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 (ACP) 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., 2001; Ovaki 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,
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Th17 cell plasticity permits the acquisition of Th1-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.

Figure 1. IL-27R is expressed at synovial ELS. (A) Representative histopathology of RA synovium from 59 patients with ELS (ELS+) and diffuse pathology (ELS−). Sequential sections were stained as indicated by IHC. (B) qPCR analysis of ELS+ and ELS− synovia for the indicated genes (number of patients: CXCL13 and AID, n = 34 ELS+, n = 24 ELS−; CXCR5, CD21L, and LTB, n = 28 ELS+, n = 20 ELS−; CCL19 and CCL21, n = 13 ELS+, n = 12 ELS−; CXCL12, n = 15 ELS+, n = 8 ELS−). (C) IL27RA expression in ELS+ and ELS− RA synovia. Synovial tissue from OA patients was used as control (error bars, SEM; n = 19 ELS+, n = 13 ELS−, n = 11 OA patients). (D) Detection of IL-27R in tonsil GCs (left) and synovial ELS (right) by IF for IL-27R and CD3, and DAPI counterstaining. Images are representative of three tissue samples. (E) IF for IL-27R and CD3 with DAPI nuclear staining in synovial ELS. Error bars indicate SEM. *, P < 0.05; **, P < 0.01; ***, P < 0.001. Bars: (A) 200 µm; (D and E) 50 µm.
Bone erosion (Niedbala et al., 2008; Kalliolias 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 µm2 per synovial section and 1.6 × 104 ± 0.5 µm2 in size; Fig. 3 B). Although the inflamed 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

IL-27R−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 and bone erosion, seen as loss of red Safranin O staining of the articular cartilage. Boxes show focal bone erosions, seen as loss of red Safranin O staining of the articular cartilage.

Figure 2. IL-27 is protective in inflammatory arthritis. (A) Histopathology scoring of AIA in WT and Il27ra−/− mice, showing arthritic index, synovial infiltration, exudate, and erosion at d3 (n = 6–7/group), d10 (n = 13/group), and d35 (n = 14–15/group). (B) Representative H&E of knee joints at d10 of AIA; boxed areas show extensive subsynovial inflammation (large box) and focal bone erosions (small box) in Il27ra−/− mice. Noninflamed control joints are shown on the right. (C) Representative images of cartilage degradation and bone erosion, seen as loss of red Safranin O staining of the articular cartilage. Boxes show focal bone erosions. (D) Anti-mBSA serum titers at d3 (n = 6–7/group), d10 (n = 5/group), and d35 (n = 6–8/group). (E) Number of IFN-γ− and IL-17− producing CD4 T cells in inguinal LNs determined by flow cytometry at d3 (n = 6–7/group), d10 (n = 8/group), and d35 (n = 14–15/group). (F) ELISA of serum IL-17 at d3 (n = 6–7/group) and d10 (n = 12–13/group) of AIA. Error bars indicate SEM. *P < 0.005; **P < 0.001; ***P < 0.001. Data are presented from two independent experiments per time point. Bars: (D) 500 µm; (C) 300 µm.
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lymphoid cells within ELS (Luther et al., 2000; Chen et al., 2002). In contrast, synovial Ccl19 expression was reduced in IL-27R deficiency. Although CCL19 and CCL21 share a common chemokine receptor (CCR7), they have a different 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 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 Il27ra−/− mice (Fig. 4 A). However, at this later time point, increased expression of the lymphoendothelial cytokines LTα and LTβ (Lta and Ltb) was observed in Il27ra−/− mice (Fig. 4 A). Similarly, synovial Prdm1 (Blimp1) expression, which supports B cell differentiation into antibody-secreting plasma cells, was also heightened in 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, F4/80+ myeloid cells were largely restricted to areas surrounding the lymphoid rich zones (Fig. 3 C). IHC detected the transcriptional regulator of Th 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 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 Il27ra−/− mice, qPCR analysis showed increased synovial expression of Bcl6 as compared with WT controls. No difference in Il6, Il21, Ltb, Vegf, Cxcl12, or Prdm1 was seen between WT and Il27ra−/− mice (Fig. 3 F). Increased Bcl6 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 IL-27R deficiency. Although CCL19 and CCL21 share a common chemokine receptor (CCR7), they have a different 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 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 Il27ra−/− mice (Fig. 4 A). However, at this later time point, increased expression of the lymphoendothelial cytokines LTα and LTβ (Lta and Ltb) was observed in Il27ra−/− mice (Fig. 4 A). Similarly, synovial Prdm1 (Blimp1) expression, which supports B cell differentiation into antibody-secreting plasma cells, was also heightened in 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 Tfh-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 the inflamed synovium. 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 Tfh-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, we examined if synovial ELS development was linked to infiltrating Pdp-expressing T cells. Synovial tissue from AIA-challenged Il27ra−/− mice showed Pdp+ cells colocalizing with B220+ and CD3+ cells at ELS (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).
To determine if IL-27 could suppress Pdp+ Th17 cell development, naive 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...
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ELSs. Although the mechanisms determining lymphoid-rich synovitis remains undefined, the ability to stratify patients with signature biomarkers such as \( \text{IL27} \) 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 (Humphrey 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

