Sphingosine-1-Phosphate Receptor 3 Promotes Recruitment of Monocyte/Macrophages in Inflammation and Atherosclerosis

Petra Keul,* Susann Lucke,* Karin von Wnuck Lipinski, Constantin Bode, Markus Graëler, Gerd Heusch, Bodo Levkau

Rationale: The role of sphingosine-1-phosphate (SIP) and its receptors in the pathogenesis of atherosclerosis has not been investigated.

Objective: We hypothesized that the S1P receptor 3 (SIP3) plays a causal role in the pathogenesis of atherosclerosis.

Methods and Results: We examined atherosclerotic lesion development in mice deficient for SIP3 and apolipoprotein (Apo)E. Although SIP3 deficiency did not affect lesion size after 25 or 45 weeks of normal chow diet, it resulted in a dramatic reduction of the monocyte/macrophage content in lesions of SIP3−/−/ApoE−/− double knockout mice. To search for putative defects in monocyte/macrophage recruitment, we examined macrophage-driven inflammation during thioglycollate-induced peritonitis. Elicited peritoneal macrophages were reduced in SIP3-deficient mice and expressed lower levels of tumor necrosis factor-α and monocyte chemoattractant protein-1. Bone marrow–derived SIP3-deficient macrophages produced less MCP-1 in response to lipopolysaccharide stimulation. In vitro, SIP was chemotactic for wild-type but not SIP3-deficient peritoneal macrophages. In vivo, SIP concentration increased rapidly in the peritoneal cavity after initiation of peritonitis. Treatment with the SIP analog FTY720 attenuated macrophage recruitment to the peritoneum. Studies in bone marrow chimeras showed that SIP3 in both hematopoietic and nonhematopoietic cells contributed to monocyte/macrophage accumulation in atherosclerotic lesions. Finally, SIP3 deficiency increased the smooth muscle cell content of atherosclerotic lesions and enhanced neointima formation after carotid ligation arguing for an antiproliferative/antimigratory role of SIP3 in the arterial injury response.

Conclusions: Our data suggest that SIP3 mediates the chemotactic effect of SIP in macrophages in vitro and in vivo and plays a causal role in atherosclerosis by promoting inflammatory monocyte/macrophage recruitment and altering smooth muscle cell behavior. (Circ Res. 2011;108:314-323.)

Key Words: sphingosine-1-phosphate (SIP) ■ atherosclerosis ■ macrophages ■ inflammation ■ vascular biology ■ lipid metabolites

Sphingosine-1-phosphate (SIP) is a bioactive lipid with key functions in the immune, inflammatory, and cardiovascular systems. SIP is abundant in plasma (200 to 1000 nmol/L), where it is contained mainly in the high-density lipoprotein fraction in a biologically active form. Accordingly, plasma SIP levels correlate positively with plasma high-density lipoprotein cholesterol and apolipoprotein Al. As a component of both plasma and interstitial fluid, SIP interacts with all vascular and nonvascular cell types that participate in the pathogenesis of atherosclerosis. All these cells have functional SIP receptors and respond to SIP in a number of different ways, which has prompted the question whether SIP and its receptors may play a role in the pathogenesis of atherosclerosis. A positive association between serum SIP levels and the severity of coronary artery stenosis has been described in humans. The effect of the SIP analog FTY720 on mouse atherosclerosis has been elucidated in 3 independent studies including one from our group. Two of these studies have shown FTY720 to attenuate the development of atherosclerosis in apolipoprotein E-deficient (ApoE−/−) and LDL-receptor deficient (LDL-R−/−) mice, whereas the third observed no effect on plaque size. Mechanistically, FTY720 does not allow discriminating between the roles of individual SIP receptors as it engages 4 of 5 SIP receptors and exhibits different receptor desensitization kinetics from SIP. The mechanism of how FTY720 inhibits atherosclerosis has also remained unknown in view of the variety of its...
potentially atheroprotective effects: it stimulates nitric oxide production in endothelial cells, inhibits the production of reactive oxygen species and chemokines such as monocyte chemoattractant protein (MCP)-1, alters the production of inflammatory cytokines, and acts as a potent immunosuppressant. As the S1P receptor 3 (S1P3) appears to contribute to the S1P3 receptor on monocyte/macrophages affects their migration to inflammation sites and atherosclerotic lesions.

Methods
An expanded Methods section is available in the Online Data Supplement at http://circres.ahajournals.org.

Mice
S1P3−/− mice were crossed to the C57BL/6 background for more than 10 generations and subsequently to ApoE−/−. FTY720 was administered orally at 1.25 mg/kg per day.7

Hematology and Flow Cytometry
Total and differential white blood cell counts were measured in EDTA-blood from the retroorbital plexus using an automated Animal ABC Coulter Counter. Flow cytometry of blood, bone marrow and peritoneal exudate was performed with fluorochrome-conjugated antibodies to CD4, CD8, CD45, B220, Gr-1, I-Ab, Ly-6G, F4/80, CD11b, and CD115 on a FC500 flow cytometer.

Immunohistochemistry
Immunohistochemistry was performed on adjacent sections with antibodies to αSMA, Mac-2 and sphingosine kinase (Sphk)1 (a kind gift from Dr Luis Obeid, Medical University of South Carolina). Collagen content was assessed by picrosirius red staining and polarized light. Immunostaining for every marker was performed in a single procedure. Automated color segmentation of images was performed, and a color threshold of chromogen stain defined using a negative isotype-matched control antibodies. The area containing all positive pixels was expressed as percentage of total plaque area.

Flow Cytometry of Single Aortae
Single-cell suspensions from aortae were prepared following a protocol graciously provided by Prof Klaus Ley (Division of Inflammation Biology, La Jolla Institute for Allergy & Immunology), as described with minor modifications. Briefly, mice were perfused with 0.02 mol/L EDTA and the carefully dissected aorta cut into small pieces and digested in an enzyme cocktail. Cells were stained with CD45-PE-Cy7, CD11b-APC (clone M1/70 or Mac-1) and I-Ab-PE as described. Annexin-V–FITC served to differentiate living from apoptotic cells. Cells negative for Annexin-V were back-gated to CD45 and examined for CD11b and I-Ab. Percentages and total numbers were determined from the entire cell suspension of each aorta.

