Innate Response Activator B Cells Aggravate Atherosclerosis by Stimulating T Helper-1 Adaptive Immunity

Ingo Hilgendorf, MD*; Igor Theurl, MD, PhD*; Louisa M.S. Gerhardt, MS; Clinton S. Robbins, PhD; Georg F. Weber, MD; Ayelet Gonen, PhD; Yoshiko Iwamoto, BS; Norbert Degousee, PhD; Tobias A.W. Holderried, MD; Carla Winter, BS; Andreas Zirlik, MD; Herbert Y. Lin, MD; Galina K. Sukhova, PhD; Jagdish Butany, MD; Barry B. Rubin, MD, PhD; Joseph L. Witztum, MD; Peter Libby, MD; Matthias Nahrendorf, MD, PhD; Ralph Weissleder, MD, PhD; Filip K. Swirski, PhD

Background—Atherosclerotic lesions grow via the accumulation of leukocytes and oxidized lipoproteins in the vessel wall. Leukocytes can attenuate or augment atherosclerosis through the release of cytokines, chemokines, and other mediators. Deciphering how leukocytes develop, oppose, and complement each other’s function and shape the course of disease can illuminate our understanding of atherosclerosis. Innate response activator (IRA) B cells are a recently described population of granulocyte macrophage colony-stimulating factor–secreting cells of hitherto unknown function in atherosclerosis.

Methods and Results—Here, we show that IRA B cells arise during atherosclerosis in mice and humans. In response to a high-cholesterol diet, IRA B cell numbers increase preferentially in secondary lymphoid organs via Myd88-dependent signaling. Mixed chimeric mice lacking B cell–derived granulocyte macrophage colony-stimulating factor develop smaller lesions with fewer macrophages and effector T cells. Mechanistically, IRA B cells promote the expansion of classic dendritic cells, which then generate interferon γ–producing T helper-1 cells. This IRA B cell–dependent T helper-1 skewing manifests in an IgG1-to-IgG2c isotype switch in the immunoglobulin response against oxidized lipoproteins.


Key Words: atherosclerosis ■ B-lymphocytes ■ dendritic cells ■ granulocyte-macrophage colony-stimulating factor ■ immunology ■ T-lymphocytes

Atherosclerosis is a lipid-driven inflammatory disease that mobilizes a diverse repertoire of leukocytes. Although macrophages accumulate in lesions in the greatest number, other leukocytes can modulate the course of disease. Over the last 20 years, many studies have explored how leukocytes influence atherosclerosis. For example, M1 macrophages, T helper-1 (T_{TH1}) cells, and B2 B cells accelerate whereas T regulatory (T_{reg}) cells and B1 B cells attenuate lesion growth by either augmenting or restraining inflammation. These observations have clinical implications because they suggest that harnessing protective leukocyte activities and silencing those that are harmful could furnish novel treatments for atherosclerosis and other inflammatory diseases.

Clinical Perspective on p 1687

Innate response activator (IRA) B cells develop in the spleen during the inflammatory phase of sepsis. IRA B cells produce granulocyte macrophage colony-stimulating factor (GM-CSF), a pleiotropic growth factor that, although dispensable to hematopoiesis in the steady state, promotes...
the survival, proliferation, and activity of various leukocytes expressing its receptor.12-14 The function and source of GM-CSF in atherosclerosis remain obscure. Even though some have reported that GM-CSF protects against atherosclerosis,15 the weight of evidence suggests that GM-CSF is atherogenic because Ldlr−/− Csf2−/− mice develop smaller lesions,16 whereas exogenous administration of GM-CSF to atherosclerotic mice increases plaque burden17 and stimulates intimal cell proliferation.18 In Apoe−/− mice, hematopoietic stem and progenitor cells elevate the expression of the common β chain of the GM-CSF receptor downstream of impaired reverse cholesterol transport, leading to proliferation, which generates leukocytosis and monocytosis.19 GM-CSF can arise from macrophages, T cells, and epithelial cells, but it remains unknown whether IRA B cells develop in atherosclerosis and, if so, whether they have functional relevance.

Methods
A detailed description of the methods is available in the online-only Data Supplement.

Animals
C57Bl/6J (wild-type [WT]), B6.SJL-PtprcaPepcb/BoyJ (CD45.1−), B6.129P2(SJL)-Myd88tm1.1Defr/J (Myd88−/−), B10.129S2(B6)-Ighmtm1Cgn/J (μMT), B6.Cg-Tg(TcraTcrb)425Cbn/J (OT-II), B6.129S7-Ldlrtm1Her/J (Ldlr−/−), and B6.129P2-Apoetm1Unc/J (Apoe−/−) mice were purchased from The Jackson Laboratory (Bar Harbor, ME). GM-CSF–deficient mice (Csf2−/−) were kindly provided by Dr Randy Seeley, University of Cincinnati (Cincinnati, OH), GM-CSF receptor–deficient mice (Csf2rb−/−) were kindly provided by Dr Jeffrey Whitsett, Cincinnati Children's Hospital Medical Center (Cincinnati, OH). All protocols were approved by the Animal Review Committee at the Massachusetts General Hospital.

Animal Experiments
Mixed bone marrow chimeras were generated by lethally irradiating 8-week-old male Ldlr−/− mice and reconstituting with a 50:50 mixture of Csf2−/− with WT (controls) and μMT BM bone marrow cells (IRA B KO knockout [KO]) or with CD45.1−, Myd88−/−, and Csf2rb−/− bone marrow. For adoptive transfer studies, 25×106 CD19+ B cells from WT and Csf2−/− mice were injected intravenously twice per mouse, 4 weeks apart.

Histology
Murine aortas and spleens were embedded in Tissue-Tek optimum cutting temperature compound (Sakura Finetek) for sectioning and staining. Human spleen samples were fixed in 10% formalin and cut using a microtome and a freezing compound (Sakura Finetek) for sectioning and staining. Murine aortas and spleens were embedded in Tissue-Tek optimum cutting temperature compound (Sakura Finetek) for sectioning and staining.

Flow Cytometry
Antibodies used for flow cytometry are listed in the online-only Data Supplement. Data were acquired on a BD LSRII and analyzed with FlowJo.

Reverse Transcription–Polymerase Chain Reaction
RNA was isolated from sorted cells with the RNeasy Micro Kit (Qiagen) and from snap-frozen aortas and spleens with the RNeasy Mini Kit (Qiagen). Quantitative real-time TaqMan polymerase chain reaction was run on a 7500 polymerase chain reaction thermal cycler (Applied Biosystems).

Cell Culture
Lineage-depleted bone marrow cells were cocultured with equal numbers of IRA B cells and murine interleukin (IL)-4 (5000 U/mL) to generate dendritic cells (DCs). Then, 1×104 IRA B cell–generated bone marrow–derived DCs were loaded with 100 μg/mL ovalbumin or BSA and cocultured with 5×105 labeled OT-II T cells over 4 days for flow cytometric assessment of proliferation. CD4+ CD25+ Treg cells were sorted from IRA B KO and control mice and cocultured with sorted CD45.1+ CD4+ CD25+ Treg cells at increasing dilutions on T cell–depleted and irradiated splenocytes loaded with 1 μg/mL anti-CD3e. Suppression of T-cell proliferation was assessed by flow cytometry after 3 days.

Statistics
Results are shown as mean±SEM. The unpaired Student t test was applied to evaluate differences between 2 study groups. One-way ANOVA with post hoc Dunnett multiple-comparisons test was performed to compare >2 groups. Values of P≤0.05 denote significant changes.