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**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 \((IL17, n = 23 \text{ ELS}^+, n = 16 \text{ ELS}^-, IL21, n = 26 \text{ ELS}^+, n = 20 \text{ ELS}^-, PDPN, BCL6, \text{ and IL10}, n = 13 \text{ ELS}^+, n = 12 \text{ ELS}^-\)\). (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 \((n = 19 \text{ ELS}^+, n = 14 \text{ ELS}^-, n = 11 \text{ OA})\). (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.
semi-quantitative analysis which grades (0–4) the degree of CD3 (T cells), CD20 (B cells), CD138 (plasma cells), and CD68 (macrophages) staining in the perivascular and submucosal lining (Fig S1). To define the presence of ectopic lymphoid follicles, lymphoid aggregates were counted in each section and graded as described previously (Manzo et al., 2005; Huniby et al., 2009), as grade 1 (G1) aggregates displaying a 2–5 radial cell number from a central blood vessel, grade 2 (G2), between 6–10 cells, or grade 3 (G3), with >10 cells. IHC staining for CD3, CD20, and CD21 was further used to confirm T/B cell segregation and the presence of follicular DC networks. Tissue with maximal G3 aggregates, staining positive for CD21 and displaying well-organized lymphoid structures, were defined as ELS’s. To minimize bias caused by anomalies in serial sectioning, all paraffin-embedded blocks were cut and stained at three levels 50 µm apart.

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 Cadiff 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 Adjutant (CFA). To prime the immune response, mice also received 160 µg of heat-inactivated Bordetella pertussis toxin as a single intraperitoneal injection (Sigma-Aldrich). 1 wk later, mice were reimmunized with an identical subcutaneous administration of mBSA in CFA. 21 d after the initial immunization, inflammatory arthritis was triggered by intraarticular 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 (Kreoqin). 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 arthritis 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. Mid sagittal serial sections (7 µm thick) were stained with H&E. For evaluation of bone and cartilage erosion, sections were stained with Safranin O and alcian blue to detect proteoglycan loss. Areas of cartilage and bone erosion were scored on a scale of 0–3 using the modified Mankin score. In addition, calcified areas were stained with 1% Alcian blue for 10 min, counterstained with methyl green, and analyzed using Image J software.

RNA was recovered as above using the RNeasy Mini kit (QIagen) and cDNA prepared using the nScript 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.

Clinical patient synovial samples were stored in RNA later at −80°C. RNA was recovered as above using the RNeasy Mini kit (QIagen) and cDNA prepared using the nScript 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 F4/80 staining, antigen retrieval was performed by incubating with 0.05% (wt/vol) Trypsin-EDTA (37°C, 30 min). Endogenous peroxidase and biontin 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 diamobenzidine 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 Flour 488–conjugated secondary antibodies, and Alexa Flour 555 or APC-conjugated streptavidin. Slides were counterstained with DAPI and mounted with Mowiol.

