OSCAR Is a Receptor for Surfactant Protein D That Activates TNF-α Release from Human CCR2+ Inflammatory Monocytes

Alexander D. Barrow, Yaseelan Palarasah, Mattia Bugatti, Alex S. Holehouse, Derek E. Byers, Michael J. Holtzman, William Vermi, Karsten Skjødt, Erika Crouch and Marco Colonna

*J Immunol* published online 25 February 2015
http://www.jimmunol.org/content/early/2015/02/24/jimmunol.1402289

Supplementary Material
http://www.jimmunol.org/content/suppl/2015/02/24/jimmunol.1402289.DCSupplemental

Subscription
Information about subscribing to *The Journal of Immunology* is online at:
http://jimmunol.org/subscription

Permissions
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts
OSCAR Is a Receptor for Surfactant Protein D That Activates TNF-α Release from Human CCR2+ Inflammatory Monocytes

Alexander D. Barrow,* Yaseelan Palarasah,† Mattia Bugatti,‡ Alex S. Holehouse,§ Michael J. Holtzman,‖ William Vermi,*‡ Karsten Skjødt,† Erika Crouch,* and Marco Colonna*

Surfactant protein D (SP-D) is critical for maintenance of lung homeostasis and provides a first line of defense to pathogens at mucosal surfaces. Polymorphisms in the SP-D-encoding gene SFTPD have been associated with chronic obstructive pulmonary disease and ulcerative colitis. Identification of the immunoreceptors that bind SP-D is essential for understanding its contribution to lung homeostasis and mucosal defense. We located a putative binding motif for the osteoclast-associated receptor (OSCAR) within the SP-D collagenous domain. An OSCAR-Fc fusion protein specifically bound to the collagenous region of recombinant SP-D and captured native SP-D from human bronchoalveolar lavage. OSCAR localized in an intracellular compartment of alveolar macrophages together with SP-D. Moreover, we found OSCAR on the surface of interstitial lung and blood CCR2+ inflammatory monocytes, which secreted TNF-α when exposed to SP-D in an OSCAR-dependent fashion. OSCAR and SP-D did not exclusively colocalize in lung, as they were also highly expressed in atherosclerotic plaques of human aorta, supporting a role for this interaction in atherosclerosis. Our results identify the OSCAR:SP-D interaction as a potential therapeutic target in chronic inflammatory diseases of the lung as well as other diseases involving tissue accumulation of SP-D, infiltration of inflammatory monocytes, and release of TNF-α. 

The Journal of Immunology, 2015, 194: 000–000.

Surfactant protein D (SP-D) is a member of the collagenous lectins (collectins), which provide a first line of humoral innate immune defense (1–3). The collectin family also includes, but is not limited to, mannan-binding lectin (MBL) and surfactant protein A (SP-A). Collectins are soluble proteins that are structurally characterized by an N-terminal collagenous region, a flexible coiled coil neck region, and a C-terminal carbohydrate recognition domain (CRD), which binds various sugars in a calcium-dependent fashion (4). The hydrophobic N-terminal region of the SP-D polypeptide encodes two cysteine (Cys) residues (Cys15 and Cys20). Multimeric SP-D dodecamers can be formed through N-terminal disulfide bonding of trimeric SP-D monomers. Within the collectin family, the formation of dodecamers is unique to SP-D, which can be observed as the characteristic cruciform structures by electron microscopy (5). The collectin family is expressed in different mucosae and plays an important tissue-specific role in the innate immune response (4).

SP-D is predominantly secreted by alveolar type II epithelial cells, but is also produced outside of the lung, in the gastrointestinal and genitai mucosae, salivary glands, prostate, kidney, pancreas, skin, and endothelial cells (6). SP-D can act as a pattern recognition receptor through binding of the CRD to evolutionary conserved glycolipids and glycoproteins associated with infectious agents, such as LPS from certain bacterial species or viral envelope glycoproteins. SP-D can thus opsonize, neutralize, and agglutinate infectious microorganisms predisposing to elimination by phagocytes. In the lung, SP-D also plays an important homeostatic role through CRD-dependent scavenging of surfactant phospholipids by alveolar macrophages (7, 8). SP-D-deficient (Sftpd−/−) mice developed accumulation of surfactant phospholipids in the lungs, as well as infiltration of monocytes and the proinflammatory activation of alveolar macrophages, leading to chronic inflammation, emphysema, and fibrosis (9, 10). Correction of some, but not all, of the pulmonary abnormalities in Sftpd−/− mice required the transgenic expression of SP-D with an intact collagenous domain (11). SP-D-deficient children were susceptible to more frequent pneumonias, and long-term outcome was worse than SP-D-deficient control children (12).

Human SFTPD genotype can influence the assembly, concentration, and biological function of SP-D in vivo (13). Interestingly, polymorphisms in SFTPD have been associated with susceptibility to chronic and infectious lung diseases, such as chronic obstructive pulmonary disease (COPD) (14, 15), emphysema (16),...
The cloning and expression of recombinant Fc-fusion proteins

The 293T were transiently transfected with 48 μg plasmid DNA/10-cm dish using Lipofectamine 2000 diluted in OptiMem (both Invitrogen), according to the manufacturer’s instructions. Fc-fusion proteins were purified from serum-free culture supernatants by protein A affinity chromatography.

Recombinant collectin and collectin-like molecules

The cloning and expression of recombinant full-length human SP-D and the full-length and mutant isoforms of rat SP-D have been described in detail before (5, 29). Briefly, S15, 20 is a recombinant rat SP-D mutant with a substitution of serine for Cys15 and Cys20 that is assembled exclusively as SP-D trimers (29). Mini SP-D is a mutant form of rat SP-D that lacks two internal exons (3, 4) encoding the SP-D collagenous domain. The neck CRD (NCRD) (trimeric neck + CRD) is a rat SP-D transmembrane mutant lacking the N-terminal peptide and collagen domains that retains lectin activity (5). Recombinant human MBL was purchased from Sino Biological (Beijing, China), and complement component 1q (C1q) purified from human serum was purchased from Complement Technology. The endotoxin level in our stock (112 μg/ml) human SP-D reagent was determined at 120 EU/ml by Limulus amebocyte lysate assay (Lonza).