Isolation of Peritoneal and Bone Marrow Macrophages, Migration Studies, and SIP Measurements
Peritoneal exudate and macrophages were collected after intraperitoneal injection of aged sterile 3% thiglycollate at the indicated times. Bone marrow–derived macrophages (BMDMs) were generated by culture of bone marrow cells with 1.5 ng/mL M-CSF for 10 days. Migration of thiglycollate-elicited peritoneal macrophages (day 4) toward 1 μmol/L S1P was measured in a modified Boyden chamber after 4 hours and quantified from at least 3 experiments performed in triplicate. MCP-1 was measured using an ElisaArray mouse MCP-1. Determination of S1P was performed by HPLC as previously published.15

Quantitative PCR
Total RNA was isolated and cDNA synthesized using RNeasy Mini Kit and Revert Aid First Strand cDNA Synthesis Kit, respectively. Real-time PCR was performed on a Bio-Rad iCycler using iQ SYBR Green and Quantitect primers. The absolute copy number of S1P1, S1P2, and S1P3 was expressed as copies per 1000 copies GAPDH [gene (normalized)=copy number of target/copy number of reference] from standard concentration curves for each gene transcript. Relative quantification of gene expression was calculated by the 2−ΔΔCT method.

Bone Marrow Transplantation
Mice were irradiated with 11 Gy (x-rays) and transplanted with 5×106 donor bone marrow cells via retroorbital injection the following day.

Quantification of Lesions
En face staining of PFA-fixed aortae was performed with 0.3% oil red O for 90 minutes. Lipid-containing stained plaque area was determined as percent from total aortic surface area using the AxioVision 4.6 software. Quantification of atherosclerotic lesion volume in the brachiocephalic artery (BCA) and aortic root was performed as described. Briefly, the entire BCA was serially sectioned in 5 μm sections and, from a random start site within the first 75 μm, every 15th section was stained with H&E and the volume of the lesion determined using the Cavalieri stereologic method [Σ(lesion area)×(distance; 75 μm)].16 Lesion area and vessel area in the aortic root were calculated from 4 consecutive 5-μm sections of 40 μm apart over the entire root. The volume fraction of the lesion was calculated as lesion volume [Σ(lesion area including valve area)×(distance; 40 μm)] divided by vessel volume [Σ(vessel area)×(distance; 40 μm)].16

Carotid Ligation, Smooth Muscle Cell Proliferation, and Migration
The left carotid artery was ligated at the bifurcation as previously described and serially sectioned over its entire length 4 weeks after surgery. Every 10th section starting at the ligation site was stained with H&E and neointimal and medial areas and neointimal cells were quantified by histomorphometry. Smooth muscle cells (SMCs) were isolated from aortae (6 to 7 aortae per preparation) by enzymatic digestion as described, plated on Vitrogen100, and used for experiments up to the sixth passage. For proliferation studies, SMCs were serum-starved for 24 hours and cultured in 1% FCS in the presence or absence of 1 μmol/L S1P and 1 nmol/L platelet-derived growth factor (PDGF), respectively, added every other day for 4 days.

Non-standardAbbreviations and Acronyms

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<tr>
<th>Acronym</th>
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<tr>
<td>ApoE</td>
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<td>BCA</td>
<td>brachiocephalic artery</td>
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<td>BMDM</td>
<td>bone marrow–derived macrophage</td>
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<td>BMT</td>
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<td>IL</td>
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<td>LPS</td>
<td>lipopolysaccharide</td>
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<td>MCP</td>
<td>monocyte chemoattractant protein</td>
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<td>PDGF</td>
<td>platelet-derived growth factor</td>
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<td>S1P</td>
<td>sphingosine-1-phosphate</td>
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<td>SMC</td>
<td>smooth muscle cell</td>
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<td>SMC</td>
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as described. Total cell numbers were determined using a Z2 cell counter. All experiments were performed in triplicate. For migration studies, cells were starved for 24 hours and seeded in DMEM with 0.25% BSA at a density of 10,000 per well on Vitrogen coated membranes in the upper well of a modified Boyden chamber. Migration to 1 μmol/L S1P, 1 mmol/L PDGF and both, respectively, was assessed after 4 hours by counting the cells migrated to the lower side of the membrane in one field of view at 10x magnification as described. Five independent experiments in triplicate were performed.

Statistical Analysis

Each experiment was performed at least 3 times as indicated, and data presented as means±SEM. Statistical significance was evaluated by a nonparametric Wilcoxon–Mann–Whitney U test. Two-sided probability values of less than 0.05 were considered significant.

Results

S1P3 Deficiency Has No Effect on Atherosclerotic Lesion Volume but Dramatically Reduces Monocyte/Macrophage Content in Atherosclerotic Lesions of S1P3−/−/ApoE−/− Mice

To analyze the effect of S1P3 deficiency on atherosclerotic lesion formation, we backcrossed S1P3 knockout mice to the C57BL/6 background for 10 generations and crossed them with ApoE−/− deficient mice. We then compared size and composition of atherosclerotic lesions in the aorta and the brachiocephalic artery (BCA) of S1P3−/−/ApoE−/− mice compared to ApoE−/− mice (Figure 2A and 2B). The collagen content did not differ significantly between the 2 genotypes (Figure 3C). Using flow cytometry of single digested aortae with antibodies to CD45, CD11b, and I-Aβ as described, we observed a lower percentage of CD45+CD11b+I-Aβ+ macrophages in S1P3−/−/ApoE−/− aortae compared to ApoE−/− aortae (45.7±2.6% versus 55.6±2.6%; Figure 2C and 2D). Total macrophage cell number per individual aorta was also lower in S1P3−/−/ApoE−/− mice compared to ApoE−/− mice (628±153 versus 1494±225; Figure 2E). Thus, macrophages were clearly reduced in the aortae of S1P3−/−/ApoE−/− mice. In contrast, no differences in total monocytes, neutrophils, or monocyte subsets (CD115+F4/80−Gr-1low and CD115+F4/80−Gr-1high) were present in the peripheral blood (Figure 3) or bone marrow (Online Figure I) of S1P3−/−/ApoE−/− and ApoE−/− mice. All hematologic parameters, as well as plasma cholesterol levels, were similar between the 2 genotypes (Figure 3C).