Results
GM-CSF–Producing IRA B Cells Expand in Atherosclerosis
We asked whether IRA B cells develop in atherosclerosis. The spleens of both Ldlr−/− and Apoe−/− mice consuming a diet high in fat and cholesterol (HCD) contained a population of GM-CSF–producing cells. Most of these were IgMhigh B220+ CD23low CD21low CD138high CD43high VLA4high IRA B cells, resembling IRA B cells generated by lipopolysaccharide stimulation (Figure 1A and Figure 1A in the online-only Data Supplement), as originally described.11 Immunofluorescence staining for GM-CSF revealed a population of GM-CSF–producing IgM+ B cells in the marginal zone and red pulp of the spleen (Figure 1B), a location where IRA B cells typically reside. Analysis of various organs showed preferential IRA B cell accumulation in the spleen, although the bone marrow and lymph nodes also harbored smaller IRA B-cell populations (Figure 1C). IRA B-cell numbers rose most dramatically and progressively in Apoe−/− mice (Figure 1D), a finding that agrees with the prevailing notion that Apoe−/− mice display more severe inflammation and atherosclerosis than Ldlr−/− mice. B cells accumulate in the aortic adventitia,20 but we did not detect IRA B cells in the aorta, indicating that IRA B cells do not furnish lesional GM-CSF21 and suggesting that IRA B cells do not affect lesions locally. Humans with severe coronary and peripheral artery disease contained more GM-CSF+ IgM+ IRA B cells in the spleen compared with humans without atherosclerotic disease (Figure 1E and Figure 1B and 1C in the online-only Data Supplement). Thus, IRA B cells accumulate in secondary lymphoid organs in humans and mice with atherosclerosis. Future studies will need to determine the exact triggers and risk factors responsible for IRA B-cell production.

During experimental sepsis, IRA B cells arise by engaging Myd88-dependent Toll-like receptors.11 To test whether IRA B cells require Myd88 in atherosclerosis, we generated mixed chimeras by lethally irradiating Ldlr−/− mice and reconstituting with a mixture of WT CD45.1+ and Myd88−/− CD45.2+ bone marrow cells (Figure 1D in the online-only Data Supplement). After reconstitution, mice consumed HCD for 12 weeks. CD45.1+ WT but not CD45.2+ Myd88−/− cells developed into IRA B cells, indicating a requirement for direct
Myd88 engagement in B cells (Figure IE in the online-only Data Supplement).

**IRA B Cells Aggravate Atherosclerosis**

Determining the impact of IRA B cells on atherosclerosis required selective depletion of GM-CSF from B cells. To achieve this, we adapted the mixed chimeric strategy (Figure 2A). Ldlr−/− mice were lethally irradiated and reconstituted with a mixture of bone marrow cells from Csf2−/− (i.e., GM-CSF−/−) and μMT mice (i.e., B cell deficient). In the reconstituted animals, B cells were the only population completely lacking the capacity to produce GM-CSF because only Csf2−/− cells could give rise to B cells. As controls, we reconstituted Ldlr−/− mice with bone marrow from Csf2−/− and WT mice, thus ensuring that differences between the groups, should any arise, would exclusively reflect B cell–derived GM-CSF deficiency while preserving GM-CSF production by other sources.

Reverse transcription–polymerase chain reaction analysis on sorted B cells, T cells, and myeloid cells confirmed the selective deletion of GM-CSF from B cells (Figure 2B). After 6 weeks of reconstitution, we profiled the leukocyte repertoires in Csf2−/−/μMT (henceforth simply referred to as IRA B KO mice) and the Csf2−/−/WT (control) mice. The blood, spleen, bone marrow, and peritoneal cavity contained similar numbers of leukocyte subsets in both groups (Figure IIA–IID in the online-only Data Supplement), indicating successful reconstitution and a similar leukocyte basal population before the triggering of disease.
After reconstitution, the animals consumed an HCD for 10 weeks. GM-CSF expression in the spleen of IRA B KO mice was reduced by 70%, which shows a dominant role for IRA B cells as a source of GM-CSF in the spleen during atherosclerosis (Figure IIE in the online-only Data Supplement). GM-CSF production by other leukocytes was similar between the groups (Figure IIF in the online-only Data Supplement), as were body weights and plasma cholesterol levels (Figure IIIA in the online-only Data Supplement). The absence of IRA B cells, however, yielded smaller atherosclerotic lesions in the aorta, particularly the aortic root (Figure 2C and 2D), diminished the lipid- and macrophage-rich areas, reduced the number of CD4 T cells, but did not change the smooth muscle cell and collagen content. The changes in lesion size and macrophage content did not depend on circulating monocyte and neutrophil number (Figure IIIB in the online-only Data Supplement), as might be expected. Moreover, blood Ly-6C<sup>high</sup> monocytes expressed similar levels of CCR2, VLA4, and CD62L (Figure IIIC in the online-only Data Supplement), which argued against a defect in the capacity of the monocytes to accumulate.
IRA B Cells Promote the Expansion of $T_{\text{H1}}$ Effector Cells

Numerous studies have identified a role for CD4 T cells in atherosclerosis. Naive CD4 T cells can differentiate into various helper subsets, exhibiting either protective or atherogenic properties. We detected fewer $T_{\text{H1}}$-dependent IgG2c T effector cells in blood, spleen, and para-aortic lymph nodes compared with controls. $T_{\text{reg}}$ cells, on the other hand, developed similarly in both groups in terms of number and suppressive function (Figure 3B and Figure 1VA and 1VB in the online-only Data Supplement).

Among effector T cells, interferon-γ (IFNγ)-producing $T_{\text{H1}}$ cells augment atherosclerosis. We detected fewer IFNγ-producing $T_{\text{H1}}$ cells in blood, spleen, and lymph nodes in IRA B KO mice compared with controls after 10 weeks of HCD feeding (Figure 3C and 3D). Neither group differed in the number of splenic $T_{\text{reg}}$ or IL-4–producing $T_{\text{H2}}$ cells (Figure 3C in the online-only Data Supplement). Do IRA B cells shape an antigen-specific $T_{\text{H1}}$ milieu? In atherosclerosis, it is thought that low-density lipoproteins generate an adaptive immune response, presumably as a result of a break in peripheral tolerance against self-antigens. Low-density lipoprotein also undergoes oxidation, which can mobilize $T_{\text{H1}}$ responses via antigen presentation in the context of oxidative stress–related danger signals. TH1 cells contribute to isotype switching and thus influence antigen-specific humoral immunity. T cell–derived IFNγ, for example, induces IgG2a/c and dampens IgG1 production, whereas IL-4 has the opposite effect.

In these experiments, IRA B KO mice were impaired in generating $T_{\text{H1}}$-dependent IgG2c antibodies against copper-oxidized and malondialdehyde-modified low-density lipoprotein, even though total IgG and IgM levels increased similarly in both groups (Figure 3E–3G and Figure 1VD–1VG in the online-only Data Supplement). Titers of the atheroprotective IgM natural antibody E06 against oxidation-specific epitopes remained unaffected (Figure 1VIC in the online-only Data Supplement). Hence, the IRA B cell number rose in secondary lymphoid organs, so did the number of effector IFNγ-producing $T_{\text{H1}}$ cells and the concentration of antigen-specific, IFNγ-dependent IgG2c. That said, we reasoned that IRA B cells did not augment T-cell numbers directly because T cells do not express the GM-CSF receptor.

IRA B Cells Promote the Generation of Classic DCs

Effector T cells arise in lymphoid organs when their T-cell receptor recognizes antigen on DCs. In the context of specific secondary signals, antigen presented on major histocompatibility complex class II (MHCII) can give rise to effector $T_{\text{H1}}$ cells that expand, enter the circulation and tissue, and participate in immunity. Unlike T cells, DCs and their precursors express the GM-CSF receptor and therefore might be directly influenced by IRA B cells. To test this hypothesis, we enumerated DCs in the spleen, where IRA B cells expand most prominently. Three populations of CD11c+ MHCII+ classic (c) DC were identifiable: CD11b+ CD8+ CD103+, CD11b– CD8+ CD103+, and CD11b+ CD8+ CD103+ (Figure 4A). Before the onset of atherosclerosis, both mouse groups contained similar numbers of all 3 subsets, in agreement with the observation...
that GM-CSF does not affect the generation of splenic DCs in the steady state. During inflammation and with increased GM-CSF, DCs expand. Consequently, over the course of HCD consumption, control mice selectively increased the number of CD11b+ cDCs (Figure 4B). In contrast, IRA B KO mice maintained their cDC numbers at steady-state levels in the spleen (Figure 4B) and lymph nodes (Figure 4C). Remarkably, not only did IRA B KO mice generate fewer cDCs, but these cDC also expressed less TH1-priming IL-12p40 (Figure 4D). Although there were no differences in CD86...
and CD40 expression, MHCII decreased slightly on CD11b+ cDCs in IRA B KO mice (Figure VA in the online-only Data Supplement). IRA B-cell deficiency affected neither the generation of granulocyte-macrophage and common dendritic cell progenitors in the bone marrow nor the number of pre-DCs in the bone marrow and spleen, which argues against IRA B cell–dependent mobilization and expansion of DC progenitors (Figure VB in the online-only Data Supplement).