Immobilization of Abs, proteins, and peptides

Collagen I from rat tails and BSA were purchased from Sigma-Aldrich. BSA (2%), collagen (2.5 μg/ml), recombinant SP-D, and isoforms (2.5 μg/ml) were immobilized onto either tissue culture or ELISA plates overnight in 100 μl of 0.1 M acetic acid at 4°C. Fc-fusion proteins (0.25 μg/ml) were immobilized onto plates in 100 μl coating buffer (15 mM Na2CO3, 35 mM NaHCO3 [pH 9.6]) overnight at 4°C. All peptides were certified LPS free by Limulus amebocyte lysate assay (Lonza). All wells were washed three times in TBS to remove excess proteins before blocking in 5% BSA in TBS for 1 h at 37°C prior to performing binding assays.

Solid- and soluble-phase SP-D–binding assays

For solid-phase SP-D–binding assays, 5 μg/ml each Fc-fusion protein in 100 μl TBS-binding buffer (10 mM Tris.HCl [pH 7.5], 150 mM NaCl, 0.1% BSA, 0.05% Tween 20 ± 5 mM CaCl2) was incubated at room temperature for 1 h in ELISA plates. Wells were then washed five times in TBS-binding buffer ± 5 mM Ca2+ before incubating with 1:5000 goat anti-human Ig-HRP conjugate (Southern Biotech) for 1 h in TBS-binding buffer ± 5 mM Ca2+. Wells were then washed an additional five times in TBS-binding buffer ± 5 mM Ca2+ before developing with O-phenylenediamine dihydrochloride, and the absorbance at 490 nm was recorded. For soluble-phase SP-D–binding assays, 2-fold dilutions of either recombinant human SP-D dodecamer (starting at 125 ng/ml) or human bronchoalveolar lavage fluid (BAL) (starting at 1/4 dilution) were made in TBS-binding buffer and incubated in Fc-fusion–coated wells for 3 h. Captured SP-D was detected using 2 μg/ml anti-human SP-D mAb (Hyb-246-04) for 1 h at room temperature, followed by rabbit anti-mouse IgG-HRP (Dako).

Generation and purification of mAbs

To generate blocking mAbs to the OSCAR ectodomain, NMRI mice were immunized s.c. three times with 20 μg human OSCAR-Fc. For generation of mAbs to the OSCAR cytoplasmic tail, mice were immunized with a synthetic peptide, representing the last 14 C-terminal residues (Cys49-GRAFAPAPGIRP) of mouse OSCAR. The synthetic peptides were coupled to diethylaminoethyl mustard (Cyclophos) or mAb was generated by cloning an irrelevant Fc-fusion into the ELISA plate wells. Positive clones for the OSCAR C-terminal cytoplasmic tail were identified by screening to the peptide used for immunization.

Plasmids

The human OSCAR-Fc construct has been described before (25). The extracellular domain of human leukocyte-associated Ig-like receptor (LAIR)-1 was amplified from plasmid DNA containing the human LAIR-1 DNA with Platinum Pfu DNA Polymerase (Invitrogen) using the following forward, 5′-CATCGCTGGAGCAGGGAAGATCAGGCG-3′ and reverse, 5′-GAATTCTAGAATGCTTACAGGGCTTG-3′ primers (XhoI and XbaI restriction sites underlined). XhoI- and XbaI-restricted PCR products were cloned into the Signal Ig plus vector, which encoded the LAIR-1 ectodomain in frame with human IgG1 Fc. Cloning and expression of Ig-like transcript (ILT)-1, -3, and -7 and trig-

Identification of the immunoreceptors that capture SP-D and transduce intracellular signaling is therefore essential for understanding how SP-D contributes to lung homeostasis and innate mucosal defense and SFTPD disease associations (3, 24). Osteoclast-associated receptor (OSCAR) is an activating receptor for collagen expressed by osteoclasts that costimulates osteo-

clastogenesis (25). OSCAR transmits intracellular signals through the associated adapter FCγ (26), which contains an ITAM that recruits the protein tyrosine kinase Syk. Although in mouse OS-

cAR is exclusively expressed in osteoclasts, human OSCAR was reported to be also expressed on monocytes, macrophages, neutrophils, and dendritic cells (26). Human OSCAR was shown to enhance the proinflammatory response of monocytes, although the monocytic subset that specifically expressed OSCAR was not de-

scribed (26, 27). The wider expression of OSCAR by human myeloid immune cells suggested to us that OSCAR might play a role in innate immunity in addition to the reported role in osteoclastogenesis. In this study, we identified SP-D as a candidate ligand for OSCAR by bioinformatics search for proteins en-

coding OSCAR-biding motifs (25). We further demonstrated that OSCAR and SP-D colocalized in alveolar macrophages and that the OSCAR:SP-D interaction triggered TNF-α production by inflammatory monocytes.

