The Journal of Immunology

RESEARCH ARTICLE | SEPTEMBER 15 2013

Characterization of Resident B Cells of Vascular Walls in Human Atherosclerotic Patients FREE

Moustafa Hamze; ... et. al

J Immunol (2013) 191 (6): 3006–3016.
https://doi.org/10.4049/jimmunol.1202870

Characterization of Resident B Cells of Vascular Walls in Human Atherosclerotic Patients

Moustafa Hamze,* Caroline Desmetz,* Marie Laurence Berthe,† Pascal Roger,‡,§ Nathalie Boulle,†,¶ Pascal Brancherau,‖ Eric Picard,‖ Caroline Guzman,* Claire Tolza,* and Paul Guglielmi*,[1]

Animal models of atherosclerosis suggest that B cells have contradictory protective or proatherogenic effects that are also subset and context dependent. To further understand the pathophysiology of human atheroma, we characterized local Ig production and functional properties of resident B cells in human arterial lesions. Ig repertoires were analyzed by RT-PCR in carotid endarterectomy samples. Cytokine, differentiation marker and transcription factor mRNA expression was studied on arterial wall lymphocytes isolated by laser capture microdissection. Ig sequence analysis revealed that individual samples each contained a limited number of B cell clones. Functional α and γ mRNAs made up the majority of H chain mRNAs in the adventitia. Clonal evolution of Ig V regions, expression of activation-induced cytidine deaminase, clonal H chain switch, and an inverted λ/κ ratio of Ig L chain usage indicated that a local differentiation process was taking place in arterial walls. Clonotypic markers revealed different plaque and adventitia Ig repertoires and a B cell recirculation between adventitia and draining lymph nodes. Microdissected mononuclear cells had an activated phenotype expressing IL-6, GM-CSF, and TNF-α, whereas IL-2, IL-4, IL-10, M-CSF, and IFN-γ were not detected. Adventitial oligoclonal resident B cells of atherosclerotic patients are mainly mature B2 (conventional) CD20$^-$ plasmablasts lacking markers of terminal differentiation to plasma cell (CD138 and Blimp-1). They present hallmarks of Ag-driven maturation and could act on inflammation and disease progression directly or by promoting polarization of other immune cells.
***The Journal of Immunology*, 2013, 191: 3006–3016.**

Atherosclerosis is characterized by a lipid-initiated chronic inflammation of vascular walls involving both innate and adaptive immune cells in the pathophysiologic process (1). Macrophages recruited in tunica intima play a crucial role during initial steps of atherosclerosis by uptaking modified lipoproteins [mainly oxidized low-density lipoproteins (OxLDL)], leading to foam cell formation, a hallmark of arterial lesions (2). Macrophages participate in inflammation by secreting cytokines, growth factors, and enzymes that increase plaque instability. The adaptive immune system is also involved in atheroma development (3). T cells are present within plaques at all stages of the disease. Activated TCRαβ$^+$ CD4$^+$ cells constitute the dominant T lymphocyte population in vascular lesions and are mainly of the Th1 cell type. Natural regulatory T cells (Tregs) or induced peripheral Tregs efficiently inhibit experimental atherosclerosis development in several experimental models, whereas Treg depletion aggravates plaque formation (4). Accordingly, immune-mediated inflammation in atherosclerosis has been initially envisioned as solely orchestrated by T cells. However, B cell depletion in animal models has recently challenged this conclusion (5, 6).

B cells home in adventitia of normal arteries as the result of a partially L-selectin–dependent physiologic process (7). B lymphocytes represent a minor component of tunica intima in normal as well as atherosclerotic vessels (7–13). However, B lymphocytes and plasma cells accumulate in lamina adventitia adjacent to arterial plaques of human patients and of atherosclerosis-prone mice and their numbers generally parallel the severity of vascular lesions (8–15). The structural organization of the inflammatory infiltrates ranges from solitary cells and small lymphoid cell clusters in early lesions to densely clustered cellular aggregates in advanced atherosclerosis. Such an organization suggests a local B cell maturation. Whether B lymphocytes are a major cell population in these tertiary lymphoid structures remains controversial.