To determine whether the changes in cDC subset and function depended on the direct interaction of GM-CSF with cDCs, we reconstituted lethally irradiated Ldlr−/− mice with a 50:50 mixture of bone marrow cells from CD45.1 WT mice and CD45.2−/− mice deficient in the common β chain of the GM-CSF-receptor (Csf2rb−/−) and placed them on an HCD for 3 months (Figure 4E). Whereas the CD45.1/CD45.2 splenic cDC chimerism was ≈50:50 among the CD8− subset, chimerism was skewed toward the CD45.1− WT cells (60:40) among CD11b+ cDCs, suggesting that Csf2rb−/− cells were impaired in generating CD11b+ cDCs (Figure 4F). This observation agrees with an earlier report that exogenous GM-CSF administration augmented the number of CD11b+ but not CD8+ cDCs in the spleen.36 Moreover, IL-12p40 expression was lower in sorted Csf2rb−/− cDCs compared with WT cDCs (Figure 4G), thereby reproducing the main effects we observed in IRA B KO mice and suggesting that IRA B cells influence cDCs directly via GM-CSF.

Because DCs can differentiate from bone marrow precursors through culture with recombinant GM-CSF and IL-4, we wondered whether IRA B cells can act as GM-CSF sources capable of generating functionally active DC. We sorted IRA B cells from lipopolysaccharide-stimulated WT mice (Figure 4H) and placed them in culture with lineage-depleted (ie, enriched for hematopoietic stem and progenitor cells) bone marrow cells and IL-4 (Figure 4I). After 8 days, MHCII+ CD11c+ CD40+ CD86+ cDCs appeared (Figure 4J). As controls, we cultured bone marrow cells with IL-4 alone or with B cells from Csf2−/− mice plus IL-4 and enumerated fewer DCs (Figure 4K). The group cultured with IRA B cells yielded more cells with characteristic DC morphology (Figure 4L), thus complementing the surface marker characteristics. To determine the functionality of IRA B cell–generated DCs, we pulsed them with ovalbumin and cocultured with ovalbumin–specific transgenic OT-II CD4+ cells that had been labeled with a tracer. In the absence of ovalbumin, OT-II cells did not proliferate, but when ovalbumin was added, T cells proliferated robustly, as determined by the progressive loss of their tracer dye (Figure 4M). Likewise, IRA B cells sorted from spleens of atherosclerotic Ldlr−/− mice generated functional bone marrow–derived DCs capable of processing ovalbumin for effective antigen presentation and OT-II cell proliferation (Figure VC and VD in the online-only Data Supplement). These experiments indicate that IRA B cells indeed stimulate the generation of mature DCs, which can promote antigen–specific T-cell expansion.

**Transfer of GM-CSF–Competent B Cells Aggravates Atherosclerosis**

If lesions are smaller in the absence of IRA B cells, could the adoptive transfer of GM-CSF–competent B cells into IRA B KO mice give rise to IRA B cells and reverse the phenotype by promoting IFNγ–producing Tbet+ cells and atherosclerosis? To test this conjecture, we adoptively transferred WT B cells (ie, B cells capable of producing GM-CSF) and Csf2−/− B cells into IRA B KO mice on an HCD twice, 4 weeks apart (Figure 5A). To establish whether IRA B cells develop in recipient animals, we transferred CD45.1 WT B cells into CD45.2−/− IRA B KO mice and profiled their phenotype after 8 weeks of an HCD. Remarkably, a population of CD45.1+ GM-CSF+ IRA B cells appeared in the spleen (Figure 5B), thus allowing us to determine the impact of IRA B–cell delivery on the development of atherosclerosis. The transfer of WT but not Csf2−/− B cells increased GM-CSF production in the spleen by >50% and gave rise to a larger number of splenic cDCs and blood effector T cells, including IFNγ–producing Tbet+ cells (Figure 5C and 5D). Moreover, we found augmented expression of the Tbet transcription factor Foxp3, the Th1–associated cytokine IFNγ in atherosclerotic lesions of mice receiving WT but not Csf2−/− B cells or vehicle only (Figure 5E). However, expression of the Th2 cytokine IL-13 remained unaffected (Figure 5F). Quantiﬁcation of lesion size and morphology, as determined by Oil Red O, Mac3, CD4, smooth muscle actin, and Masson trichrome staining, correlated these findings with those reported in Figure 2. Mice receiving WT B cells had larger lesions with more macrophages and T cells compared with mice receiving Csf2−/− or no B cells (Figure 5H–5L). Together, these data indicate that IRA B cells aggravate atherosclerosis by stimulating DC production and shifting the host response toward Th1–associated immunity (Figure 6).

**Discussion**

DCs are professional antigen-presenting cells that, in the context of secondary signals such as IL-12, can generate IFNγ–producing Tbet+ cells capable of activating macrophages and promoting isotype switching in B cells. In atherosclerosis, the Th1–type immunity promotes disease, but the orchestrating pathways remain poorly understood.37 This study reveals that IRA B cells can shape immunity in atherosclerosis. By expressing GM-CSF in microenvironments that support the production of mature DCs, IRA B cells operate in a strategic location and deliver a potent signal that instructs the host to mount an adaptive-like immune response.

In murine disease models that depend on antigen sensitization and challenge such as rheumatoid arthritis, multiple sclerosis, and myocarditis, GM-CSF deficiency ameliorates disease,44–46 suggesting a major role for the growth factor in DC-mediated generation of adaptive immunity. Our data expand on these observations by showing that, in atherosclerosis, IRA B cells are major sources of DC-promoting GM-CSF. In the steady state when IRA B cells are exceedingly rare or when they are absent altogether, splenic DCs develop normally, indicating that cellular sources other than IRA B cells maintain this population. In response to danger, however, mobilization of IRA B cells stimulates the developmental expansion of mature CD11b+ cDCs, a subset with...
a dependence on GM-CSF in atherosclerosis that was previously unrecognized. These changes translate to the increase in IFNγ-producing T cells and oxidized low-density lipoprotein–specific and TH1-dependent IgG2c antibodies.

Assessing the role of B cells in atherosclerosis is complex, in part because of the difficulty in separating the intrinsic biological effects of B cells from the effects of the antibodies they secrete and because of the increasing evidence for a variety of functionally distinct B-cell subsets.42 Considerable data support an atheroprotective role of B1 cells, particularly B1a cells, which are believed to protect against atherosclerosis by secreting natural oxidized lipoprotein–scavenging IgM antibodies. Controversy surrounds the role of B2 cells, however, which are the main producers of adaptive IgG antibodies. Clinically, high antioxidized low-density lipoprotein IgG levels in cardiovascular patients positively correlate with disease burden.43,44 But how do they function? On the one hand, IgG-mediated antigen scavenging may provide protection, similar to natural IgM antibodies. On the other hand, IgG isotypes bind variably to different Fc receptors, which can either activate or inhibit target cells such as macrophages, regardless of antigen binding. Signaling via different Fc receptors can thus have

Figure 5. Transfer of granulocyte macrophage colony-stimulating factor (GM-CSF)–competent B cells aggravates atherosclerosis.