Materials and Methods

Bioinformatics

To initially identify putative OSCAR-binding candidate proteins for further scrutiny, an exhaustive protein BLAST search was carried out using all permutations of the 9-aa minimum OSCAR-binding motif and side chain–binding variants defined previously (25): [G/A][P/G][P/I][A][A/S][G/F/D/S][Y][A/R][P/Q]. In addition, a less stringent but longer 12-aa con-

sensus OSCAR-binding sequence, derived from the same data and used to generate the minimum OSCAR-binding sequence, was also used: GXPGPX/GFX GXF (where X is any amino acid). BLAST searches were done with an expected threshold of 20,000, a word size of 2, and using the PAM30 matrix, as recommended by National Center for Biotechnology Information when searching for short, nearly exact matches. Candidate motifs in both collagen and noncollagen proteins were identified. For noncollagen proteins, putative motifs were selected in which protein BLAST provided an alignment of 80% or better, although one or two noncollagen proteins, putative motifs were selected in which protein

binding motif variant sequences was required for a motif to be recognized, although for the vast majority a perfect alignment was obtained. In the non-

collagen proteins, the biological roles of each protein could be broadly clas-

sified into receptor proteins, secreted proteins, or extracellular matrix proteins.
flasks in RPMI 1640 plus 10% FCS, and mAbs were purified from culture supernatant by protein A affinity chromatography.

Abs

Goat anti-human OSCAR polyclonal Ab was purchased from Santa Cruz Biotechnologies (25). The SP-D mAb 245-01 was purchased from Enzo Life Sciences. The anti–SP-D mAb 246-04 was purchased from Bioporto Diagnostics (Gentofte, Denmark). The mAb KP1, which recognizes human CD68, was purchased from Serotec. Donkey anti-goat IgG Alexa 568 and donkey anti-mouse IgG Alexa 488 were purchased from Invitrogen.

Purified and PE-conjugated anti-human OSCAR mAb 11.1CN5 was purchased from Beckman Coulter. The HLA-DR-allophycocyanin, CD16- FITC, and CD56-PE-Cy7 anti-human Abs, used to define human monocytes, granulocytes, and NK cells, respectively, were purchased from BD Pharmingen, and the CD14-Pacific Blue, CD45-AF700, and CCR2-PerCP-Cy5.5 anti-human Abs were all purchased from BioLegend. Mouse mAb to Thy1.2 and goat anti-mouse mAb 245-01 were purchased from Novocasta Laboratories. Mouse mAb to human CD163, which recognizes cells of the monocyte/macrophage lineage, was from Neomarkers. mAb clone 13-9-17 was used in immunostainings for the OSCAR C terminus. Rabbit anti–SP-D clone H-120 was from Santa Cruz. Rabbit isotype control Ab was from Cell Signaling, and mouse IgG1 isotype control was from BD Biosciences. For immunohistochemistry, primary Abs were revealed with Envision Dako Polymer HRP.

Microscopy

Paraffin-embedded human lung sections from COPD and normal control subjects were deparaffinated using citrilotene (Vector Laboratories). Sections were then rehydrated in a graded ethanol series before Ag retrieval by boiling in Ag retrieval solution (Vector Laboratories) in a microwave, according to the manufacturer’s instructions. Sections were blocked in fish gel (Sigma-Aldrich) for 1 h before incubating with primary Abs diluted in fish gel gel overnight at 4°C. Slides were then washed three times in large volumes of PBS before incubating individually with secondary Abs, respectively. Tumor-specific enhancement of fluorescent immunostaining was performed after each individual secondary Ab step, according to the manufacturer’s instructions (Invitrogen). For confocal microscopy, lung sections were mounted with vectashield containing DAPI, which stained nuclei blue (Vector Laboratories), and analyzed on an Olympus Fluoview FV1000 confocal microscope. For light microscopy, sections stained immunohistochemically were photographed using the DP-70 Olympus digital camera mounted on the Olympus BX60 microscope.

Human subjects and BAL isolation

Human clinical samples were obtained from lung transplant donors and recipients, as described previously (31). In brief, lung explants were harvested at the time of lung transplantation from COPD recipients (n = 2) with very severe disease (GOLD Stage 4). Control samples were obtained from normal donors (n = 3) using lung explants that were otherwise not useable for transplantation. BAL was performed under general anesthesia from normal donors (n = 3) using lung explants that were otherwise not useable for transplantation. BAL was performed under general anesthesia from normal donors (n = 3) using lung explants that were otherwise not useable for transplantation. BAL was performed under general anesthesia from normal donors (n = 3) using lung explants that were otherwise not useable for transplantation.

Flow cytometry

Cells were prepared from human lung explant tissue using protease digestion, as described previously (31). Single-cell suspensions were generated from minced lung tissue that was subjected to collagenase (Liberase Blendzyme III; Roche), hyaluronidase (Sigma-Aldrich), and DNase I (grade II; Roche) digestion for 45 min at 37°C. For flow cytometry, frozen aliquots of cell preparations were thawed and washed in complete medium before analysis. Following FcR blockade, cell suspensions were incubated with labeled Abs on ice prior to flow cytometric analysis. For peripheral blood leukocytes, granulocytes were defined by electronic gating as side scatter(+)CD45(+)CD56(−) CD16(−) cells and monocytes as side scatter(+)CD45(+)CD56(−)CD16(+) cells. Monocytes were further distinguished based on expression of CD14, CD16, and CCR2 (27).

OSCAR internalization assays

Purified monocytes were left untreated (0 min) or treated with 2.5 μg/ml recombinant human SP-D at 37°C for 5, 15, 30, and 60 min, respectively. Monocytes were then placed on ice and washed twice with ice-cold PBS before transferring into 35 mm dishes with a 10 cm2 coverslip. After washing three times in PBS, OSCAR internalization was determined by flow cytometry as a reduction in monocyte cell surface staining with non-blocking anti-OSCAR mAb, 11.1CN5.

Monocyte isolation

Human monocytes were isolated from 50 ml blood using the Monocyte Negative Isolation Kit (Invitrogen), according to the manufacturer’s instructions.

Cytokine analysis

A total of 100,000 monocytes in flat-bottom 96-well plates was stimulated with 2.5 μg/ml recombinant human SP-D in the presence or absence of 5 μg/ml purified mAbs. TNF-α in tissue culture supernatants was determined using the BD CBA human inflammatory cytokine kit (BD Biosciences).