S1P3 Deficiency Attenuates Macrophage Recruitment During Thioglycollate-Induced Sterile Peritonitis

We hypothesized that a defect in macrophage recruitment per se may be caused by the absence of S1P3 and underlie the
day 1 was not different between the 2 genotypes (9.15 ± 1.84 × 10^6/mouse).

We then compared the expression of S1P3, S1P2, and S1P1 receptors both in thioglycollate-elicited peritoneal macrophages and BMDMs by real-time PCR (Figure 4B and 4C). In both macrophage types, expression of S1P1 and S1P2 was 2 to 3-fold higher than that of S1P3 (determined as absolute copies of gene transcript per 1000 copies GAPDH; Figure 4B). Gene transcript number was comparable between peritoneal and BMDMs for all 3 S1P receptors (Figure 4C).

**SIP3-Deficient Macrophages Exhibit an Altered Cytokine Expression Profile Compared With Controls**

We then tested for alterations in the expression of inflammatory chemokines, cytokines, and cytokine receptors in S1P3−/− peritoneal macrophages by real-time PCR. We found MCP-1 and tumor necrosis factor (TNF)α gene expression to be reduced by 70% to 80% in S1P3−/− macrophages (Figure 5C), whereas other genes were unchanged at the mRNA (interleukin [IL]-4, IL-6, IL-10, IL-1α, MIP-1α, GM-CSF, CCR2; Figure 5C) or protein level (iNOS, arginase-1, CCR2, CCR7, CX3CR1, and CD80; data not shown). In agreement, protein levels of MCP-1 were reduced more than 150-fold in the peritoneal exudates of S1P3−/− mice compared to controls as measured by ELISA (Figure 5C, inset). Incubation of BMDMs with S1P did not have any effect on basal or lipopolysaccharide (LPS)-stimulated MCP-1 expression in wild-type or S1P3−/− macrophages (Figure 5C, inset).}

**SIP Levels Increase in the Inflamed Peritoneum In Vivo; SIP Chemoattracts Macrophages via SIP3 In Vitro; FTY720 Abolishes Peritoneal Macrophage Recruitment In Vivo**

We measured SIP levels in the peritoneal exudate by HPLC at different times after induction of inflammation as described15 and observed a time-dependent increase of SIP levels in the peritoneal fluid with a maximum at 24 hours and a subsequent decrease (Figure 6A). We hypothesized that such an SIP increase might be biologically important and tested it in 2 ways. Firstly, we examined whether SIP may be a chemoattractant for thioglycollate-elicited peritoneal macrophages in vitro. This was, indeed, the case as...
wild-type macrophages migrated toward a 1 μmol/L S1P gradient in Boyden chamber experiments (Figure 6B). In contrast, S1P3−/− macrophages did not migrate toward S1P (Figure 6B), suggesting that S1P3 is responsible for mediating the chemotactic response to S1P. Secondly, we eliminated any biological effects that S1P gradients may have in vivo by treating mice with the S1P analog FTY720 as previously described for lymphocytes.20 This resulted in a ~80% reduction in the number of elicited macrophages after thioglycolate application (Figure 6C), suggesting that S1P gradients may be required for effective monocyte/macrophage recruitment to the inflamed peritoneum in vivo.

Sphingosine Kinase 1 Is Expressed in Lesions of Atherosclerosis

Immunohistochemistry for Sphk1 of atherosclerotic lesions of ApoE−/− mice showed that the enzyme was abundantly expressed there and colocalized mainly with macrophages (Figure 6D). This suggested that S1P-synthesizing enzymes such as Sphk1 may promote local production of S1P in atherosclerotic lesions.

S1P3 in Both Hematopoietic and Nonhematopoietic Cells Is Required for Monocyte/Macrophage Accumulation in Atherosclerotic Lesions

To examine the role of the monocyte/macrophage S1P3 in the recruitment of inflammatory cells to atherosclerotic lesions, we generated bone marrow chimeras by reconstituting the bone marrow of sublethally irradiated ApoE−/− mice with that of S1P3−/−/ApoE−/− mice and vice versa. Successful bone marrow substitution was verified by diagnostic PCR for the deleted and wild-type S1P3 allele on genomic DNA from total bone marrow substitution was verified by diagnostic PCR for the deleted and wild-type S1P3 allele on genomic DNA from total bone marrow chimeras compared to the donor and recipient chimera DNA. 

Figure 3. No differences in myeloid cell populations and monocyte subsets in the peripheral blood of S1P3−/−/ApoE−/− and ApoE−/− mice. Peripheral blood monocytes and neutrophils of 45-week-old mice were analyzed by flow cytometry. A, Monocytes were identified as F4/80+ CD115+ cells (dot plots) and analyzed for expression of Ly-6C and Ly-6G using Gr-1 (histograms). Shown are the 2 monocyte subsets (Ly-6Chigh and Ly-6Glow). B, Neutrophils were identified using CD11b and Ly-6G and analyzed for expression of Ly-6C (dot plots) and S1P3 (donor) and ApoE−/− (recipient) chimeras (Figure 7A). Lesion size did not differ significantly between the chimeras after 25 weeks but their monocyte/macrophage content was reduced by ~26% in the S1P3−/−/ApoE−/− bone marrow chimeras compared to the S1P3−/−/ApoE−/− bone marrow chimeras (26.25±2.03% versus 19.51±1.59%; Figure 7B and 7C). This suggested that expression of S1P3 in monocyte/macrophages partially contributes to their accumulation in atherosclerotic lesions. Analysis of the SMC content of the same lesions showed it was increased in the S1P3−/−/ApoE−/− bone marrow chimeras compared to the S1P3−/−/ApoE−/− bone marrow chimeras (26.25±2.03% versus 19.51±1.59%; Figure 7B and 7C). This suggested that expression of S1P3 in monocyte/macrophages partially contributes to their accumulation in atherosclerotic lesions. Analysis of the SMC content of the same lesions showed it was increased in the S1P3−/−/ApoE−/− bone marrow chimeras compared to the S1P3−/−/ApoE−/− bone marrow chimeras (5.89±0.93% versus 3.10±0.26%; Figure 7D).