A, Experimental strategy for B-cell adoptive transfer. Naive innate response activator (IRA) B knockout (KO) mice were divided into 3 groups receiving either 2.5×10^7 CD19+ B cells from wild-type (WT; gray) or Csf2−/− (white) mice (n=7 per group) or vehicle (Dulbecco PBS) alone (black; n=5) at weeks 0 and 4 of a 8-week period of high-fat and -cholesterol diet (HCD) feeding. B, Representative dot plots showing identification of IRA B cells in the spleen of a CD45.2+ IRA B KO recipient on an HCD 8 weeks after transfer of 25×10^6 CD45.1+ WT B cells twice, 4 weeks apart. C, Quantification of GM-CSF (Csf2) expression in whole-spleen tissue of IRA B KO mice 8 weeks after transfer of WT (gray), Csf2−/− (white; n=7 per group), or no B cells (black; n=5) by real-time polymerase chain reaction (PCR). Results are presented as means±SEM-fold change in 2^ΔΔCt. *P≤0.05, WT vs the other groups by ANOVA. D, Enumeration of spleen classic dendritic cells (cDCs), blood T effector cells, and blood interferon-γ (IFNγ)–producing T cells in recipients of WT (gray) cells compared with those receiving Csf2−/− (white) B cells (n=7 per group) or vehicle (black; n=5) after 8 weeks of HCD feeding. Results are presented as means±SEM. *P≤0.05, WT vs the other groups by ANOVA. E through L, Quantification of T helper-1 (Th1), transforming growth factor-β1 (TGFβ1), and interleukin (IL)-17 expression in aortic tissue of WT (gray) vs Csf2−/− (white) B-cell recipients (n=7 per group) and vehicle group (black; n=5) by real-time PCR. Results are presented as means±SEM-fold change in 2^ΔΔCt. *P≤0.05, WT vs the other groups by ANOVA. H, Quantification of Oil Red O (ORO)–rich areas in aortic root sections of recipients of WT (gray) vs Csf2−/− (white) B cells (n=7 per group) and vehicle group (black; n=5) on the right and representative images on the left. Results are presented as means±SEM. *P≤0.05, WT vs the other groups by ANOVA. I through L, Representative images and quantification of Mac3, CD4, and smooth muscle actin (SMA)–positive and Masson trichrome staining in aortic root sections of the 3 groups. Results are presented as means±SEM. *P≤0.05, WT vs the other groups by ANOVA.
motactic protein-3/Chemokine ligand 7. Although the role of can aggravate atherosclerosis by generating TH1-priming cDCs. These subsets in atherosclerosis is still unknown, our study on arrows, spatial relationship. TLR indicates Toll-like receptor.

Immunity. Solid arrows depict functional relationship; dashed arrows, spatial relationship. TLR indicates Toll-like receptor.

opposing effects on atherosclerosis, as studies in mice deficient for either the activating Fcy receptors or the inhibitory Fcγ receptor IIb have shown. Adding to the complexity, IgG subclasses exhibit different activation-to-inhibition ratios. IRA B cell—dependent production of the IgG2c isotype, which has the highest ratio, may therefore be consistent with the observation that IRA B cells aggravate atherosclerosis. Beyond antibodies, B cells are also sources of cytokines and chemokines such as regulatory IL-10 and monocyte-mobilizing Monocyte chemotactic protein-3/Chemokine ligand 4. Although the role of these subsets in atherosclerosis is still unknown, our study on another class of mediator, a growth factor, reveals that B cells can aggravate atherosclerosis by generating TH1-priming cDCs.

One somewhat puzzling observation is that a B cell should be a major source of GM-CSF in the first place. After all, B cells participate fundamentally in humoral immunity, so it may be counterintuitive that B cells should also act in the generation of DCs, the cells specialized in the afferent limb of the T-cell response. Yet, IRA B cells may be ideally suited for a sentinel role in adaptive immunity. The spleen screens blood for pathogens, and B cells are the most numerous occupants in the spleen. B cells physically interact with DCs in the spleen to initiate T cell—dependent immunity. Moreover, recent studies have shown that signaling via Myd88 in B cells is important to DC function in lupus and TH1 priming. The finding that IRA B cells require signaling via Myd88 raises the possibility that the link between Myd88 signaling in B cells and DC function in lupus likewise involves B cell—derived GM-CSF. Strategically located and equipped with a plethora of receptors capable of recognizing molecular patterns, IRA B cells may indeed represent a cellular node that bridges innate and adaptive immunity.

The function of the pleiotropic cytokine GM-CSF depends on concentration, location, and timing of expression. Although it is remarkable that a small population of B cells secreting GM-CSF elicited a significant difference in lesion size, Oil Red O area, and macrophage and T-cell content, it should be noted that other leukocytes, including macrophages and T cells, can also produce GM-CSF. Therefore, attention to the cellular source may be critical to understanding the pleiotropic behavior of a cytokine. This study focused on the interplay of GM-CSF-producing IRA B cells with DCs partly because IRA B cells selectively increased in secondary lymphoid organs where DC reside. Even though we did not observe effects of IRA B cells on monocytois and neutrophila, IRA B cells could elicit other effects on myeloid cells as disease progresses. Similarly, the absence of IRA B cells in the aorta in our setting does not preclude their accumulation and local influence in more advanced disease. Future studies will need to determine how alternative cellular sources of GM-CSF at various stages of disease influence atherosclerosis.

Statins have proven benefit in reducing cardiovascular events in individuals in broad categories of risk, in part through direct anti-inflammatory actions. Yet, despite treatment with the best available therapeutics, a considerable burden of residual events threatens individuals prone to complications of atherosclerosis. This challenge has energized efforts at targeting inflammation. Understanding the complex, redundant, and interlinked networks of innate and adaptive immunity implicated in atherogenesis is essential to the development of effective but nuanced immune-targeting approaches. An integrated, systems-wide model that charts the immune system recognizes harmful atherosclerosis-promoting molecular patterns, how it incorporates and propagates this information, and how it ultimately affects disease should aid the development of specific and finely tuned treatments. The function of IRA B cells described here illuminates a previously unknown regulatory node operating in atherosclerosis and is worthy of consideration as a candidate for therapeutic intervention.

Sources of Funding
We thank Michael Waring and Adam Chicoine (Harvard Medical School) for sorting cells. We also thank Eugenia Shvartz, Thibaut Quillard (Brigham and Women's Hospital), and Benjamin G. Chousterman (Massachusetts General Hospital) for technical support, as well as thank Andrew H. Lichtman (Brigham and Women's Hospital) for fruitful discussion.

Acknowledgments
We thank Michael Waring and Adam Chicoine (Harvard Medical School) for sorting cells. We also thank Eugenia Shvartz, Thibaut Quillard (Brigham and Women's Hospital), and Benjamin G. Chousterman (Massachusetts General Hospital) for technical support, as well as thank Andrew H. Lichtman (Brigham and Women's Hospital) for fruitful discussion.

None.
References


**CLINICAL PERSPECTIVE**

Atherosclerosis is a lipid-driven inflammatory disease, yet treatment regimens currently lack genuinely anti-inflammatory approaches. The growth of human and mouse atherosclerotic lesions is characterized by the influx of functionally diverse leukocytes to the vessel wall. Because leukocytosis is a risk factor for complications of atherosclerosis in humans, understanding how leukocytes affect the course of disease is important and may lead to new strategies that either augment or attenuate particular leukocyte function. This study shows that a previously unknown leukocyte population plays an important role in atherosclerosis. Innate response activator B cells develop in lymphoid organs in humans with atherosclerosis at high numbers and in the 2 major mouse models. Functionally, innate response activator B cells aggravate atherosclerosis by shaping Th1-type adaptive immunity. The study identifies an upstream node of leukocyte communication and suggests that targeting innate response activator B cell function might be a strategy for the treatment of cardiovascular disease.
Innate Response Activator B Cells Aggravate Atherosclerosis by Stimulating T Helper-1 Adaptive Immunity


*Circulation.* 2014;129:1677-1687; originally published online January 31, 2014; doi: 10.1161/CIRCULATIONAHA.113.006381

*Circulation* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231

Copyright © 2014 American Heart Association, Inc. All rights reserved.

Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:

http://circ.ahajournals.org/content/129/16/1677

Data Supplement (unedited) at:

http://circ.ahajournals.org/content/suppl/2014/01/31/CIRCULATIONAHA.113.006381.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in *Circulation* can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:

http://www.lww.com/reprints

Subscriptions: Information about subscribing to *Circulation* is online at:

http://circ.ahajournals.org/subscriptions/
SUPPLEMENTAL MATERIAL

Overarching aims and description of the study. **Aim 1:** To quantify IRA B cells in two mouse models of atherosclerosis and in human atherosclerosis. These data are shown in Figure 1 and Supplemental Figure 1. **Aim 2:** To determine whether IRA B cells are important in mouse atherosclerosis and to profile key features such as lesion size, cell accumulation, etc. To achieve this, mixed chimeric mice were generated (described below). These data are shown in Figure 2 and Supplemental Figures 2 and 3. **Aim 3:** To profile the observed differences in T cells more rigorously. These data are shown in Figure 3 and Supplemental Figure 4. **Aim 4:** To link IRA B cells with the observed differences mechanistically. These data are shown in Figure 4 and Supplemental Figure 5 describing the interaction between IRA B cells and Dendritic cells. **Aim 5:** To rescue the phenotype and thus link IRA B cells to the phenotype functionally. These data are shown in Figure 5. Overall, the study used 235 mice. After generation of mixed chimeric mice, the blood leukocyte profile was analyzed and only animals that were reconstituted successfully were placed in the study. Typically ~93% of mixed chimeras were reconstituted and used in the study. The number of mice used in each experiment is indicated in the Figure legends. All mice admitted to the study survived the intended duration of the study.

Supplemental Methods

Animal models and in vivo interventions. **Mixed bone marrow chimeras:** 8 weeks old male Ldlr–/– mice were lethally irradiated (950cGy) and reconstituted with a 50:50 mixture of Csf2–/– with WT (Controls) and µMT bone marrow cells (IRA B KO), respectively. In analogy male Ldlr–/– were reconstituted with a 50:50 mixture of CD45.1+ and Myd88–/– or Csf2rb–/– bone marrow. To induce atherosclerosis Ldlr–/– mice consumed a high-fat/cholesterol diet (HCD; D12108C, Research Diets, New Brunswick, NJ, USA) and Apoe–/– were placed on a Western diet (TD.88137, Harlan Teklad, Indianapolis, IN, USA) at 8 weeks of age for different time periods as indicated in the text. Bone marrow chimeras were switched to HCD 6 weeks after reconstitution. **Adoptive transfer:** B cells from WT and Csf2–/– mice were isolated by magnetic cell separation. Pooled cell suspensions from spleens and peritoneal lavages were incubated with 4 µl anti-CD19-PE Ab (Biolegend, San Diego, CA, USA) per 1 x 10⁸ cells in sterile 2% FBS (fetal bovine serum, Atlanta Biologicals, Lawrenceville, GA, USA), 0.5% BSA (bovine serum albumin, MP Biomedicals, Solon, OH, USA) in PBS for 30 min on ice, washed and incubated with 100 µl anti-PE MACS beads (Miltenyi Biotec, Auburn, CA, USA) per 1 x 10⁸ cells in 0.5% BSA, 2mM EDTA in PBS for another 30 min on ice. Labeled cells were positively selected in a Midi MACS separator and LS column according to the manufacturer’s instructions. Cells were manually counted in a Neubauer chamber, a purity of 93% and viability of over 95% were confirmed by flow cytometric analysis and Trypan blue staining, respectively. At 6 weeks after reconstitution IRA B KO mice received either 25 x 10⁸ B cells/mouse from WT or Csf2–/– mice by tail vein injection. Mice were placed on HCD and received another 25 x 10⁸ B cells/mouse after 4 weeks. Mice were sacrificed after 8 weeks on HCD. When 25 x 10⁸ CD45.1+ CD19+ cells were transferred, twice, 4 weeks apart into CD45.2+ IRA B KO mice, 66,542 ± 24,556 CD45.1+ IRA B cells were still retrieved after 8 weeks (n = 3, mean ± SEM).

Cell isolation. Peripheral blood was collected by retroorbital bleeding with heparinized capillaries, and erythrocytes were lysed in RBC Lysis buffer (Biolegend). Peritoneal lavages and organs were harvested at day of sacrifice. Spleens, femurs, aortas and paraaortic lymph nodes (1 proximal, 1 abdominal, 2 distal lymph nodes at aortic bifurcation per mouse) were excised after vascular perfusion with 10 ml sterile PBS. Minced spleens and flushed bone marrow were strained through a 40 µm-nylon mesh (BD Biosciences, San Jose, CA, USA). Spleen cell suspensions were further subjected to RBC lysis. Aortas were minced and digested in 450 U/ml collagenase I, 125 U/ml collagenase XI, 60 U/ml DNase I and 60 U/ml hyaluronidase (Sigma-Aldrich, St. Louis, MO, USA) PBS for 1 h at 37°C while shaking. Lymph nodes were minced and digested in 168 U/ml collagenase III (Worthington Biochemicals, Lakewood, NJ, USA), 60 U/ml DNase I (Sigma-Aldrich), 2% FBS RPMI-1640 (Cellgro, Manassas, VA, USA) for 1h at 37°C while shaking. Cells were counted in a Neubauer chamber. One femur contains ~5% of all bone marrow cells ¹. Bone marrow cell counts were extrapolated accordingly. **Cell sorting:** IRA B cells were expanded in vivo by 4 daily intraperitoneal injections of 25mg LPS per mouse or by 3 months of HCD in
Ldlr/+ mice. Spleens from LPS stimulated WT and Csf2/+ mice and from atherosclerotic Ldlr/+ mice were homogenized and incubated with 4 µl anti-CD138-Biotin Ab (clone 281-2, BD Biosciences) per 1 x 10⁸ cells in sterile 2% FBS, 0.5% BSA in PBS for 30 min on ice, followed by incubation with 100 µl anti-Biotin MACS beads (Miltenyi Biotec) per 1 x 10⁸ cells in 0.5% BSA, 2mM EDTA in PBS for another 30 min on ice. Cells were positively selected with a Midi MACS separator and LS column and stained for anti-IgM-Fitc (BD Biosciences), anti-CD45.2-PerCp-Cy5.5 (BD Biosciences), anti-CD23-PECy7 (Biolegend), anti-CD43-APC (BD Biosciences), Streptavidin-Alexa Fluor 700 (Life Technologies, Carlsbad, CA, USA), anti-CD19-APCCy7 (Biolegend). CD45.2⁺, CD23low, IgMhigh, IgD³⁺, CD138high cells were sorted on a FACS Aria II cell sorter (BD Biosciences). Splenocytes from OT-II mice were stained with anti-CD45.2-Fitc (BD Biosciences), anti-CD4-PE (BD Biosciences), anti-CD25-APC (BD Biosciences), and transgenic CD4⁺ CD25⁻ T cells were sorted on a FACS Aria II cell sorter. Splenocytes from IRA B KO and controls and from CD45.1⁺ C57Bl/6J mice were incubated with 4 µl anti-CD19-Biotin Ab (BD Biosciences) and anti-CD11b-Biotin (BD Biosciences) per 1 x 10⁸ cells in sterile 2% FBS, 0.5% BSA in PBS for 30 min on ice, followed by incubation with 100 µl anti-Biotin MACS beads (Miltenyi Biotec) per 1 x 10⁸ cells in 0.5% BSA, 2mM EDTA in PBS for another 30 min on ice. Cells were negatively selected with a Midi MACS separator and LS column enriching for T cells and stained for anti-CD45.2-Fitc (BD Biosciences), anti-CD4-PE (BD Biosciences), anti-CD25-APC (BD Biosciences), and anti-CD45.1-Alexa700 (Biolegend). Regulatory T cells (Treg) from IRA B KO and control mice were sorted as CD45.2⁺ CD4⁺ CD25⁺ cells, while conventional T cells (Tconv) were sorted as CD45.1⁺ CD4⁺ CD25⁻ cells on a FACS Aria II cell sorter (BD Biosciences). TCRβ⁺ B220⁻ MHCIi⁺, CD11chigh cDC were sorted from splenocytes directly into RLT buffer for subsequent RNA isolation.