Statistical analysis

Statistical significance was determined using GraphPad Prism 6.0. Statistical differences were determined by two-tailed Student t test. A p value <0.05 was considered significant.

Study approval

All studies were reviewed and approved by institutional human and animal studies committees, and all experiments were carried out according to national and regional legislation and regulations. Informed consent was obtained from all subjects included in this study.

Results

OSCAR is a receptor for SP-D

We hypothesized that OSCAR may interact with collagenous molecules other than extracellular matrix collagens, which may have immunological roles. We conducted a bioinformatics search using two partially overlapping linear amino acid sequences (see Materials and Methods) derived from the previously defined triple-helical OSCAR-binding motif (25). The search yielded 22 noncollagen-based sequences (Table I) and 16 putative collagen-based OSCAR-binding motifs (Supplemental Table I). The collects SP-A, SP-D, and MBL, and collectin-like molecules, such as C1q (Table I), represented good candidates for interacting with OSCAR-expressing leukocytes because they play central roles in tissue-specific immunity (1). Focusing on SP-D, the minimum 9-aa OSCAR-binding motif used in the bioinformatics search aligned with 77.8% direct amino acid sequence identity to the SP-D sequence 106–114 (GGPGPVGPG) (Supplemental Fig. 1A). The 12-aa consensus OSCAR-binding motif used in the bioinformatics search aligned with 83.3% direct amino acid identity with the SP-D sequence 106–117 (GGPGPVGPG) (Supplemental Fig. 1B). The putative OSCAR-binding motifs are encoded by exon 3 of human SFTPD, which encodes part of the C terminus collagenous domain (Supplemental Fig. 1A). Because the 9- and 12-aa search motifs are largely overlapping, we conclude that each trimeric subunit of the SP-D monomer encodes one triple-helical OSCAR-binding sequence. Dodecameric SP-D, comprised of four trimeric subunits, would thus be expected to encode four triple-helical OSCAR-binding motifs.

We next determined whether OSCAR could bind to some of the collectin or collectin-like molecules identified from the motif search (Table I). We assayed for binding of a human OSCAR Fc-fusion protein (OSCAR-Fc) to recombinant forms of SP-D, in addition to C1q and MBL proteins (Fig. 1). OSCAR-Fc bound to full-length dodecameric human and rat SP-D and trimeric subunits of rat SP-D (Fig. 1A). OSCAR-Fc did not bind to Mini SP-D, a recombinant rat SP-D lacking the SP-D collagenous domain encoded by exons 2 and 3 of the SP-D gene (5), or a recombinant protein encoding the NCRD region of rat SP-D (Fig. 1B). The putative OSCAR-binding motifs are encoded by exon 3 of human SFTPD, which encodes part of the SP-D collagenous domain (Supplemental Fig. 1A). Because the 9- and 12-aa search motifs are largely overlapping, we conclude that each trimeric subunit of the SP-D monomer encodes one triple-helical OSCAR-binding sequence. Dodecameric SP-D, comprised of four trimeric subunits, would thus be expected to encode four triple-helical OSCAR-binding motifs.
wholly dependent on, the presence of 5 mM Ca²⁺ (Fig. 1A). Because collagen lacks lectin activity and neither recombinant lectin domains (NCRD) nor Mini SP-D, which encodes an intact lectin domain, bind to OSCAR (Fig. 1A), we conclude the small increase in calcium-dependent binding of OSCAR-Fc to SP-D or collagen must be mediated through OSCAR binding to collagen domains and not the SP-D lectin domain. SP-D binding was not observed for Fc-fusion proteins that encoded the extracellular domains of human LAIR1 or ILT3, which are known to bind collagen (33, 34), or TREM1, TREM2, ILT1, and ILT7 (Fig. 1A and data not shown). Although SP-D was recently shown to bind LAIR1 (35), we only detected SP-D binding to mouse LAIR1, but not human LAIR1 (data not shown). This discrepancy may depend on the sensitivity of our assay and the relative affinities of mouse and human LAIR1 for SP-D. In conclusion, our results show that OSCAR can bind specifically to the SP-D collagenous domain.

Because SP-D is secreted as a soluble protein associated with lung surfactant, we next determined whether OSCAR could bind to soluble SP-D, as might reflect conditions in vivo. We incubated dilutions of human BAL (Fig. 1B) in wells coated with OSCAR-Fc or LAIR1-Fc. The amount of protein captured by the immobilized Fc-fusion proteins was then detected using the Hyb-246-04 mAb, which is specific for the SP-D CRD (6). Dose-dependent binding of a protein reactive with the Hyb-246-04 mAb was observed to immobilized OSCAR-Fc, but not to LAIR1-Fc (Fig. 1B). These results suggest OSCAR-Fc can capture native SP-D from human BAL. However, because we have detected a putative OSCAR-binding motif in SP-A (Table I) and SP-A has been shown to bind to IgGs (36), it may be possible that solid-phase OSCAR-Fc could also be capturing SP-A from BAL. Captured SP-A may, in turn, bind to the Fc portion of the secondary Abs used to detect bound SP-D. We therefore determined whether immobilized OSCAR-Fc could capture soluble recombinant human SP-D dodecamer in the absence of SP-A. Solid-phase OSCAR-Fc, but not LAIR1-Fc, captured soluble recombinant human SP-D dodecamer (Fig. 1C). These results show that OSCAR can bind to soluble SP-D dodecamer.