Neointima Formation After Carotid Ligation Is Increased in S1P3−/− Mice

To follow up on the finding of an elevated SMC content in atherosclerotic lesions of S1P3−/−/ApoE−/− mice, we used the carotid artery ligation model.21,22 There, we observed a larger neointima formation in S1P3−/−/ApoE−/− mice compared to S1P3−/−/ApoE−/− mice (5.89±0.93% versus 3.10±0.26%; Figure 7D).
PDGF-BB-induced SMC migration as published\textsuperscript{18} and was equally effective in wild-type and S1P\textsuperscript{3−/−} SMCs (Figure 8C). Proliferation in response to PDGF-BB was similar in SMCs from both genotypes and was unaffected by S1P (Figure 8D).

Discussion

Our study is the first to address the role of S1P\textsubscript{3} in the pathogenesis of atherosclerosis in vivo. Our initial observation was that macrophage content was decreased in atherosclerotic lesions of S1P\textsuperscript{3−/−}/ApoE\textsuperscript{−/−} double knockout mice. Using bone marrow chimeras, we could partially attribute this to the lack of S1P\textsubscript{3} in hematopoietic cells. A possible scenario how this may occur is that monocyte/macrophages are chemotacttracted toward an increased S1P level inside the lesion, to which they respond via their S1P\textsubscript{3} receptor. This resembles the action of the bone fide chemokines in atherosclerosis. Several of our observations support such a scenario: S1P was chemotactic for macrophages in vitro; migration to S1P was dependent on the macrophage S1P\textsubscript{3} receptor in vitro, and S1P\textsubscript{3}-deficient mice recruited less monocyte/macrophages in the peritonitis model. During peritonitis, S1P levels increased locally in the inflamed peritoneum, thereby providing a...
Sphk1, macrophages (Mac-2), and SMCs (αSMA). The S1P content of atherosclerotic lesions of ApoE−/− mice has been shown to reduce the macrophage gradient out of lymph nodes by FTY720.23 In respect to atherosclerosis, FTY720 has been shown to reduce the macrophage content of atherosclerotic lesions in vivo. Furthermore, Sphk1 expression is increased in endothelial cells in models of acute lung injury induced by TNFα expression can be induced in vitro by several cytokines such as TNFα and IL-1β that are also present and active in atherosclerotic lesions of ApoE−/− mice.16 Although we could not measure the S1P content of atherosclerotic lesions directly, we found an abundant expression of Sphk1, which was colocalized mainly with macrophages. It is known that Sphk1 expression can be induced in vitro by several cytokines such as TNFα and IL-1β that are also present and active in atherosclerotic lesions in vivo. Furthermore, Sphk1 expression is increased in endothelial cells in models of acute lung injury induced by LPS or thrombin.25 Thus activated macrophages as well as vascular cells such as the endothelium may be potential sources of S1P in the lesion (as well as in the inflamed peritoneum in analogy).

Our finding that S1P is chemotactic for thioglycollate-elicited peritoneal macrophages in vitro is in agreement with its chemotactic effect in RAW264.7 monocytes as well as in mouse BMDMs.26 However, there are also reports of S1P lacking a chemotactic effect in mouse BMDMs but inhibiting migration toward C5a and CXCL12.27 Such differences may be attributable to the different tissue sources of the used macrophages, as well as their different activation and differentiation states. For instance, the S1P responsiveness of the thioglycollate-elicited inflammatory macrophages (used immediately after isolation for experiments as in our study)
may very well differ from that of BMDMs generated from hematopoietic precursors by long-term culture with M-CSF.\textsuperscript{27} In addition, different S1P receptors have apparently different effects on monocyte/macrophage migration: S1P\textsubscript{2}-deficient mice have been shown to recruit more peritoneal macrophages in the same peritonitis model as used in our study, whereas BMDMs from S1P\textsubscript{3}\textsuperscript{-/-} mice were unresponsive to the migration-inhibitory effect of S1P on C5a and CXCL12.\textsuperscript{27} This has lead to the suggestion that plasma S1P restrains macrophages from immigrating to inflammatory sites via S1P\textsubscript{2}.\textsuperscript{27} Another option may be that S1P\textsubscript{2} retains macrophages inside the lesion once they have immigrated (provided the S1P content of the lesion is, indeed, increased). Our data indicate that S1P and/or S1P\textsubscript{1} agonists have been shown to inhibit monocyte/macrophage migration but also their activation profile: A scenario in which S1P\textsubscript{2} prevents and S1P\textsubscript{3} promotes monocyte/macrophage recruitment is reminiscent of the functional antagonism of 2 other S1P receptors, S1P\textsubscript{1} and S1P\textsubscript{3}, in endothelial cell migration.\textsuperscript{26} The S1P\textsubscript{1} receptor does not appear to play a role at least in macrophage recruitment to the infiltrated peritoneum as shown using S1P\textsubscript{1} hematopoietic chimeras\textsuperscript{27} and supported by our own data in mice carrying a conditional deletion of S1P\textsubscript{3} in myeloid cells (S1P\textsubscript{1}\textsuperscript{LysoMCre}, data not shown).

Despite the somewhat macrophage-centric view we have adopted here, it must be clearly established that nonhematopoietic components also contribute to the altered monocyte/macrophage recruitment in S1P\textsubscript{3}-deficient mice. The macrophage content of lesions in the hematopoietic chimeras lacking S1P\textsubscript{3} was significantly reduced but this reduction was modest compared to that in the global S1P\textsubscript{3} knockout without bone marrow transplantation. In addition, wild-type mice transplanted with S1P\textsubscript{3}\textsuperscript{-/-} bone marrow and S1P\textsubscript{3}\textsuperscript{-/-} mice transplanted with wild-type bone marrow, respectively, showed no difference in peritoneal monocyte/macrophage recruitment after thioglycollate injection (Online Figure III), suggesting that S1P\textsubscript{3} in the hematopoietic and the nonhematopoietic components is equally important. Whether its lack in either one is also sufficient to alter recruitment cannot be deduced from the data as we have not excluded possible effect of irradiation and stromal repopulation on the peritoneal response.