**Serum analysis. Cholesterol measurement:** Serum was collected after overnight fasting. Total cholesterol levels were measured with the Cholesterol E colorimetric assay (Wako Chemicals, Richmond, VA, USA) in a Safire² microplate reader (Tecan, Maennedorf, Switzerland) according to the manufacturer’s instructions. VLDL, LDL and HDL cholesterol were determined by Skylight Biotech (Skylight Biotech, Inc., Japan) Immunoglobulin (Ig) measurement: Total serum IgG and IgM were measured by ELISA (Bethyl Laboratories, Montgomery, TX, USA) according to the manufacturer’s instructions. Isotype- and antigen-specific antibody titers were determined by chemiluminescent enzyme immunoassays as previously described ². In brief, antigens were coated at 5 µg/mL PBS overnight at 4°C (IgG and IgG₂c (goat anti-ms-IgG (Pierce 31160)), IgG₁ (Rat anti-ms-IgG₁ (BD 553445)), AB-12, CuOxLDL, MDA-LDL). The plates were blocked with 1% BSA in TBS, serially diluted antisera from individual mice were added, and the plates incubated for 1.5h at room temperature. Bound plasma immunoglobulin (Ig) isotype levels were detected with various anti-mouse Ig isotype-specific alkaline phosphatase (AP) conjugates (Abcam) using LumiPhos 530 (Lumigen, Southfield, MI, USA) solution, and a Dynex Luminometer (Dynex Technologies, Chantilly, VA, USA). Data are expressed as relative light units counted per 100 milliseconds (RLU/100 ms). **GM-CSF ELISA:** GM-CSF was measured in undiluted serum with the Mouse GM-CSF Quantikine ELISA Kit (assay range 7.8-500pg/ml) according to the manufacturer’s instructions.

**Histology.** Spleens were embedded in Tissue-Tek O.C.T compound (Sakura Finetek, Torrance, CA, USA), frozen in ice-cold 2-Methylbutane (Fisher Scientific, Fair Lawn, NJ, USA) and sectioned into 6 µm slices yielding 30-40 sections per mouse. The following antibodies were used for immunofluorescence staining: Anti-GM-CSF (clone MP1-31G6; Abcam, Cambridge, MA, USA), secondary biotinylated anti-rat IgG (Vector Laboratories, Burlingame, CA, USA), streptavidin-Alexa Flour 594 (Life technologies), and FITC anti-IgM (clone II/41; BD Biosciences). Images were recorded using a BX63 motorized microscope (Olympus, Center Valley, PA, USA). Murine aortic roots were embedded in Tissue-Tek O.C.T compound, frozen and sectioned into 5 µm slices yielding 30-40 sections per root. Sections that capture the maximum lesion area were used to compare lesion sizes between study groups. Adjacent sections were used for additional immunohistochemical staining. Following stains were performed to assess lesions size and composition: Hematoxylin and eosin (H&E), Oil-Red-O (ORO; Sigma-Aldrich) for lipids, anti-Mac3 (clone M3/84; BD Biosciences) for macrophages, anti-α-smooth muscle actin (ab5694; Abcam) for smooth muscle cells (SMA), Masson’s Trichrome staining for collagen (Masson), anti-CD4 (clone RM4-5; BD Biosciences) for T helper cells. Biotinylated secondary antibodies
and avidin-complex were used, and all sections counterstained with hematoxylin. Images were recorded using a Nanozoomer 2.0RS (Hamamatsu Photonics, Hamamatsu City, Japan). En-face ORO staining was performed on pinned aortas after fixation in 10% formalin. Human spleen samples were obtained from surgical specimens and autopsy at the Department of Pathology, Toronto General Hospital, Toronto, ON, Canada. All immunohistochemistry studies on human patients samples were approved by the research ethics board at University Health Network. Spleens from 4 patients without a history or signs of cardiovascular disease upon examination were compared to those from 4 patients with symptomatic cardiovascular disease. Samples were fixed in 10% formalin and embedded in paraffin for histologic sectioning (4 µm thick slices). Following dewaxing and heat-induced antigen retrieval sections were blocked with donkey serum for 10min and stained with primary antibodies rabbit anti-human GM-CSF (bs-3790R, Bioss Inc. MA, USA) and goat anti-human IgM (NB7436, Novus Biologicals, CO, USA) over night. Donkey anti-rabbit Cy3 and donkey anti-goat Cy5 were used as secondary antibodies (Millipore, Billerica, MA, USA) for immunohistochemical staining. Images were recorded with an Olympus Fluo View 1000 confocal laser scanning microscope (Olympus, Tokyo, Japan).

Flow Cytometry. Cell suspensions were stained in PBS supplemented with sterile 2% FBS and 0.5% BSA. The following monoclonal antibodies were used for flow cytometric analysis: anti-Ly6C (clone AL-21, BD Biosciences), anti-CD34 (clone RAM34, BD Biosciences), anti-IgM (clone II/41, BD Biosciences), anti-CD45.1 (clone A20, Biolegend), anti-CD45.2 (clone 104, BD Biosciences), anti-CD86 (clone GL1, BD Biosciences), anti-CD3e (clone 145-2C11, ebioscience), anti-CD4 (clone GK1.5, Biolegend), anti-CD8 (clone 53-6.7, BD Biosciences), anti-CD90.2 (clone 53-2.1, BD Biosciences), anti-TCRβ (clone H57-597, Biolegend), anti-CD19 (clone 6D5, Biolegend), anti-B220 (clone RA3-6B2, BD Biosciences), anti-CD25 (clone PC61, BD Biosciences), anti-MHCII (clone AF6-120.1, BD Biosciences), anti-F4/80 (clone BM8, Biolegend), anti-CD49b (clone DX5, BD Biosciences), anti-NK1.1 (clone PK136, BD Biosciences), anti-CD11b (clone M1/70, BD Biosciences), anti-CD11c (clone HL3, BD Biosciences), anti-CD115 (clone AFS98, ebioscience), anti-CD21 (clone 7E6, Biolegend), anti-CD23 (clone B3B4, Biolegend), anti-CD40 (clone 3/23, Biolegend), anti-CD43 (clone S7, BD Biosciences), anti-CD93 (clone AA4.1, BD Biosciences), anti-CD49d/VLA4 (clone R1-2, BD Biosciences), anti-CD44 (clone B3B4, Biolegend), anti-CD40 (clone 145-2C11, ebioscience), anti-CD4 (clone 3/23, Biolegend), anti-CD25 (clone PC61, BD Biosciences), anti-MHCII (clone IM7, Biolegend), anti-CD117/ckit (clone 2B8, BD Biosciences), anti-Ly6A/Sca1 (clone D7, ebioscience), anti-CD127/ILRα (clone A7R34, ebioscience), anti-CD103 (clone 2E7, Biolegend), anti-Ter119 (clone Ter-119, BD Biosciences), anti-GM-CSF (clone A7R34, ebioscience), anti-CD138 (clone 281-2, BD Biosciences), anti-CD127/ILRα (clone IM7, Biolegend), anti-CD117/ckit (clone 2B8, BD Biosciences), anti-Ly6A/Sca1 (clone D7, ebioscience), anti-CD127/ILRα (clone A7R34, ebioscience), anti-CD103 (clone 2E7, Biolegend), anti-Ter119 (clone Ter-119, BD Biosciences), anti-GM-CSF (clone MP1-22E9, BD Biosciences), anti-Foxp3 (clone XMG1.2, BD Biosciences), anti-CD103 (clone 2E7, Biolegend), anti-Ly6A/Sca1 (clone D7, ebioscience), anti-CD49d/VLA4 (clone R1-2, BD Biosciences), anti-CD44 (clone B3B4, Biolegend), anti-CD40 (clone 145-2C11, ebioscience), anti-CD4 (clone 3/23, Biolegend), anti-CD25 (clone PC61, BD Biosciences), anti-MHCII (clone IM7, Biolegend), anti-CD117/ckit (clone 2B8, BD Biosciences), anti-Ly6A/Sca1 (clone D7, ebioscience), anti-CD127/ILRα (clone A7R34, ebioscience), anti-CD103 (clone 2E7, Biolegend), anti-Ter119 (clone Ter-119, BD Biosciences), anti-GM-CSF (clone MP1-22E9, BD Biosciences), anti-Foxp3 (clone XMG1.2, BD Biosciences). For intracellular staining cells were fixed and permeabilized with BD Cytofix/Cytoperm (clone XMG1.2, BD Biosciences), anti-Foxp3 (clone FJK-16s, ebioscience), anti-IFNγ (clone 104, BD Biosciences), anti-CD103 (clone 2E7, Biolegend), anti-Ly6A/Sca1 (clone D7, ebioscience), anti-CD49d/VLA4 (clone R1-2, BD Biosciences), anti-CD44 (clone B3B4, Biolegend), anti-CD40 (clone 145-2C11, ebioscience), anti-CD4 (clone 3/23, Biolegend), anti-CD25 (clone PC61, BD Biosciences), anti-MHCII (clone IM7, Biolegend), anti-CD117/ckit (clone 2B8, BD Biosciences), anti-Ly6A/Sca1 (clone D7, ebioscience), anti-CD127/ILRα (clone A7R34, ebioscience), anti-CD103 (clone 2E7, Biolegend), anti-Ter119 (clone Ter-119, BD Biosciences), anti-GM-CSF (clone MP1-22E9, BD Biosciences), anti-Foxp3 (clone XMG1.2, BD Biosciences). For intracellular staining cells were fixed and permeabilized with BD Cytofix/Cytoperm (BD Biosciences) according to the manufacturer’s instructions. For intracellular staining of IFNγ, IL-4, and IL-17, cell suspensions were stimulated in 2% FBS RPMI-1640 medium with 20 ng/ml PMA and 1 µg/ml ionomycin (Sigma-Aldrich) in the presence of GolgiStop and GolgiPlug (BD Biosciences) for 3 hours at 37°C, 5% CO2 prior to fixation and permeabilization. For proliferation assays, target cells were labeled with Cell Tracer Violet (Life Technologies) and live cells were identified with Fixable Viability Dye eFluor 780 (ebioscience). Data were acquired on a LSRII and analyzed with FlowJo (Tree Star, Ashland, OR, USA). Specifically, monocytes were identified as CD45+, Lin- (Lin1 = Ter119, CD3, CD90.2, CD19, B220, NK1.1, CD49b, Ly6G), CD11b+, MHCIIlow, CD11clow, CD115+ cells, subdivided into Ly6Chigh and Ly6Clow cells. Neutrophils were identified as CD45+, Lin1-, CD11b+, MHCIIlow, CD11clow, SSChigh, Ly6Cint cells. Unless otherwise noted, B cells were identified as CD45+, CD19+ cells. CD4+ and CD8+ T cells were identified within the CD45+, CD19− population. Classical Dendritic cells (DC) were identified as CD45+, CD11b+, MHCIIhigh, CD11clow. PreDC were identified as CD45+, Lin1-, F4/80+, CD11b+, CD115+, MHCIIlow, CD11clow cells. Lin2− (Lin2 = Ter119, CD3, CD90.2, CD19, B220, NK1.1, CD49b, Gr-1, CD11b, CD11c, IL7Rα), ki67+, Sca1+, CD34high, CD16/32high myeloid progenitors were identified as GMP when CD115+ and as ckithigh MDP and ckitlow CDP when CD115−.