<table>
<thead>
<tr>
<th>Biological Class</th>
<th>Protein Name</th>
<th>Uniprot</th>
<th>Sequence</th>
<th>Position</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracellular matrix and adhesion</td>
<td>EMILIN-1</td>
<td>Q9Y6C2</td>
<td>GPPGPPGLQGPP</td>
<td>820</td>
<td>Secreted adhesive protein, involved in elastic fiber anchoring</td>
</tr>
<tr>
<td></td>
<td>EMILIN-2</td>
<td>Q9BXX0</td>
<td>GPPGAPPGVGSP</td>
<td>829</td>
<td>Secreted adhesive protein, involved in elastic fiber anchoring/vessel assembly</td>
</tr>
<tr>
<td>Protein sidekick-2</td>
<td></td>
<td></td>
<td>TVPGAEGFAGAP</td>
<td>876</td>
<td></td>
</tr>
<tr>
<td>Receptors</td>
<td>Collectin-12 (scavenger receptor with C-type lectin type I)</td>
<td>Q5KU26</td>
<td>GPPGAPGER</td>
<td>476</td>
<td>Pathogen recognition/phagocytosis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GYPGPKRLGPLP</td>
<td>557</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macrophage receptor with collagenous structure (MARCO)</td>
<td>Q9UEW3</td>
<td>GPPGLAGFP</td>
<td>286</td>
<td>Pattern recognition receptor—binds bacteria</td>
</tr>
<tr>
<td></td>
<td>Scavenger receptor class A member 3 (SCARA3)</td>
<td>Q6AZY7</td>
<td>GPPGPPGPR</td>
<td>457</td>
<td>Scavenges oxidative species</td>
</tr>
<tr>
<td></td>
<td>Scavenger receptor class A member 5 (SCARA5)</td>
<td>Q6ZMJ2</td>
<td>GPPGPPGSDQ</td>
<td>306</td>
<td>Ferritin receptor—nontransferrin-dependent delivery of iron</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Implicated in excitatory synapse regulation on hippocampus neurons</td>
</tr>
<tr>
<td>Secreted C1q-related factor</td>
<td></td>
<td></td>
<td>GPPGPPGDP</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Cell proliferation-inducing protein 41</td>
<td>A1KY36</td>
<td></td>
<td>GLPGPFGPGIG</td>
<td>523</td>
<td></td>
</tr>
<tr>
<td>Collagen and calcium-binding EGF domain-containing protein 1</td>
<td>Q6UXH8</td>
<td></td>
<td>GAPGPRGSQGPP</td>
<td>321</td>
<td>Angiogenic and lymphangioblastic growth during embryogenesis</td>
</tr>
<tr>
<td>Complement C1q-like protein 4</td>
<td>Q86Z23</td>
<td></td>
<td>GPPGPPGPRPP</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Complement C1q subcomponent subunit B</td>
<td>P02746</td>
<td></td>
<td>GPPGAPGAP</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Complement C1q subcomponent subunit C</td>
<td>P02747</td>
<td></td>
<td>GPPGAPGPK</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Complement C1q TNF-related protein 2</td>
<td>Q9BXJ5</td>
<td></td>
<td>GPPGSGMGMR</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>Ectodysplasin-A (EDA)</td>
<td>Q92838</td>
<td></td>
<td>GPPGPPGPPGQD</td>
<td>189</td>
<td></td>
</tr>
<tr>
<td>Ficolin-2</td>
<td>Q15485</td>
<td></td>
<td>GPPGPNAGP</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>Ficolin-3</td>
<td>Q75636</td>
<td></td>
<td>GAPGQQGPP</td>
<td>57</td>
<td>May activate lectin complement pathway</td>
</tr>
<tr>
<td>Mannose-binding protein C</td>
<td>P11226</td>
<td></td>
<td>GNPGPSGSPGPK</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Surfactant protein A</td>
<td>Q81WL2</td>
<td></td>
<td>GPPGPMGPP</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Surfactant protein D</td>
<td>P35247</td>
<td></td>
<td>GPPGPPGVP</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Gliomedin</td>
<td>Q6ZMI3</td>
<td></td>
<td>GPPGPPGPPGAP</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>premRNA 3’ end processing protein WDR33</td>
<td>Q9C0J8</td>
<td></td>
<td>GPPGPPGMQGPP</td>
<td>742</td>
<td></td>
</tr>
</tbody>
</table>
To test whether OSCAR could act as a receptor for SP-D, we performed a sensitive GFP-inducible assay using NFAT-GFP reporter cells, which have been successfully used to determine immunoreceptor:ligand interactions (37) (Fig. 1D). In this assay, clustering of the OSCAR ectodomain fused to the TCR CD3ζ signaling chain will result in ITAM signaling and transactivation of a transgene encoding GFP (25, 37). GFP was induced by OSCAR-CD3ζ/NFAT-GFP reporter cells cultured on tissue culture plates coated with human SP-D, collagen I, recombinant rat dodecameric or trimeric (S15, 20) SP-D, but not BSA, Mini SP-D, or NCRD (Fig. 1D). OSCAR-CD3ζ/NFAT-GFP reporter cells also expressed GFP when cultured with soluble human SP-D dodecamer, but not soluble collagen I (Fig. 1E). These results show that OSCAR is a receptor for dodecameric SP-D either as a plate-bound aggregated ligand or as soluble SP-D dodecamer.

OSCAR is expressed in intracellular compartments of human alveolar macrophages that contain SP-D

Human OSCAR has previously been located by immunohistochemistry in osteoclasts and their precursors but not in monocytes or macrophages in tissues outside of bone (25). Because SP-D is secreted in lung surfactant where it is readily taken up by alveolar macrophages and monocytes exhibit greater infiltration of inflamed lung airways (38), we next determined OSCAR and SP-D expression in lungs from control and COPD subjects. OSCAR was expressed in alveolar macrophages with a seemingly intracellular granular pattern, whereas SP-D was predominantly expressed in alveolar type II epithelial cells (Fig. 2A). Immunofluorescence analysis for OSCAR and the monocyte/macrophage marker CD68 confirmed the localization of OSCAR in intracellular compartments of CD68+ alveolar macrophages (Fig. 2B). A few infiltrating CD68+ interstitial monocytic cells displayed a membrane pattern of OSCAR staining in COPD sections (Fig. 2B). Because immunohistochemical and immunocytochemical electron microscopy studies had found SP-D localized to endocytic compartments and associated with phagolysosomal structures in human and rat alveolar macrophages (6, 39), we hypothesized that OSCAR and SP-D may colocalize in the same intracellular compartments of alveolar macrophages. Accordingly, double immunofluorescence for OSCAR and SP-D in lung sections demonstrated intracellular colocalization of OSCAR and SP-D in alveolar macrophages.
These data show that OSCAR interacts with SP-D in alveolar macrophages and OSCAR is expressed by tissue-infiltrating monocytes in COPD.