B cells have originally been presented as atheroprotective. Indeed, B cell deficiency in *Ldlr*$^{-/-}$ mice was associated with an increase in arterial lesion area (16). Moreover, splenectomy aggravates plaque formation in aortas of *Apoe*$^{-/-}$ mice, whereas reinfusion of splenic B cells limits disease progression (17). Part of the B lymphocyte–related protection depends on Ig production. Impaired maturation of B1 (innate-like B cells secreting natural antibodies) and marginal zone B cells producing natural Abs, and particularly anti-OxLDL IgM of the T15 clonotype, accelerates

*Centre de Pharmacologie & Innovation dans le Diabète FRE 3400 Centre National de la Recherche Scientifique–Université Montpellier 1, 34093 Montpellier, France; †Laboratoire de Biologie Cellulaire et Hormonale, Centre Hospitalier Universitaire Arnaud de Villeneuve, 34295 Montpellier, France; ‡Service d'Anatomie et Cytologie Pathologiques, Centre Hospitalier Universitaire Carémeau, 30029 Nîmes, France; §Université Montpellier 1, 34967 Montpellier, France; ¶Institut de Recherche en Cancérologie de Montpellier, INSERM, U896, 34298 Montpellier, France; and ‖Service de Chirurgie Vasculaire, Centre Hospitalier Universitaire Carémeau, 30029 Nîmes, France

[1]Current address: UMR 5235, Centre National de la Recherche Scientifique/Université Montpellier 2, Montpellier, France.

Received for publication October 17, 2012. Accepted for publication July 19, 2013.

This work was supported by the regular dotation of Université Montpellier 1 and Centre National de la Recherche Scientifique to FRE 3400. C.D. was supported by a grant from the Fondation Lefoulon Delalande.

The sequences presented in this article have been submitted to the EMBL database (http://www.ebi.ac.uk/embl/Access/index.html) under accession numbers HF541880–HF541920.

Address correspondence and reprint requests to Dr. Paul Guglielmi, UMR5235, DAA, cc107, CNRS/Université Montpellier 2, Place Eugène Bataillon, 34095 Montpellier cedex 5, France. E-mail address: paul.guglielmi@inserm.fr

The online version of this article contains supplemental material.

Abbreviations used in this article: AID, activation-induced cytidine deaminase; Be, effector B (lymphocyte); LCM, laser-capture microdissection; OxLDL, oxidized low-density lipoprotein; Treg, regulatory T cell.

atherosclerosis in hyperlipidemic mice (18). Presence of protective IgG and IgA has been demonstrated in sera of laboratory animals immunized with OxLDL (19, 20). However, titers of anti-OxLDL IgG correlate well with atherosclerosis severity in mouse models (21–23), whereas findings in humans are controversial (24, 25). Two independent reports have demonstrated the proatherogenic role of B2 (conventional) lymphocytes (5, 6). This apparent discrepancy with earlier concepts is likely because splenectomy selectively depletes B1a cells, whereas anti-CD20 Abs preferentially target mature B2 lymphocytes (26, 27). Whether B2 cells exert their proatherogenic effects by reducing T lymphocyte activation or in their own right is still an unresolved question. Recently, the protective role of resident B lymphocytes in diseased arterial wall was shown to be subset and context dependent (28).

In this article, we have characterized Ig repertoires and functional properties of arterial wall infiltrating B cells in advanced human atherosclerosis, with a special emphasis on the adventitial population. We demonstrate that most resident B lymphocytes expressed switched isotypes of Ig H chains (frequently and sometimes exclusively of the IgA type) that also featured hypermutated V regions. B cell responses were oligoclonal with a bias for a recurrent use of some particular V region genes. Clonal diversification of V regions by additional somatic mutations, clonal H chain switch, inversion of the λ/κ ratio of L chain usage, and activation-induced cytidine deaminase (AID) expression witnessed a skewed recruitment and an in situ maturation of arterial wall B cells. The resident B2-type lymphocytes were $CD20^-$ activated plasmablasts expressing IL-6, GM-CSF, and TNF-α.

Materials and Methods

Patients and surgery

Tissues from patients undergoing carotid endarterectomy were obtained from the Montpellier-Nîmes University Hospital. All patients gave written informed consent according to the university hospital ethical committee guidelines. Samples from a first group of 19 patients (7 women and 12 men, from 52 to 86 y old) were used for mRNA expression and laser-capture microdissection (LCM) experiments. Specimens from a second group of 5 patients (1 woman and 4 men, from 66 to 77 y old) served exclusively for imaging purposes. The surgical procedure to ablate vascular lesions involved dissection though the tunica media. Therefore, the resulting tissue samples further termed "plaque" and "adventitia" contain, respectively. the tunica intima or adventitia and in both cases a portion of the smooth muscle cell layer. When requested by the surgical protocol, one of the deep lateral cervical lymph nodes ($n = 9$) was removed and included in our analysis.