Reverse transcription PCR. Cells: 1 x 10^5 sorted CD3+, CD19+, CD11b− splenic cells were lysed in RLT buffer with 1% β-mercaptoethanol. RNA was isolated with the RNeasy Micro Kit (Qiagen, Venlo, Netherlands) followed by cDNA transcription with the iScript Select cDNA Synthesis Kit (Bio Rad,
T cells were added to T-irradiated T cell-depleted splenocytes in a total volume of 200µl/well. Sorted CD45.2 Technologies) according to the manufacturer’s instructions and 3 x 10^6 irradiated with 30Gy prior to loading with 1 µg/ml anti-CD3e (clone 145-2C11, ebioscience) where medium. T cell-depleted splenocytes were transferred to a U-bottom 96-well plate (3 x 10^5 and LS column negatively selected cells were counted in the flow-through and resuspended in complete Biotin Ab (clone 53-2.1, BD Bioscience) at 4 µl/1 x 10^7 in a flat-bottom 96-well plate. For T cell proliferation assays 1 x 10^5 from atherosclerotic Ldlr–/– spleens were homogenized in RLT buffer with 1% β-mercaptoethanol followed by RNA extraction with the RNeasy Mini Kit (Qiagen, Venlo, Netherlands). Quantitative real-time TaqMan PCR for Tbet/Tbx21 (Mm01290062_m1; Applied Biosystems), Foxp3 (Mm00475162_m1; Applied Biosystems), GATA3 (Mm00484683_m1; Applied Biosystems), RORyt (Mm01261022_m1; Applied Biosystems), IFNγ (Mm01168134_m1; Applied Biosystems), IL-4 (Mm00445259_m1; Applied Biosystems), IL-10 (Mm00439614_m1; Applied Biosystems), IL-12b (Mm00434174_m1; Applied Biosystems), IL-17a (Mm00439618_m1; Applied Biosystems), TGFβ1 (Mm01178820_m1; Applied Biosystems), Csf2 (Mm01290062_m1; Applied Biosystems) and housekeeping gene β-actin (4352341E; Applied Biosystems). 7 x 10^5 Lin– bone marrow cells were cultured in 1 ml RPMI-1640 supplemented with 10% FBS, 25 mM HEPES, 2mM L-glutamine, 50 µM β-mercaptoethanol, 100 U/ml penicillin, 100 U/ml streptomycin (complete medium) in a 24 well plate (Cellgro). 7 x10^5 LPS induced IRA B cells and corresponding Csf2–/– B cells, respectively, were added to the culture together with 5000 U/ml murine IL-4 (Peprotech, Rocky Hill, NJ, USA) at day 0 and day 5 with replacing medium. Adherent cells were harvested after 8 days of culture, counted and stained for Dendritic cell (DC) marker expression with flow cytometric antibodies. In analogy 1 x10^5 IRA B cells (IgMhigh, CD23low, CD43high, CD138high) isolated from atherosclerotic Ldlr–/– mice (3 months on HCD) were co-culture with 1 x10^6 Lin– bone marrow cells in a flat-bottom 96-well plate. For T cell proliferation assays 1 x 10^5 WT IRA B cell generated bone marrow derived DC (BMDC) were transferred into U-shaped wells of a 96-well plate and loaded with 100 µg/ml ovalbumin (OVA; Sigma-Aldrich A7641) or 100 µg/ml BSA in a final volume of 200 µl/well. Ldlr–/– IRA B cell generated BMDC were kept in the flat-bottom 96-well plate and loaded with 100 µg/ml OVA or BSA. Sorted CD4+CD25– T cells from OT-II mice were stained with Cell Tracer Violet (Life Technologies) according to the manufacturer’s instructions. Thereafter 5 x 10^5 OT-II CD4 T cells were added to each well and harvested after 4 days of co-culturing for flow cytometric assessment of proliferation cycles. For Treg suppression assay C57Bl/6J splenocytes were incubated with anti-CD90.2-Biotin Ab (clone 53-2.1, BD Bioscience) at 4 µl/1 x 10^6 cells followed by incubation with 100 µl anti-Biotin MACS beads (Miltenyi Biotec) per 1 x 10^8 cells. After passing through a Midi MACS separator and LS column negatively selected cells were counted in the lineage depleted flow-through. 7 x 10^5 Lin– bone marrow cells were cultured in 1 ml RPMI-1640 supplemented with 10% body weight). Semi-quantitative PCR for GM-CSF (csf2, primers 5’-TCAAGAGGGCCTGAAACCTCC-3’ and 5’-AAATCTTCCAGGCGGTCTGC-3’) and housekeeping gene rpl19 (Mm01178820_m1; Applied Biosystems), Csf2 (Mm00450960_m1; Applied Biosystems), Foxp3 (Mm00475162_m1; Applied Biosystems), GATA3 (Mm00484683_m1; Applied Biosystems), RORyt (Mm01261022_m1; Applied Biosystems), IFNγ (Mm01168134_m1; Applied Biosystems), IL-4 (Mm00445259_m1; Applied Biosystems), IL-10 (Mm00439614_m1; Applied Biosystems), IL-12b (Mm00434174_m1; Applied Biosystems), IL-17a (Mm00439618_m1; Applied Biosystems), TGFβ1 (Mm01178820_m1; Applied Biosystems), Csf2 (Mm01290062_m1; Applied Biosystems) and housekeeping gene β-actin (4352341E; Applied Biosystems) was run on a 7500 PCR thermal cycler (Applied Biosystems). Cell culture. Bone marrow cells from CD45.1+ mice were incubated with anti-CD3-Biotin (clone 145-2C11, Biolegend), anti-CD90.2-Biotin (clone 53-2.1, BD Biosciences), anti-CD19-Biotin (clone 6D5, Biolegend), anti-B220-Biotin (clone RA3-6B2, BD Biosciences), anti-NK1.1-Biotin (clone PK136, BD Biosciences), anti-Ly6G-Biotin (clone 1A8, Biolegend) Ab at 4 µl/1 x 10^7 cells followed by incubation with 100 µl anti-Biotin MACS beads (Miltenyi Biotec) per 1 x 10^8 cells. After passing through a Midi MACS separator and LS column negatively selected cells were counted in the lineage depleted flow-through. 7 x 10^5 Lin– bone marrow cells were cultured in 1 ml RPMI-1640 supplemented with 10% β-actin (4352341E; Applied Biosystems).
Supplemental Figure 1: IRA B cell phenotype and ontogeny. (A) Surface marker expression profile of IRA B cells isolated from spleens of LPS challenged C57Bl/6 (4 x 25mg/day LPS i.p.) and atherosclerotic \( \text{Ldlr}^{--} \) and \( \text{Apoe}^{--} \) mice (3 months on HCD). GM-CSF\(^+\) leukocytes are depicted in red and GM-CSF\(^-\) leukocytes in grey. (B) Isotype staining controls on human spleen sections. (C) Characteristics of patients with and without cardiovascular disease (CVD). (D) \( \text{Ldlr}^{--} \) mice were lethally irradiated, reconstituted with a 50:50 mixture of CD45.1\(^+\) WT and CD45.2\(^+\) \( \text{Myd88}^{--} \) bone marrow and placed on HCD for 3 months. (E) Discrimination of \( \text{Myd88}^{--} \) and \( \text{Myd88}^{+/+} \) (WT) splenocytes based on CD45.2 and CD45.1 staining and flow cytometry. Further staining for GM-CSF, B220 and IgM allowed for identification of GM-CSF\(^+\) IRA B cells in the CD45.1\(^+\) WT but not the CD45.2\(^+\) \( \text{Myd88}^{--} \) B cell population. Representative dot plots are shown for one of three mixed chimeras.)
Supplemental Figure 2: Leukocyte subsets in reconstituted mixed bone marrow chimeras. (A) Enumeration of monocytes (Mono), neutrophils (Neutro), CD4+ and CD8+ T cells (CD4 Tc, CD8 Tc), CD19+ B cells (CD19 B) in the spleen of control (gray) and IRA B KO (white) mice 6 weeks after reconstitution. Results are presented as mean ± SEM, n = 6 per group., (B) Identification and quantification of splenic B cell subsets in both groups 6 weeks after reconstitution. The CD21^{high}CD23^{low} population contains marginal zone B cells, CD21^{low}CD23^{low} cells encompass B1 and plasma cells, and B2/T2 cells are CD23^{high}. Results are presented as mean ± SEM, n = 6 per group, controls in gray and IRA B KO mice in white. (C) Splenic B cell expression of antigen presenting and costimulatory molecules MHCII, CD86 and CD40 as determined by flow cytometry. Results are presented as mean fluorescence intensity (MFI) ± SEM, n = 6 per group. (D) Leukocyte subsets in blood, spleen, bone marrow and peritoneum of control (gray) and IRA B KO (white) mice 6 weeks after reconstitution. Results are presented as mean ± SEM, n = 6 per group. (E) Quantification of GM-CSF (Csf2) expression in whole spleen tissue of IRA B KO (white) and control (gray) mice by real-time PCR. Results are presented as mean ± SEM fold change of 2^{ΔCt}, ** p ≤ 0.01, n ≥ 20 per group. (F) Relative contribution of non-B cells to leukocyte derived GM-CSF production as assessed by flow cytometry. Results are presented as mean ± SEM, n = 7 per group.
Supplemental Figure 3: IRA B cell deficiency does not affect monocytosis and hypercholesterolemia. (A) Measurement of total body weight, serum levels of total cholesterol (n ≥ 10 per group) and VLDL, LDL and HDL cholesterol (3 pooled samples of n ≥ 6 mice per group) after 10 week HCD feeding. Results are presented as mean ± SEM. (B) Enumeration of total monocytes, Ly6C<sup>hi</sup> monocytes, neutrophils and CD11b<sup>low</sup> F4/80<sup>hi</sup> red pulp macrophages in blood, spleen or bone marrow after 10 week HCD feeding. Results are presented as mean ± SEM, n ≥ 10 per group, * p ≤ 0.05, controls in gray and IRA B KO mice in white. (C) Expression of CCR2, VLA4 and CD62L on Ly6C<sup>hi</sup> blood monocytes after 10 week HCD feeding as determined by flow cytometry. Quantification of MFI presented as mean ± SEM fold change between control (gray) and IRA B KO (white) mice, n ≥ 10 per group.
Supplemental Figure 4: IRA B cells influence T_{H1} cell-dependent anti-OxLDL isotype switching but not T_{reg} suppressive function. (A) Regulatory T cell (T_{reg}) suppression assay. WT CD4^{+} CD25^{-} conventional T cell (T_{conv}) were co-cultured with CD4^{+} CD25^{+} T_{reg} cells sorted from IRA B KO and control mice after 10 week HCD feeding at increasing dilutions as indicated. Representative histograms show proliferation of cell tracer dye-labeled T_{conv} cells in response to soluble anti-CD3e (1 µg/ml) and T cell-depleted, irradiated spleen stimulator cells under the suppressive influence of T_{reg} cells. (B) Dose-dependent quantification of T_{reg}-induced suppression of T_{conv} proliferation. Results are presented as mean ± SEM, n = 4 per group, controls in gray circles and IRA B KO mice in white squares. (C) On the left representative dot plot showing intracellular staining of CD3^{+} CD4^{+} T cells for IL-4 and IL-17. On the right quantification of IL-4-producing T_{H2} and IL-17-producing T_{H17} cells in spleens of IRA B KO (white) and control (gray) mice after 10 week HCD feeding. Results are presented as mean ± SEM, n = 7 per group. (D) Antibody binding dilution curves for total serum IgG_{2c} and IgG_{1} antibodies. Results are presented as mean for triplicates of pooled samples, n ≥ 6 per group, controls in gray circles and IRA B KO mice in white squares. (E, F) Quantification of IgG_{1} and total IgG antibody titers against MDA-LDL and copper-oxidized LDL (CuOxLDL) in 1:25 diluted individual serum samples, n ≥ 10 per group. Results are presented as mean ± SEM, * p ≤ 0.05, controls in gray and IRA B KO mice in white. (G) Quantification of anti-AB1-2-IgM (EO6) antibody titers in 1:25 diluted individual serum samples, n ≥ 10 per group. Results are presented as mean ± SEM, controls in gray and IRA B KO mice in white.
Supplemental Figure 5: IRA B cell deficiency does not affect generation of cDC progenitors.