**Lung interstitial myeloid cells and blood monocytes express OSCAR on the cell surface**

Immunofluorescence analysis of lung tissues showed that OSCAR was expressed not only in alveolar macrophages but also in few CD68⁺ interstitial myeloid cells (Fig. 2B). Interestingly, in these cells OSCAR displayed a membrane pattern. Flow cytometric analysis revealed a marked OSCAR surface expression also on monocytes (Fig. 3A, upper histograms), whereas alveolar macrophages showed poor OSCAR surface expression, consistent with a predominant intracellular distribution (Fig. 3A, lower histograms). Although OSCAR had been previously found on blood monocytes and neutrophils (26), it was unclear whether it was expressed on a specialized monocyte subset. A recent mRNA profiling of human monocyte subsets suggested that OSCAR may be expressed on the CCR2⁺ inflammatory monocytes, but not CCR2⁻ patrolling monocytes (40). We conclusively demonstrated that OSCAR was preferentially expressed on CCR2⁺ inflammatory monocytes by flow cytometry (Fig. 3B). In contrast to a previous report using the anti-human OSCAR mAb 11.1CN5 (26), we did not detect OSCAR staining on neutrophils (Fig. 3B). We conclude that OSCAR has two distinct patterns of expression. In alveolar macrophages, OSCAR is predominantly found in an intracellular compartment; in lung interstitial myeloid cells and blood inflammatory monocyes, OSCAR is mainly expressed on the cell surface.

**OSCAR stimulates the secretion of TNF-α by CCR2⁺ inflammatory monocytes**

To study the impact of OSCAR in monocyte functions, we immunized mice with our human OSCAR-Fc and generated a panel of novel mAbs to human OSCAR (Supplemental Fig. 2). Among several mAb that stained OSCAR-CD3ζ/NFAT-GFP reporter cells (Supplemental Fig. 2A) and human blood monocytes (Supplemental Fig. 2B), we selected mAb that could block binding of OSCAR-Fc to collagen I (Supplemental Fig. 3A). Using this approach, we identified four blocking mAbs (11.20.02, 11.20.06, 11.20.08, and 11.20.25), which were subsequently purified and titrated based on their ability to block OSCAR-CD3ζ/NFAT-GFP reporter cell signaling on plates coated with either collagen I (Supplemental Fig. 3B), rat SP-D (Supplemental Fig. 3C), or human SP-D (Supplemental Fig. 3D). Two mAbs, 11.20.08 and 11.20.25, were most effective in blocking GFP expression in reporter cells with peak blocking activities observed at 5 μg/ml. We next determined whether SP-D could stimulate the release of proinflammatory cytokines by human blood CCR2⁺ monocytes through engagement of OSCAR. A recombinant human SP-D
dodecamer stimulated TNF-α release by blood CCR2+ monocytes from two different donors, which was blocked by the anti-human OSCAR mAbs 11.20.08 and 11.20.25, respectively (Fig. 4A). OSCAR was not internalized by monocytes exposed to SP-D (Supplemental Fig. 3E). We conclude the SP-D/OSCAR interaction triggers a proinflammatory response in CCR2+ monocytes.

OSCAR is expressed in lipid-laden macrophages infiltrating atherosclerotic plaques

Although SP-D has been implicated in atherosclerosis (22, 23), the mechanism is poorly understood. We hypothesized that SP-D may engage OSCAR in the atherosclerotic plaque, promoting inflammation. To test this hypothesis, we investigated OSCAR expression in atherosclerotic lesions of human aorta. OSCAR was strongly expressed in numerous lipid-laden macrophages infiltrating the tunica intima and in fewer macrophages penetrating the tunica media. SP-D was found in the vascular endothelium as well as in many smooth muscular cells of the tunica media, consistent with previous reports (22, 41) (Fig. 4B). These data suggest that SP-D may contribute to atherosclerosis by binding OSCAR on inflammatory monocytes that infiltrate the atherosclerotic plaque and stimulating the release of TNF-α, which will exacerbate the vascular lesion.

Discussion

In humans and mice, OSCAR is expressed by osteoclasts and their precursors and can bind to collagens exposed on bone surfaces to costimulate osteoclastogenesis (25). In humans, OSCAR is additionally expressed on monocytes, macrophages, and dendritic cells (26), suggesting that OSCAR may play a role in the immune response. Motivated by this hypothesis, we designed a bioinformatics search for OSCAR-binding motifs in collagenous molecules that might provide insight into OSCAR immunobiology. We identified putative OSCAR-binding motifs in the collectins, MBL, SP-A, and SP-D, and collectin-like molecules, such as C1q, and ficolins, that all play important roles in innate immunity (1). Of the putative ligands tested, we detected binding of OSCAR-Fc to SP-D, but not to MBL or C1q. OSCAR may not bind to C1q because we only detected OSCAR-binding motifs in the B and C chains of C1q and none in the A chain (Table I). Because OSCAR only binds to triple-helical motifs in collagenous molecules and not to linear motifs (25), C1q therefore lacks a motif in the A chain to form a triple-helical sequence capable of binding OSCAR. Further structural and biophysical studies are required to determine the precise molecular binding specificities of OSCAR for collectin and collectin-like molecules.