Laser-capture microdissection

Carotid endarterectomy samples ($n = 6$, patients 14 to 19 y old) were immediately extensively washed in PBS, immersed in RCL2 fixative (Alphelys, Plaisir, France), and embedded in paraffin, as previously described (29). RCL2 is an alcohol based formalin-free fixative suitable for subsequent nucleic acid studies, but some difficulties may arise and cause discrepancies in immunohistochemical reactivity for certain Ags (30). As indicated by the manufacturer (www.alphelys.com/alph01/prod/rcl2/us/rcl2_histo.php) and in our hands, too, the use of anti-CD19 or anti-IgH Abs resulted in inconstant staining and precluded their validation as reliable reagents in this particular experimental setting. Tissue sections (of 7-μm thickness) were affixed onto Superfrost glass slides, deparaffinized for 5 min in absolute ethanol at 60°C, and then stained by H&E in RNase-free conditions. Sections were then kept in a desiccation chamber for at least 15 min. LCM was then performed using a PixCell II apparatus (Arcturus Molecular Devices) of the microdissection platform of Le Centre Hospitalier Universitaire de Montpellier, Laboratoire de Biologie Cellulaire et Hormonale, Hôpital Arnaud de Villeneuve, Montpellier, France. The different specimens of patients 14, 16, and 19 were obtained from different sections in temporally independent experiments. Depending on the sample, 60–1340 spots were collected, corresponding to 100–2500 mononuclear cells of lymphocytic appearance. The caps containing the thermolabile polymer-cell composites were affixed to 0.5-ml tubes containing 400 μl QIAGEN RLT buffer, reversed to maintain contact between cells and buffer for 1 h at room temperature. To ensure optimal nucleic acid recovery, tubes were subsequently placed 30 min in an oven at 42°C, in a wet atmosphere, then vortexed and centrifuged.

Immunostaining of arterial tissues

After extensive washing in PBS, adventitia and plaque tissue samples were fixed in 4% formalin. Atherosclerotic plaque specimens were decalcified for 72 h in 10% EDTA 1% paraformaldehyde, pH 7.4, at room temperature. Arterial samples were then paraffin embedded and 3-μm-thick sections affixed to glass slides. Tissues were subsequently deparaffinized (Histoclear 10 min 2×, absolute ethanol 5 min 2×, 96% ethanol 5 min 2×, and rinsed in distilled water), immersed for 30 min in PBS containing 2% FCS, and stained with H&E or labeled for 30 min with fluorochrome-conjugated reagents. Whenever needed, Ag retrieval was performed, according to standard procedures, using citrate buffer. Rabbit $F(ab')_2$ polyclonal anti-human IgG/FITC, IgA/FITC, IgM/FITC (DakoCytomation F0315, F0316, F0317; final dilution 1/20), mouse IgG2A anti-human CD7/FITC (Beckman Coulter IM0585; final dilution 1/3), mouse IgG1 anti-human CD19/APC–Alexa Fluor 750 (Beckman Coulter A94681; final dilution 1/10), or mouse IgG1 anti-human CD19/PE (Miltenyi Biotec 130-091-247; final dilution 1/10) were used for direct immunofluorescence. Specificity of the anti-Ig conjugates was checked on a panel of monoclonal lymphoblastoid or neoplastic B cell lines and on normal PBMCs. These reagents were also devoid of background staining on the fibrous trabeculae of patients' lymph nodes. After three washes in PBS, slides were counterstained with DAPI (300 nM) for 5 min, washed in PBS, and mounted in ProLong Gold antifade reagent (P36930; Invitrogen). Anti-CD3ε (Confirm, 2GV6; Ventana), anti-CD20 (Confirm, L26; Ventana), and anti-CD138 (B-A38, Ventana) mAbs were used as a first layer and immunostaining was then performed automatically with a DAKO Autostainer (Universal staining system; DakoCytomation, Trappes, France) using the streptavidin–peroxidase method.

