 in lymphoid aggregates (Fig. 5 G). Thus, synovial ELS in Il27ra−/− mice are associated with an increase in synovial Th17 and Tfh effector cytokines and peripheral Pdp+ Th17 cell numbers. Therefore, IL-27 negatively regulates ELS development at sites of chronic inflammation through a potential impact on Th17 cells that can acquire Tfh-like properties.

IL-27 expression is decreased in lymphoid-rich synovitis

To translate our animal studies to clinical RA, expression of Th17/Tfh signatures were examined in synovial biopsies from ELS+ and ELS− RA patients. In line with our mouse data, IL17 and IL21 were elevated in patients with ELS+ synovitis, whereas no IL17 transcripts were detected in patients with diffuse pathology (Fig. 6 A). PDPN, BCL6, and IL10 expression was comparable in both patient groups.

Consistent with data presented in Fig. 5 G, IF again confirmed the localization of Pdp in T cell–rich lymphoid aggregates in ELS+ synovia (Fig. 6 B). Although Pdp expression was also seen in lymphatic compartments and synovial lining, it is perhaps significant that Pdp was only observed in ELS featuring full T/B cell segregation. Thus, Pdp detection in ELS may indicate functional GCs.

To link synovial histopathology with IL-27 involvement, expression of IL-27p28 (IL27) and Epstein–Barr virus–induced gene-3 (EBI3) were quantified in ELS+ and ELS− RA patient biopsies and OA control tissue. Expression of IL27 was significantly higher in ELS+ RA patients compared with ELS− RA and OA biopsies (Fig. 6 C). Although EBI3 showed a similar pattern of expression, the increase in ELS+ tissue was not significant (P = 0.8360; Fig. 6 C). Detection of IL27

Figure 5. Pdp-expressing T helper cells are found at synovial ELS in Il27ra−/− mice. (A–D and G) AIA was established in WT and Il27ra−/− mice, and pathology was assessed at d10. (A) IHC of serial sections stained for CD3, B220, and Pdp in Il27ra−/− mice. ELS in sequential sections are shown boxed. Images are representative of four sections from two independent experiments. (B) qPCR of synovial Pdpn expression (n = 15/group from 3 independent experiments). (C and D) Number of Pdp+ CD4 cells (C) and IL-17+ and IL-17+Pdp+ Th17 cells (D) in inguinal LNs determined by flow cytometry (n = 8–9/group). Data are representative of two independent experiments. (E and F) WT CD4 T cells were activated under Th17-polarizing conditions with the indicated amount of IL-27 (0–100 ng/ml). Pdp+ Th17 cell differentiation was determined by flow cytometry. Representative flow cytometry (E) and graphs (n = 3 mice) showing the number of CD4+Pdp+ T cells and CD4+IL-17+Pdp+ T cells (Pdp+ Th17 cells; F) after 4 d of culture. E and F are representative of three independent experiments. (G) Detection of Pdp+ T cells at synovial ELS in Il27ra−/− mice by IF for Pdp and CD3 with DAPI nuclear staining. Images are representative of four sections from two independent experiments. Error bars indicate SEM. *, P < 0.05; **, P < 0.01. Bars: (A) 300 µm left, 200 µm right; (G, left) 200 µm left; (G, merged image) 100 µm.
Although the mechanisms determining lymphoid-rich synovitis remains undefined, the ability to stratify patients with signature biomarkers such as IL27 has the potential to inform treatment decisions by ensuring patients receive the most efficacious form of therapy for their type of disease.