Our study demonstrates that human OSCAR is a novel myeloid immunoreceptor for SP-D expressed by alveolar macrophages and inflammatory CCR2+ monocytes, which triggers the release of TNF-α in inflammatory CCR2+ monocytes exposed to SP-D. The identification of SP-D receptors is essential to fully understand the function of SP-D in different tissues and organs in the context of infections and inflammation. Previous studies have shown that SP-D or the closely related collectin SP-A can interact with distinct immunoreceptors, resulting in different functional outcomes. When not bound to a pathogen, SP-D and SP-A bind through their
lactin domains to SIRP-α, delivering an inhibitory signal, which prevents activation of mononuclear phagocytes and secretion of inflammatory cytokines (24). In contrast, when microorganisms or cell debris are bound to the C-type lectin domain, SP-D and SP-A interact through their free collagen-like domain to CD91/calreticulin, promoting cell activation (24). SP-D also binds to CD14, interfering with the binding of LPS to the CD14-TRIR-MD2 complex, thereby reducing macrophage inflammatory responses elicited by LPS (42, 43). Finally, a recent study showed that the Ig-superfamily receptor LAIR1, which is known to bind collagen, also binds to SP-D, delivering an inhibitory signal that reduces inflammation (35). Because the OSCAR:SP-D interaction promotes activation of inflammatory monocytes, we conclude that the ultimate functional effect of SP-D depends on the balance between inhibitory and activating receptors engaged at any one time in a given tissue.

Our study also demonstrates that, in alveolar macrophages, OSCAR is predominantly found in an intracellular compartment where it colocalizes with SP-D. This result suggests that OSCAR may capture SP-D in the alveolar space and drive SP-D internalization into a phagolysosomal compartment in alveolar macrophages where SP-D and its cargo are processed and degraded. The internalization of SP-D may be crucial for the phagocytosis and killing of pathogens or the removal of necrotic and apoptotic cells in the lung as well as in various other mucosal and organs (2, 44). However, we did not detect any OSCAR internalization in monocytes exposed to SP-D. It is possible that alveolar macrophages are capable of internalizing OSCAR:SP-D complexes, because macrophages are more phagocytic than monocytes. The distribution of OSCAR between the cell membrane and the endosomal compartment in different myeloid cells might also depend on the relative abundance of SP-D to which these cells are exposed in their microenvironment. Alternatively, the different subcellular localizations of OSCAR in alveolar macrophages and monocytes could be caused by the alternative splicing of OSCAR transcripts encoding OSCAR isoforms with different subcellular trafficking properties (45). Future studies to determine the role, if any, OSCAR isoforms may play in the cell biology and Ag processing of SP-D for alveolar macrophages and dendritic cells are therefore merited.

Previous studies have implicated SP-D in atherosclerosis and coronary heart disease (22, 23, 41). We found that OSCAR is highly expressed in CD163+ monocytes and macrophages could be caused by the alternative splicing of OSCAR transcripts encoding OSCAR isoforms with different subcellular trafficking properties (45). Future studies to determine the role, if any, OSCAR isoforms may play in the cell biology and Ag processing of SP-D for alveolar macrophages and dendritic cells are therefore merited.

Our study also demonstrates that, in alveolar macrophages, OSCAR is predominantly found in an intracellular compartment where it colocalizes with SP-D. This result suggests that OSCAR may capture SP-D in the alveolar space and drive SP-D internalization into a phagolysosomal compartment in alveolar macrophages where SP-D and its cargo are processed and degraded. The internalization of SP-D may be crucial for the phagocytosis and killing of pathogens or the removal of necrotic and apoptotic cells in the lung as well as in various other mucosal and organs (2, 44). However, we did not detect any OSCAR internalization in monocytes exposed to SP-D. It is possible that alveolar macrophages are capable of internalizing OSCAR:SP-D complexes, because macrophages are more phagocytic than monocytes. The distribution of OSCAR between the cell membrane and the endosomal compartment in different myeloid cells might also depend on the relative abundance of SP-D to which these cells are exposed in their microenvironment. Alternatively, the different subcellular localizations of OSCAR in alveolar macrophages and monocytes could be caused by the alternative splicing of OSCAR transcripts encoding OSCAR isoforms with different subcellular trafficking properties (45). Future studies to determine the role, if any, OSCAR isoforms may play in the cell biology and Ag processing of SP-D for alveolar macrophages and dendritic cells are therefore merited.

Previous studies have implicated SP-D in atherosclerosis and coronary heart disease (22, 23, 41). We found that OSCAR is highly expressed in CD163+ monocytes and macrophages infiltrating the atherosclerotic plaques in aorta. We envision that exposure of these OSCAR+ monocytes and macrophages to SP-D produced by endothelial cells in the tunica intima and by smooth muscular cells in the tunica media may lead to the production of TNF-α, exacerbating the degenerative process. Similar mechanisms may operate in lung tissue. For example, monocytes can traffic into the lung during the steady state (46), but do not preferentially enter airway mucosal surfaces, unless there is a proinflammatory or chemotactic stimulus (38). Therefore, CCR2+ monocytes that patrol lung interstitial tissues in the steady state may not become exposed to SP-D secreted in airway lung surfactant. In contrast, monocytes increasingly infiltrate the airways in response to a proinflammatory or chemotactic stimuli (38). Thus, upon tissue damage or the induction of proinflammatory stimuli in the lung airways, as might be operating in lung pa-
thologies like COPD, CCR2+ monocytes will traffic from blood to the damaged tissues, whereupon they may then become exposed to SP-D and release TNF-α. Thus, our characterization of the OSCAR:SP-D interaction and its functional impact in the secretion of proinflammatory cytokines by CCR2+ monocytes recruited to the tissues may have important therapeutic implications not only for inflammatory diseases of the lung and the mucosa but also for atherosclerosis and its complications.