The most probable nonhematopoietic component in question is the endothelium: it is constantly exposed to the plasma S1P pool and needs it for maintenance of regular barrier function and prevention of vascular leakage.\textsuperscript{29} In addition, S1P and/or S1P\textsubscript{1} agonists have been shown to inhibit monocyte adhesion to TNF\textalpha-activated endothelium\textsuperscript{30,31} as well as the recruitment of neutrophils to postischemic inflammation.\textsuperscript{32} The exact mechanisms have not been elucidated as several adhesion molecules and chemokines are differently affected by S1P and respond differently to low versus high S1P concentrations.\textsuperscript{4} However, there is also contrary evidence in favor of a proinflammatory role of S1P in the endothelium: Sphk1 is stimulated by inflammatory cytokines in endothelial cells and the S1P it generates stimulates COX-2 activity and PGE\textsubscript{2} release\textsuperscript{24,25}; it also mediates TNF\textalpha-stimulated adhesion molecule expression and promotes neutrophil adhesion (for a comprehensive review, see elsewhere).\textsuperscript{6} Finally, the same cytokines that use S1P for the propagation of inflammation can also be restrained by the same S1P as taking place during inflammatory lung injury, where the initial increase in vascular permeability by LPS or PAR-1 is restored by their induction of S1P production.\textsuperscript{24,25} Thus, S1P appears to play a role both in the propagation and limitation of vascular inflammation. Therefore, any net effect S1P may have on monocyte/macrophage recruitment in vivo must be the result of simultaneous signaling by several S1P receptors on endothelial and inflammatory cells.

Finally, S1P signaling via the S1P\textsubscript{3} receptor not only affects macrophage migration but also their activation profile: Thioglycollate-elicited S1P\textsubscript{3}\textsuperscript{-/-} peritoneal macrophages exhibited reduced TNF\textalpha and MCP-1 expression suggesting a proinflammatory role for S1P\textsubscript{3}. Previously, an antiinflam-
tory role for S1P and a proinflammatory one for S1P2, respectively, have been suggested based on S1P effects observed in BMDMs stimulated with LPS/IFN-γ. Although we did not see any S1P effects on basal or LPS/IFN-γ-stimulated cytokine expression (neither in wild-type nor S1P2−/− BMDMs), we did observe a blunted MCP-1 response to LPS in S1P3−/− macrophages. Thus S1P receptor signaling may affect cytokine expression of macrophages even in the absence of exogenous S1P. This may not only influence monocyte/macrophage function but also indirectly, via MCP-1, their recruitment in vivo.

The elevated SMC content we have seen in lesions of S1P3−/−/ApoE−/− mice and the enhanced neointima formation after carotid ligation suggest that S1P3 also affects SMC phenotype. Despite numerous studies on S1P receptors in SMCs in vitro, only 2 studies have examined their role in vivo. In these, administration of a S1P/S1P3 antagonist in rats inhibited neointima formation after balloon injury of the carotid and neointima formation after carotid ligation was enhanced in S1P3−/− mice. The potent inhibition of PDGF-BB-induced migration by S1P and its lack of effect on basal migration that we see in our study confirm previous in vitro reports. Although an enhanced proliferation by S1P has also been described before e.g. for human SMCs, although S1P3−/− mice will need to be addressed in future studies, which need to take into consideration the fact that SMCs from different vessels express different S1P receptors and regulate them differently after vascular injury. Nevertheless, our carotid ligation data point to an antiproliferative/antimigratory role of S1P on SMCs in the arterial injury response that may explain the shift toward the more SMC-rich plaque composition in S1P3−/−/ApoE−/− mice.

In summary, further studies are needed to dissect the role of S1P receptors on vascular endothelial, smooth muscle and hematopoietic cells in the context of atherosclerosis. This would help to design novel pharmacological approaches to atherosclerosis based on S1P agonists and antagonists.

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Disclosures
None.

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**Novelty and Significance**

**What Is Known?**

- Sphingosine-1-phosphate (S1P) is a biologically active sphingolipid that regulates vascular permeability and vessel tone, immunity, and inflammation. In plasma, S1P is contained mainly in the high-density lipoprotein fraction and its concentrations are elevated in patients with coronary artery disease.

- S1P exerts many of its functions via 5 G protein-coupled receptors named S1P1 to S1P5 that are differentially expressed on vascular and hematopoietic cells.

- The S1P analog FTY720 inhibits atherosclerosis in mice but this observation does not allow the discrimination between the roles of individual S1P receptors because FTY720 engages them all except S1P2. Whereas the S1P2 receptor seems to promote atherogenesis, the role of S1P5 in atherosclerosis is unknown.

**What New Information Does This Article Contribute?**

- We show that the size of atherosclerotic lesions is similar, but the monocyte/macrophage content is dramatically reduced in S1P2-deficient mice on the atherosclerosis-susceptible ApoE−/− background. Replacement of the bone marrow of ApoE−/− mice with S1P2-deficient bone marrow and vice versa demonstrates that S1P2 in both hematopoietic and nonhematopoietic cells contributes to macrophage accumulation in atherosclerotic lesions.

- S1P2 deficiency leads to a reduction of inflammatory macrophage recruitment to the peritoneum. Macrophages deficient for S1P2 have an altered expression of inflammatory cytokines and produce less MCP-1 in response to stimulation with bacterial lipopolysaccharide.

- S1P induces macrophage migration in vitro via the S1P2 receptor. In vivo, S1P concentrations increase rapidly in the peritoneal cavity during inflammation.