**MATERIALS AND METHODS**

**Clinical patient samples.** Synovial tissue was collected from a total of 59 RA patients fulfilling the ACR criteria and undergoing arthroplastic surgery (n = 23) or ultrasound-guided synovial biopsy (n = 36) and 13 OA patients who underwent total joint replacement as control samples. Demographic data are provided in Table S1. The majority of patients had received stable-dose methotrexate, and none were on biologics. Paired paraffin-embedded tissue and RNA samples were prepared from all patients to allow cross-referencing between histological assessments and qPCR gene expression analysis. Procedures were approved by the hospital Ethics Committee (REC/98/11/27 Guys and St. Thomas’ NHS Trust and REC 05/Q0703/198 Barts and The London NHS Trust) and performed after informed written consent.

For histological grading of tissues, 5-µm paraffin-embedded sections were stained with hematoxylin and eosin (H&E) to define the predominant histomorphological pattern of RA synovitis as either diffuse or aggregate. Synovial inflammation was graded as described previously (Humby et al., 2009), which is based on the enlargement of the synovial lining cell layer (score 0–3), the density of resident cells (0–3) and the extent of the inflammatory infiltrate (0–3) to yield a score ranging between 0 and 9. The degree of immune cell infiltration was further characterized by IHC using a

Figure 6. IL-27 expression reflects synovial histopathology in RA. (A) qPCR analysis of the indicated genes in synovia from ELS+ and ELS− RA patients (IL17, n = 23 ELS+, n = 16 ELS−; IL21, n = 26 ELS+, n = 20 ELS−; PDPN, BCL6, and IL10, n = 13 ELS+, n = 12 ELS−). (B) Detection of Pdp+ cells at synovial ELS by IF for Pdp and CD3 with DAPI nuclear staining. Images are representative of three tissue samples. (C) qPCR of IL27 and EBI3 expression in ELS+ and ELS− RA synovia, and OA control patients (n = 19 ELS+, n = 14 ELS−, n = 11 OA). (D) Synovial IL27 gene expression plotted against synovitis and IHC scores for CD3, CD20, CD138, and CD68 cells. Error bars indicate SEM; *, P < 0.05; **, P < 0.01. Bars, 50 µm.
genes for 18S rRNA and ACTB. Genes were normalized against the expression of the housekeeping genes as an arthritic index. The aggregate score for all parameters is presented as an arthritic index.

Animals. Il27ra−/− mice have been described previously (Yoshida et al., 2001). Mice were on a C57BL/6 background and were bred under specific pathogen-free conditions at Monash Institute of Medical Research (Clayton, Victoria, Australia) and Cardiff University (Cardiff, Wales). All experiments were endorsed by the Monash University Animal Ethics Committee and UK Home Office-approved project license PPL 30/2928.

Murine AIA. AIA was established in adult (8–12 wk) Il27ra−/− mice and age/sex-matched WT controls, as described previously (Nowell et al., 2009). In brief, mice were immunized by subcutaneous administration of 100 µl mBSA (1 mg/ml; Sigma-Aldrich) emulsified in an equal volume of Complete Freund’s Adjuvant (CFA). To prime the immune response, mice were also treated with 100 µg of heat-inactivated Bordetella pertussis toxin as a single intra-peritoneal injection (Sigma-Aldrich). 1 wk later, mice were immunized with an identical subcutaneous administration of mBSA in CFA. 21 d after the initial immunization, inflammatory arthritis was triggered by intra-articular administration of 10 µl mBSA (10 mg/ml) in the right stifle joint. Animals were inspected daily for arthritis development by measuring knee joint diameters using a POCO 2T micrometer (Kreeplim). A minimum of six animals per time point was culled at intervals (days 3, 10, and 35) over the course of the disease, and joint pathology assessed histologically. Cumulative arthritic scores were generated according to the severity of synovial inflammation, exudate, hyperplasia, and joint erosion (see below).