Acknowledgments

We thank Dr. Maria G. Quisgaard for providing BAL fluid and Loralyn Benoit, Stoyan Ivanov, and Hani Suleiman for scientific discussions and technical assistance.

Disclosures

A.D.B. is a named inventor on a patent application from the University of Cambridge: Modulation of the activity and differentiation of cells expressing the osteoclast-associated receptor. U.S. Patent Application 13126237.

References


**Supplemental Table I.** Amino-acid sequences and positions of putative OSCAR-binding motifs within different collagens.

<table>
<thead>
<tr>
<th>Collagen type</th>
<th>Uniprot</th>
<th>Sequence</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collagen alpha 1 (I)</td>
<td>P02452</td>
<td>GPPGPAGFA</td>
<td>806</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GPPGATGFP</td>
<td>869</td>
</tr>
<tr>
<td>Collagen alpha 1 (II)</td>
<td>P02458</td>
<td>GAPGPAEG</td>
<td>480</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GAPGPSFQ</td>
<td>657</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GPPGPAGSA</td>
<td>807</td>
</tr>
<tr>
<td>Collagen alpha-1(III) chain</td>
<td>P02461</td>
<td>GAPGPAGSR</td>
<td>1074</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GPPGPAGFP</td>
<td>804</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GPPGAAGFP</td>
<td>867</td>
</tr>
<tr>
<td>Collagen alpha-1(IV) chain</td>
<td>P02462</td>
<td>GPPGASGYP</td>
<td>94</td>
</tr>
<tr>
<td>Collagen alpha-1(V) chain</td>
<td>P20908</td>
<td>GPPGPAGSP</td>
<td>1081</td>
</tr>
<tr>
<td>Collagen alpha-1(VII) chain</td>
<td>Q02388</td>
<td>GPPGPAGSR</td>
<td>1498</td>
</tr>
<tr>
<td>Collagen alpha-1(XI) chain</td>
<td>P20849</td>
<td>GPPGAGEP</td>
<td>302</td>
</tr>
<tr>
<td>Collagen alpha-1(XVI) chain</td>
<td>Q07092</td>
<td>GPPGPAGER</td>
<td>1401</td>
</tr>
<tr>
<td>Collagen alpha-1(XVII) chain</td>
<td>Q9UMD9</td>
<td>GPPGPAGSR</td>
<td>1412</td>
</tr>
<tr>
<td>Collagen alpha-1(XXVII) chain</td>
<td>Q8IZC6</td>
<td>GPPGPAGSR</td>
<td>1340</td>
</tr>
<tr>
<td>Collagen alpha-1(XVIII) chain</td>
<td>P39060</td>
<td>GPPGAPAGAR</td>
<td>986</td>
</tr>
<tr>
<td>Collagen alpha-2(I) chain</td>
<td>P08123</td>
<td>GPPGPAGSR</td>
<td>769</td>
</tr>
<tr>
<td>Collagen alpha-2(V) chain</td>
<td>P05997</td>
<td>GPPGPAGSR</td>
<td>669</td>
</tr>
<tr>
<td>Collagen alpha-2(XI) chain</td>
<td>P13942</td>
<td>GPPGPAGSP</td>
<td>1009</td>
</tr>
<tr>
<td>Collagen alpha-3(V) chain</td>
<td>P25940</td>
<td>GPPGASGEP</td>
<td>1295</td>
</tr>
<tr>
<td>Collagen alpha-5(IV) chain</td>
<td>P29400</td>
<td>GPPGAPGFP</td>
<td>533</td>
</tr>
</tbody>
</table>
**Supplemental Figure 1.** Molecular characteristics and predicted OSCAR-binding sites of SP-D. (A) Amino acid alignment of human SP-D (SP-D) with the minimum OSCAR-binding motif (OSCAR) (31). Direct amino acid sequence identify (*); signal peptide, lower case; Cys 15 and 20 involved in the formation of the disulphide bonds required for the stable assembly of SP-D dodecamers and higher order multimers, underlined; alternating exons, black/blue; exon boundaries, red. (B) Alignment of the 12 amino acid residue (res) OSCAR-binding search (Srch) sequence (seq) reveals an extended putative OSCAR-binding motif.
Supplemental Figure 2. Generation of novel anti-human OSCAR mAbs. Histogram plots for immunostainings with anti-human OSCAR mAb clones: 11.20.02, 11.20.06, 11.20.08, 11.20.25 or 11.1CN5 (32) for either: (A) OSCAR-CD3ζ NFAT-GFP reporter cells (open histograms) compared to parental 2B4 NFAT-GFP reporters cells (gray histograms) or (B) human blood monocytes (Gate R1, open histograms) compared to IgG1 (gray histograms). Representative immunostaining from one of two donors is shown. All blood monocytes in gate R1 expressed CD14 and all other cells outside gate R1 (e.g. low FSC/SSC lymphocytes) did not express OSCAR (Data not shown).
Supplemental Figure 3. Screening for OSCAR blocking mAbs. (A) OSCAR-Fc binding to collagen I in the presence of tissue culture supernatants from different anti-human OSCAR hybridomas. Percentage (%) GFP expression from OSCAR-CD3ζ NFAT-GFP reporter cells cultured on tissue culture plates coated with: (B) collagen I; recombinant (C) rat or (D) human SP-D in the presence of different concentrations of purified mAbs: 11.20.02, 11.20.06, 11.20.08, 11.20.25, 11.1CN5 or IgG1 (0-5µg/ml, x-axis), respectively. (E) OSCAR cell surface expression on monocytes left untreated (blue, 0’) or treated with 2.5µg/ml human SP-D for 5 (green), 15 (orange), 30 (cyan) and 60 (pink) mins, respectively compared to IgG1 isotype control (red).