(A) Expression of MHCII, CD86, and CD40 on CD8^-CD11b^+ splenic cDC as determined by flow cytometry in IRA B KO (white) and control (gray) mice after 10 week HCD feeding. On the left representative histograms show mean fluorescence intensities (MFI) for MHCII, CD86 and CD40 compared to isotype controls (dashed line). On the right quantification of MFI presented as mean ± SEM fold change between control (gray) and IRA B KO (white) mice, n ≥ 10 per group, * p ≤ 0.05. 

(B) Enumeration of granulocyte-macrophage progenitors (GMP), common dendritic cell progenitor (CDP) and preDC precursor in bone marrow and spleen after 10 week HCD feeding. Results are presented as mean ± SEM, n ≥ 10 per group, controls in gray and IRA B KO mice in white. 

(C) Flow assisted cell sorting of CD23^low^IgM^high^CD43^high^CD138^high^ (IRAB_{Ldlr-/-} HCD) cells from atherosclerotic Ldlr^--^ mice (3 months on HCD). Dashed lines represent isotype controls. 

(D) CD4^+^ CD25^-^ OT-II cells were co-cultured
with IRA B_{Ldr−/− HCD} cell-generated BMDC loaded with chicken ovalbumin (100µg/ml) or BSA (100µg/ml) for 4 days. Representative histograms show cell divisions of CD4^{+} OT-II cells labeled with a cell tracer dye.

**Supplemental References:**