Studies with pharmacological S1P analogs in mice have suggested that excessive activation and/or desensitization of S1P receptors may suppress atherosclerosis but the receptors involved have not been identified. We report that the S1P1 receptor, S1P2, on both vascular and hematopoietic cells is required for monocyte/macrophage infiltration of atherosclerotic lesions, as well as their recruitment during peritoneal inflammation. We show that S1P1 promotes migration of macrophages to S1P and alters their cytokine expression profile. In addition, S1P2 prevents smooth muscle cell proliferation and migration in response to arterial injury. This suggests that a specific blockade of S1P2 may be a new therapeutic option to suppress inflammation in atherosclerotic lesions.
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Materials and Methods

Mice

C57BL/6 mice were obtained from the Jackson Laboratory. S1P3\(^{-/-}\) mice were kindly provided by J. Chun (The Scripps, La Jolla, CA, USA) and were crossbred to the C57BL/6 background for more than 10 generations. ApoE\(^{-/-}\) and S1P3\(^{-/-}\) mice were crossbred to generate S1P3\(^{-/-}\)/ApoE\(^{-/-}\) double knockout mice. Male mice were used in all experiments. FTY720 was administered with the drinking water at a dose of 1.25 mg/kg/d as described\(^1\).

Hematology and flow cytometry

Blood was collected from the retroorbital plexus into EDTA tubes at the time of sacrifice. Total and differential blood counts were measured using an automated Animal ABC Coulter Counter (VetABC, scil animal care company, Viernheim, Germany). For analysis of leukocytes in blood, bone marrow and peritoneal lavage by flow cytometry, red blood cells were lysed using ACK buffer (0.15 M NH\(_4\)Cl; 1 mM KHCO\(_3\); 0.1 mM Na\(_2\)EDTA; pH 7.2-7.4) for 2 minutes at room temperature. The cells were stained with fluorochrome-conjugated combinations of the following monoclonal antibodies: CD4 (Acris, Herford, Germany), CD8, CD45, B220, Gr-1 (reacts with Ly-6G and Ly-6C; Ly-6C is only expressed by monocytes), I-A\(^b\) and Ly-6G (all from BD Biosciences, Heidelberg, Germany), F4/80 (AbD Serotec, Düsseldorf, Germany), CD11b (Miltenyi Biotec, Bergisch Gladbach, Germany) and CD115 (eBioscience, Frankfurt, Germany) and were analyzed using a FC500 flow cytometer (Beckman Coulter, Krefeld, Germany). The size of each cell population was determined as a product of the total white blood cell count and the percentage of the respective cell population. Lipid analysis was performed using commercially available assays (Biocon Diagnostik, Vöhl/Marienheide, Germany).
Isolation of peritoneal and bone marrow macrophages

Peritoneal macrophages were collected after intraperitoneal injection of aged, sterile 3% thioglycollate (Sigma Aldrich, Munich, Germany) at the indicated times. To isolate them and obtain peritoneal fluid, 4 ml of pre-warmed PBS was injected into the abdominal cavity and aspirated. After centrifugation for 5 minutes at 1200 rpm and 4°C, the supernatant was frozen for subsequent S1P analysis, while the cells were counted and directly analyzed using flow cytometry or used for RNA isolation for gene expression studies. Bone marrow-derived macrophages were generated by the following procedure: Bone marrow was isolated from tibiae and femora by snipping off the ends of the bones and flushing out the bone marrow into a dish; cells were transferred into a polypropylene tube by passing them through a 70 µm cell strainer; after centrifugation (5 min, 1300 rpm, RT), red blood cells were lysed using ACK buffer and the washed cells were plated and cultured for 10 days with 1.5 ng/ml macrophage colony-stimulating factor (M-CSF; R&D Systems, Wiesbaden, Germany). Stimulation with LPS (Sigma Aldrich, Munich, Germany) and S1P (Biomol, Hamburg, Germany) was performed as indicated in the results section and total RNA was isolated as described below.

RNA isolation and quantitative PCR analysis of gene expression

Total RNA was isolated from mouse peritoneal macrophages and bone marrow-derived macrophages using RNeasy Mini Kit (Qiagen, Hilden, Germany) according to the manufacturer's protocol. cDNA was synthesized using the Revert Aid First Strand cDNA Synthesis Kit (Fermentas, St. Leon-Rot, Germany). Quantitative real-time PCR was performed using an iCycler and iQ SYBR Green Supermix (BioRad, Munich, Germany) and Quantitect primer assays (Qiagen, Hilden, Germany). Absolute quantification of gene expression was performed with a standard concentration curve for S1P$_1$, S1P$_2$, S1P$_3$ and GAPDH transcripts generated from macrophage RNA beforehand using defined concentrations of PCR products for each amplified gene. The linear equation of the standard curve
allows a determination of the logarithm of the copy number of any unknown sample. The absolute copy number of S1P₁, S1P₂ and S1P₃ was expressed as copies per 1000 copies GAPDH [gene (normalized) = copy number of target/copy number of reference]. Where relative quantification of gene expression was calculated, expression of genes was normalized to an endogenous reference (GAPDH or β-actin as indicated) and calculated by the $2^{\Delta \Delta CT}$ method.

*S1P measurements*

Determination of S1P was performed by HPLC according to established protocols. Briefly, lipids were extracted from plasma by successive addition of 1 ml of methanol, 200 µl of 6 M HCl and twice 2 ml of chloroform. Chloroform phases were retrieved by centrifugation, and chloroform was removed by vacuum-drying in a speed-vac. Subsequently, samples were dissolved in 200 µl of dioxane, 200 µl of 70mM K₂HPO₄ and 200 µl of 9-fluorenylmethyl chloroformate (FMOC-Cl) solution for derivatization of sphingolipids. For chromatographic detection of sphingolipids (Merck-Hitachi Elite LaChrom System, VWR), 10 µl of sample was injected by cut-injection method with an injection-pump delivery rate of 1.3 ml/min into an eluent containing methanol, 70 mM K₂HPO₄, and H₂O. Columns used for the separation of sphingolipids by reversed phase HPLC were a 250×4.6 mm Kromasil 100-5 C18 column and a 17×4 mm Kromasil 100-5 C18 pre-column (CS Chromatographie Service, Langerwehe, Germany) set to 35°C. Detection was performed with a fluorescence detector (excitation 263 nm, emission 316 nm).