In vitro T cell cultures. Naive CD4 T cells (CD4+CD25−CD44loCD62Lhi) 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). 105 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 LNs 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-IL-17 (TC11-18H10.1), anti-IFN-γ (XMG1.2), and anti-podoplanin (8.1.1). Cells were acquired using a FACS Canto 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 by 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). Non-specific 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 mental groups were compared across multiple time points, a two-way analysis of variance (ANOVA) was used with the Bonferroni post-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 mental groups were compared across multiple time points, a two-way analysis of variance (ANOVA) was used with the Bonferroni post-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 mental groups were compared across multiple time points, a two-way analysis of variance (ANOVA) was used with the Bonferroni post-test.

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.20132307/DC1.

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The authors declare no competing financial interests.

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. Nerviani, and C. Pitaisal contributed clinical samples, histopathological characterization, and analysis of clinical samples. G.W. Jones, S.A. Jones, and B.J. Jenkins wrote the paper.

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REFERENCES


Figure S1. Immunohistochemistry reference atlas for CD3, CD20, CD138, CD68 synovial lining, and CD68 sublining scoring of the inflammatory infiltrate in clinical RA synovial tissue. Bars, 100 μm.
Table S1. Clinical characteristics of RA (n = 59) and OA control patients (n = 11)

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<td></td>
</tr>
<tr>
<td>Large joint</td>
<td>50</td>
<td>54</td>
<td>100</td>
</tr>
<tr>
<td>Small joint</td>
<td>50</td>
<td>46</td>
<td>-</td>
</tr>
<tr>
<td>Disease Duration (mean± SD)</td>
<td>5.8±4.5</td>
<td>10±7</td>
<td>N/A</td>
</tr>
<tr>
<td>DMARDs (%)</td>
<td>53</td>
<td>57</td>
<td>-</td>
</tr>
<tr>
<td>RF* and/or ACPA* (%)</td>
<td>67</td>
<td>70</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table S2. Primer sequences for SYBR green-based qPCR analysis of gene expression in mouse synovium recovered during experimental inflammatory arthritis

<table>
<thead>
<tr>
<th>Name</th>
<th>Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>18S forward</td>
<td>5’-GTAACCCGTGAACCCCATTT-3’</td>
</tr>
<tr>
<td>18S reverse</td>
<td>5’-CCATCCAATCGGATAGCG-3’</td>
</tr>
<tr>
<td>Bcl6 forward</td>
<td>5’-CCCTGCAACTGGAAGAGCATAAG-3’</td>
</tr>
<tr>
<td>Bcl6 reverse</td>
<td>5’-AGTATGGAGCGACATCTCTTAT-3’</td>
</tr>
<tr>
<td>Ccl19 forward</td>
<td>5’-GCACACAGTCTCTCTAGGCTC-3’</td>
</tr>
<tr>
<td>Ccl19 reverse</td>
<td>5’-AGTGCGGCTGGGAGGTCCA-3’</td>
</tr>
<tr>
<td>Ccl21 forward</td>
<td>5’-CCCTGGACCCAGGCACTGA-3’</td>
</tr>
<tr>
<td>Ccl21 reverse</td>
<td>5’-TGCCGCGGATAGGGACACGCTT-3’</td>
</tr>
<tr>
<td>Cxcl12 forward</td>
<td>5’-GCCGCTCTCGCATCAGTGACGGTAA-3’</td>
</tr>
<tr>
<td>Cxcl12 reverse</td>
<td>5’-GCCTGAGCGTCCTGGGCCGA-3’</td>
</tr>
<tr>
<td>Cxcl13 forward</td>
<td>5’-TGCCCCAAAATCGAAGTTGTGATCT-3’</td>
</tr>
<tr>
<td>Cxcl13 reverse</td>
<td>5’-ACTACCTGGACCTGGGAGGTGA-3’</td>
</tr>
<tr>
<td>Il6 forward</td>
<td>5’-ATGGGACTACGAACTCGG-3’</td>
</tr>
<tr>
<td>Il6 reverse</td>
<td>5’-TGAGGACTCTGCCTTGCTT-3’</td>
</tr>
<tr>
<td>Vegf forward</td>
<td>5’-GCACACAGGACGGCTGAAGA-3’</td>
</tr>
<tr>
<td>Vegf reverse</td>
<td>5’-CCCACGACAGAAGACAG-3’</td>
</tr>
</tbody>
</table>