Knee joints were fixed in neutral buffered formalin (10% vol/vol) and decalcified in 10% (vol/vol) formic acid at 4°C before embedding in paraffin. Microwave serial sections (7 µm thick) were stained with H&E. For evaluation of bone and cartilage erosion, sections were stained with Safranin O and Fast Green (Sigma-Aldrich). Two independent observers, blinded to the experimental groups, scored the sections for subsynovial inflammation (0 = normal 5 = ablation of adipose tissue due to leukocyte infiltrate), synovial exudate (0 = normal to 3 = substantial number of cells with large fibrin deposits), synovial hyperplasia (0 = normal 1–3 cells thick to 3 = over 3 layers thick with overgrowth onto joint surfaces with evidence of cartilage/bone erosion), and cartilage/bone erosion (0 = normal 3 = destruction of a significant part of the bone). The aggregate score for all parameters is presented as an arthritic index.

Quantitative real-time PCR. For mouse samples, the amplified synovium was recovered by dissection before storage in RNAlater (Ambion) at −80°C. Total cellular RNA was extracted using TRIzol reagent (Bionicle) and further purified using the RNeasy Mini kit with on-column DNAse treatment (QiAGEN). RNA was converted to cDNA using the nanoScript 2 Reverse Transcription kit (Promega), Expression of mouse genes was determined using the 7900HT Fast or the QuantStudio 12K Flex Real-Time PCR System, and data acquisition and analyses were performed using the Sequences Detection System Version 2.3 software and ExpressionSuite software version 1.0.3 (all from Life Technologies). Sequences of primers used with SYBR Green reagents (Invitrogen) can be seen in Table S2. All other genes were analyzed using TaqMan primers, probes, and reaction buffers (Life Technologies). Genes were normalized against the expression of the housekeeping genes for 18S rRNA and GAPDH.

Clinical patient synovial samples were stored in RNAlater at −80°C. RNA was recovered as above using the RNeasy Mini kit (QiAGEN) and cDNA prepared using the Thermoscript RT-PCR System for First-Strand cDNA Synthesis kit (Invitrogen). Gene expression was quantified using TaqMan primers, probes, and reaction buffers and acquired on a 7900HT Fast Real Time PCR System (all Life Technologies). Genes were normalized against the expression of the housekeeping genes for 18S rRNA and GAPDH.

Immunohistochemistry. Leukocyte and follicular markers were detected in paraffin sections using primary antibodies to murine CD3 (Dako), F4/80 (AbD Serotec), B220 (BD), CD21, and Bcl-6 (Santa Cruz Biotechnology, Inc.) and podoplanin (BioLegend). Antigen unmasking was achieved by heating in 10 mM sodium citrate buffer containing 0.05% (wt/vol) Tween 20 (95°C, 40 min). For 4F4/80 staining, antigen retrieval was performed by incubating with 0.05% (wt/vol) Trypsin-EDTA (37°C, 30 min). Endogenous peroxidase and biotin activity was blocked using 3% (vol/vol) H2O2 and an avidin/biotin blocking kit (Vector Laboratories), respectively. Sections were incubated in serum appropriate to the secondary antibody before primary antibody incubations. Antibody labeling was detected using biotinylated secondary antibodies (Dako), the Vectastain ABC kit and diaminobenzidine chromagen (Vector Laboratories). Sections were counterstained with hematoxylin. The Leica QWin microscope imaging software was used for quantification of staining. Colocalization of lymphoid cells was determined by staining of serial, sequential sections.

Immunofluorescence. Paraffin-embedded sections were rehydrated before antigen unmasking by incubating in target retrieval solution (Dako) at 95°C for 35 min for human synovium or 10 mM sodium citrate buffer containing 0.05% (wt/vol) Tween 20 (95°C, 40 min) for mouse. Endogenous biotin activity was blocked using the avidin/biotin blocking kit (Vector Laboratories). Human synovial sections were incubated with serum-free protein block (Dako) before incubation with goat anti-human IL-27R (R&D Systems), mouse anti–human podoplanin, or mouse anti–human CD3 (both Dako). Mouse sections were blocked with goat serum before incubation with antibodies to podoplanin (BioLegend) or CD3 (Dako). Antibody labeling was detected using combinations of biotinylated and Alexa Fluor 488–conjugated secondary antibodies, and Alexa Fluor 555 or APC-conjugated streptavidin. Slides were counter stained with DAPI and mounted with Mowiol.