*Bone marrow transplantation*

Mice were irradiated with 11 Gy and transplanted with 5 x 10⁶ donor bone marrow cells via retroorbital injection the following day. At the time of sacrifice (25 weeks), diagnostic PCR with primers for deleted S1P₃ and the wildtype S1P₃ gene was performed with DNA isolated
from blood leukocytes (Qiagen, Hilden, Germany) to confirm complete bone marrow substitution. Peripheral blood cell counts were measured by VetABC and individual cell populations quantified by flow cytometry as described above.

**Quantification of lesion volume**

Quantification of atherosclerotic lesion volume in the brachiocephalic artery (BCA) and the aortic root was performed as previously described\(^3\). After sacrifice, mice were perfusion-fixed with 4.5% neutral-buffered formaldehyde and the BCA was dissected from the bifurcation off the aortic arch to the branching point of the right subclavian and common carotid artery, and embedded in paraffin. The entire BCA was serially sectioned in 5 µm sections. Beginning from a random start site within the first 75 µm, every 15\(^{th}\) section was stained with haemalaune and eosine. Images were captured with a Zeiss Axio Cam, and lesion area was quantified using AxioVision 4.6 software (Carl Zeiss Vision GmbH, Jena, Germany). The volume of the BCA lesion was determined using the Cavalieri stereologic method \[\Sigma (\text{lesion area}) \times (\text{distance; 75} \, \mu\text{m})\]. The aortic root was embedded in paraffin and both lesion area and vessel area were calculated from four consecutive 5 µm sections 40 µm apart that cover the entire root of the aorta; the volume fraction of the lesion was calculated as the lesion volume \[\Sigma (\text{lesion area including valve area}) \times (\text{distance; 40} \, \mu\text{m})\] divided by vessel volume \[\Sigma (\text{vessel area}) \times (\text{distance; 40} \, \mu\text{m})\] as described\(^3\). All analyses were performed without knowledge of the tissue source.

**Oil Red O staining of aortae**

PFA-fixed aortae were carefully cleaned from all adventitial fat, washed in isopropanol/H\(_2\)O (2:1) for 5 min and stained with 0.3% Oil Red O for 90 min in 24 well plates at RT. After two washes with isopropanol/H\(_2\)O (2:1) for 2 min, the aortae were transferred to 24-well plates and stored in PBS at 4°C. For en face quantification of lipids, the aortae were placed on a
black silicone plate and cut open starting at the lesser curvature. The aortae were then pinned down with acupuncture needles, and pictures were taken with a Nikon DS-2Mv camera system. Lipid-containing plaque area was determined as percent of Oil Red O-stained area from the total aortic surface area using the AxioVision 4.6 software.

**Immunohistochemistry**

Immunohistochemistry was performed on sections adjacent to that used for quantification of lesion area and using the following antibodies: mouse anti-human α smooth muscle-actin (αSMA, Dako, Glostrup, Denmark), rat anti-mouse Mac-2 (Cedarlane Laboratories, Hornby, Canada) and rabbit anti-human sphingosine kinase 1 (a kind gift from Dr. Lina Obeid, Medical University of South Carolina). Primary antibodies were incubated for 1 hour at room temperature in 3% serum matched to the species of the secondary antibodies followed by biotinylated secondary antibodies for 30 minutes and horseradish peroxidase-conjugated streptavidin for 45 minutes. Visualization was performed with diaminobenzidine and counterstaining of nuclei with haemalaune. Collagen content was assessed using picrosirius red staining and polarized light. Immunostaining for every marker was performed in a single procedure for all sections. An isotype-matched antibody was used on adjacent sections as a negative control. Automated colour segmentation of images was performed and a colour threshold of chromogen stain was defined using the negative control, above which the stain was considered positive (Zeiss AxioVision Rel. 4.6 software). The area containing all positive pixels (µm²) was expressed as percentage of total plaque area.

**Flow cytometry of single aortae**

Single cell suspensions from the aorta were prepared following a protocol graciously provided by Prof. Klaus Ley, Division of Inflammation Biology, La Jolla Institute for Allergy & Immunology, as previously described with minor modifications as to the detection of
apoptotic cells. Briefly, mice were perfused with 0.02 M EDTA through the left ventricle, and the carefully dissected aorta was cut into small pieces and digested in an enzyme cocktail (450U collagenase Type I, 250U collagenase Type XI, 120U hyaluronidase type I-S; all from Sigma, Hamburg, Germany) and 120U DNase I (Roche, Mannheim, Germany) for 60 min at 37°C. The digested tissue was sent through 70 µm cell strainers, pelleted and incubated in 10% FCS/RPMI for 30 min at 37°C. The cells were washed and stained using CD45-PE-Cy7 (BD, Heidelberg, Germany), CD11b-APC (clone M1/70 (or Mac-1) as used in⁴; Milteny, Bergisch Gladbach, Germany) and I-A<sup>b</sup>-PE (BD, Heidelberg, Germany). Annexin-V-FITC (Beckman Coulter, Krefeld, Germany) served to differentiate living from apoptotic cells. Cells negative for Annexin-V were backgated to CD45 and examined for surface expression of CD11b and I-A<sup>b</sup>. Percentage and total number of Annexin-V<sup>-</sup>CD45<sup>+</sup>I-A<sup>b</sup><sup>+</sup>CD11b<sup>+</sup> cells from all CD11b<sup>+</sup> cells was determined quantitatively by measuring the entire cell suspension. Each aorta was assessed individually.

**Macrophage migration assay**

Migration of macrophages was measured in a modified Boyden chamber assay. The upper wells of the chamber were loaded with thioglycollate-elicited peritoneal macrophages (freshly isolated at day 4 after injection of thioglycollate), and the lower wells were supplemented with 1 µM S1P (Biomol, Hamburg, Germany). Migration was quantified after 4 h incubation at 37°C and 5% CO<sub>2</sub>. Cells that had not migrated were removed from the top side of the membrane, and staining was performed with a Hemacolor fast staining Kit (VWR International, Darmstadt, Germany). Migration was quantified from at least three experiments performed in triplicate as indicated.
MCP-1 assay

The MCP-1 Assay (ElisArray mouse MCP-1, SABiosciences, Frederick, MD, USA) was performed using peritoneal lavage fluid according to the manufacturer’s protocol.