In vitro T cell cultures. Naive CD4 T cells (CD4+CD25−CD44+CD62L+) were cultured in RPMI-1640 supplemented with 10% (vol/vol) FCS, 2 mM l-glutamine, 100 U/ml penicillin, 100 µg/ml streptomycin, 1 mM sodium pyruvate, and 50 µM 2-mercaptoethanol (all from Invitrogen). 106 cells were cultured in 96-well plates coated with anti-CD3 (1 µg/ml; 145–2C11) and soluble anti-CD28 (5 µg/ml; 37.51). Cultures contained recombinant TGFβ (1 ng/ml) and IL-6 (20 ng/ml) with or without IL-27 (1–100 ng/ml) as indicated.

Flow cytometry. Inguinal LN were recovered and single-cell suspensions prepared and analyzed by flow cytometry. For intracellular cytokine staining, cells were cultured with PMA (50 ng/ml), ionomycin (500 ng/ml), and monensin (5 µM; all from Sigma-Aldrich) for 4 h. Cells were stained for cell surface markers, then fixed and permeabilized in Cytofix/Cytoperm (BD) before intracellular detection of cytokines. Flow cytometric analysis of cells was performed using anti-CD4 (RM4-5), anti-CD3 (17A2), anti–IFN-γ (TC11–18H10.1), anti–IL-17 (XMG1.2), and anti–podoplanin (8.1.1). Cells were acquired using a FACSCanto II (BD) or CyAn ADP (Beckman Coulter) flow cytometer and analyzed using FlowJo software (Tree Star). Cell numbers were determined by multiplying the percentage obtained by flow cytometry with the total cell count.

Enzyme-linked immunosorbent assay (ELISA). IL-17A levels were determined in mouse serum using a commercial murine IL-17A ELISA kit (BioLegend). Serum antibody titers to mBSA were determined by coating
microtiter plates with mBSA diluted in PBS (5 μg/ml). Nonspecific binding sites were blocked with 5% (wt/vol) milk extract in PBS containing 0.05% (wt/vol) Tween-20. Sera were diluted 1/1,000 in PBS containing milk extract and Tween-20 before adding to the microplates for 2 h. Antibody levels were detected using HRP-conjugated anti-mouse IgG and tetramethylbenzidine substrate. Absorbance was measured at 450 nm.

Statistics. Statistical analysis was performed using GraphPad Prism software. For assessment of arthritic indices, significant differences were determined using the nonparametric Mann Whitney U test. Otherwise, statistical differences were determined using the unpaired Student’s t test. Where experimental groups were compared across multiple time points, a two-way analysis of variance (ANOVA) was used with the Bonferroni post-test. For clinical samples, data displaying nonnormal distribution was analyzed using the nonparametric Mann Whitney U test. Normally distributed data were analyzed using the Student’s t test. P < 0.05 was considered significant. Graphs represent mean ± SEM.

Online supplemental material. Fig. S1 shows a histopathology reference atlas for scoring RA synovial tissue. Table S1 shows the clinical characteristics of the RA and OA patients. Table S2 lists primer sequences used in this study for SYBR Green-based qPCR. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20152307/DC1.

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Authors contributions: G.W. Jones, S.A. Jones, and B.J. Jenkins designed the study and performed the experiments. C.J. Greenhill, L. McLeod, and A.S. Williams contributed to the analysis of experimental arthritis samples. A. Cardus contributed to analysis of in vitro experiments. M. Bombardieri, V. Rocher-Ros, A. Neviani, and C. Pitalis contributed clinical specimens, histopathological characterization, and analysis of clinical samples. G.W. Jones, S.A. Jones, and B.J. Jenkins wrote the paper.

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