Smooth muscle cell proliferation and migration

SMC were isolated from aortae of wild type and S1P3−/− mice (6-7 aortae per preparation) by enzymatic digestion as described5 and used for experiments up to the 6th passage. Briefly, aortae were incubated in digestion mix (2 mg/ml BSA, 1 mg/ml collagenase 3, 0.375 mg/ml soybean trypsin inhibitor and 0.125 mg/ml elastase type III in DMEM) for 30 min at 37°C, after which the adventitia was peeled off, the aortae cut into small pieces and incubated in digestion mix for another 3 hours at 37°C. Cells were then plated on Vitrogen100 (Celtrix, Landsdale, USA)-coated tissue culture dishes in 15% fetal calf serum (FCS)/DMEM with 2 mM glutamin and 1 mM pyruvate. For proliferation studies, SMC were serum starved for 24 hours and cultured in 1% FCS in the presence or absence of 1 µm S1P and 1 nm PDGF, respectively, added every other day for 4 days as described6. Total cell numbers per dish were determined using a Z2 cell counter (Beckmann Coulter, Krefeld, Germany) and proliferation was expressed as percent of that of unstimulated cells. All experiments were performed in triplicate. For migration studies, cells were starved for 24 hours in 1% FCS and seeded in DMEM with 0.25% BSA at a density of 10,000 per well on Vitrogen100-coated membranes in the upper well of a modified Boyden chamber. Migration to 1 µm S1P, 1 nm PDGF and both, respectively, was assessed after 4 hours of incubation at 37°C in 4% CO2 as described6 by counting the cells migrated to the lower side of the membrane in one field of view at 10x magnification (after methanol fixation and staining with a Hemacolor Kit; Merck, Darmstadt, Germany). All migration experiments were performed in triplicate, and five independent experiments were performed.
Carotid ligation studies

The left carotid artery was surgically exposed and ligated at the bifurcation as previously described \(^5\). The whole carotid artery was harvested 4 weeks after the surgery, and serially sectioned over its entire length. Every 10\(^{th}\) section starting at the ligation site was stained with haemalaune and eosine. Neointimal and medial areas were quantified by histomorphometry using the AxioVision 4.6 Software (Carl Zeiss Vision GmbH) and the cells in the neointima were counted on each section.

Statistical Analysis

Each experiment was performed at least three times as indicated in the figure legends, and data are presented as mean ± SEM. Statistical significance was evaluated by a nonparametric Wilcoxon-Mann-Whitney u-test. Two-sided probability values less than 0.05 were considered significant.

Supplemental figure legends

**Figure I.** S1P₃ deficiency does not alter myeloid cells distribution and content in the bone marrow. A, Bone marrow cells of ApoE⁻/⁻ and S1P₃⁻/⁻/ApoE⁻/⁻ mice on normal chow for 45 weeks were stained for CD11b, Ly-6G and Gr-1 and analyzed by flow cytometry. Myeloid cells were identified with CD11b and further subdivided into neutrophils (CD11b⁺Ly-6G⁺) and Ly-6Cʰⁱⁿʰ and Ly-6Cˡᵒʷ monocytes (CD11b⁺Ly-6G⁻Gr-1⁺ and CD11b⁺Ly-6G⁻Gr-1⁻, respectively). Representative dot plots and histograms are shown. B, Total myeloid cell counts per femur of ApoE⁻/⁻ and ApoE⁻/⁻/S1P₃⁻/⁻ mice shown as mean ± SEM (n = 6 each; n.s. = not significant).

**Figure II.** Quantification of macrophages in the peritoneum. Thioglycollate-elicited peritoneal macrophages were collected at day 4 after injection and analyzed using flow cytometry. Macrophages were quantified using A, F4/80 and Gr-1 (F4/80⁺Gr-1⁻) and B, CD11b and Ly-6G (CD11b⁺Ly-6G⁻). Representative density plots are shown.

**Figure III.** Peritoneal macrophage recruitment in S1P₃⁺ (donor)→C57BL/6 (recipient) and C57BL/6 (donor)→S1P₃⁻/⁻ (recipient) bone marrow chimera. Peritoneal macrophages were isolated 96 hours after i.p. injection of thioglycollate 10 weeks after bone marrow transplantation. Macrophage numbers were calculated by multiplying the percentage of F4/80⁺Gr-1⁻ cells as determined by flow cytometry with the total number of cells in the peritoneal exsudate. n.s. = not significant.
Bone marrow

ApoE−/−

ApoE−/−/S1P3−/−

SSC

CD11b

Gr-1

Ly-6G

CD11b+Ly-6G−

Gr-1

Supplemental figure I

B

Parameter | ApoE−/− (n=6) | S1P3−/−/ApoE−/− (n=6) | p value |
---|---|---|---|
Total BM cells [10⁶/femur] | 24.60 ± 1.51 | 24.28 ± 1.62 | n.s. |
Myeloid cells [10⁶/femur] | 13.75 ± 0.89 | 11.21 ± 1.18 | n.s. |
Neutrophils [10⁶/femur] | 8.91 ± 0.62 | 7.04 ± 0.81 | n.s. |
Gr-1+(Ly-6Chigh) monocytes [10⁶/femur] | 3.24 ± 0.36 | 2.91 ± 0.36 | n.s. |
Gr-1−(Ly-6Clow) monocytes [10⁶/femur] | 1.26 ± 0.11 | 1.03 ± 0.22 | n.s. |
Supplemental figure II

A  F4/80/Gr-1

B  CD11b/Ly-6G

Gr1+ F4/80 - 0.6%
F4/80+ Gr1 - 84.1%

Ly-6G+CD11b low 13.9%
Ly-6G+CD11b high 78.9%

Supplemental figure II
Peritoneal macrophage recruitment in BM chimera

Supplemental figure III