RNA extraction

Portions of the plaque samples corresponding to intraplaque hemorrhage, thrombosis, or necrosis were eliminated to minimize contamination by nonresident cells. Before preparation of whole-tissue extracts, adventitia and plaque specimens ($n = 13$, patients 1 to 13) were thoroughly washed with PBS to eliminate blood cells and chopped into small pieces. Tissue fragments were resuspended in Tripure isolation reagent (Roche) and homogenized with a Polytron apparatus. Samples were then processed to extract RNAs according to the manufacturer's protocol. RNAs were prepared from microdissection samples using the QIAGEN QIAshredder system and RNeasy mini kits.

Reverse transcription

A total of 300 ng RNA (adventitias and plaques) or the totality of extracted RNAs (microdissections) were denaturated 5 min at 70°C and reverse transcribed in a total volume of 40 μl containing 2 μl 2'-deoxynucleoside 5'-triphosphate mix (10 mM each), 8 μl 5× buffer, 4 μl 0.1M DTT, 1 μl oligo-dT primer (1 μg/μl), and 1 μl SuperScript III reverse transcriptase (Invitrogen) for 40 min at 37°C, 40 min at 40°C, and 40 min at 42°C. Finally, RT was heat inactivated for 15 min at 70°C.

PCR amplification

PCR was carried out with specific primers (see detailed list in Supplemental Fig. 1) and thermostable DNA polymerases (recombinant Taq polymerase [Invitrogen] or Ex Taq polymerase [Takara]). Reactions (50 μl) were amplified using the following protocol: one cycle of 94°C for 10 min; 26 (32 or 36) cycles of 94°C for 45 s, 55°C for 30 s, and 70°C for 1 min 30 s; and one cycle of 10 min at 72°C. In some instances, second-round PCRs were performed with specific Ig nested primers, using the same protocol with 26 cycles. All the primer pair combinations used in this study yield readily detectable amplification products in single-round PCRs (32 cycles) using total spleen cell cDNAs as templates.

The RT-PCR system designed to characterize expressed Ig sequences is based on the use of 14 VH, 13 Vκ, and 15 Vλ upstream primers able to amplify almost full-length open reading frames belonging to all known V region families. Reverse primers were chosen sufficiently downstream to allow, when necessary, the unambiguous identification of the classes and subclasses of expressed constant regions.

Cloning

PCR products were characterized on 2% agarose gels, purified as recommended by QIAquick and cloned into PCR II Topo vector (Invitrogen).

Ligation reactions were transfected to competent *Escherichia coli*, by heat shock at 42°C for 1 min, as recommended by the manufacturer. Transformed bacteria (100 μl) were plated onto Luria-Bertani Petri dishes containing 100 μg/ml ampicillin and 0.17 mg/ml X-Gal.

Plasmid preparation and sequencing

Plasmids were extracted from bacteria following an alkaline lysis protocol. Nucleic acid sequences were commercially purchased from MWG. Mutation analysis of the V region sequences were performed using the V Quest software of the international ImMunoGeneTics information system (IMGT, www.imgt.org; Ref. 31). Fully annotated nucleotide sequences of the adventitial Ig H and L chain cDNAs are available from the European Molecular Biology Laboratory database under accession numbers HF541880–HF541920 (www.ebi.ac.uk/embl/Access/index.html).

Results

Lymphoid cells in arterial wall samples

Plaque specimens were 3 cm long on average and consisted of most of the carotid artery circumference, which greatly differed in size for each patient. They often contained hemorrhagic, necrotic, and calcified areas. Adventitial tissue samples were more homogeneous upon macroscopic examination, had a crescent shape (5 mm length, 4 mm maximal width, and 2 mm thickness), and weighed 15–40 mg. Owing to the discontinuity and heterogeneity in inflammatory elements and fibrous content, total cell counts in specimens used for whole-tissue RNA extraction were almost impossible to achieve in intimal plaques and could be determined only indirectly in adventitial samples. For the latter, estimations made from representative H&E-stained slides used for LCM (3 patients) and DAPI-stained slides (5 patients) resulted in a range of 5–15 $\times$ 10^5 nucleated cells per adventitial specimen. Cells with a lymphocyte or plasma cell morphology accounted for 10–30% (plaque specimens; nine patients) or for 30–70% (adventitial specimens; eight patients) of the total cell content. Intimal plaque immune cells were mainly found as diffuse infiltrates in the subendothelial region or in the fibrous cap. Adventitial lymphocytes were closely associated with the vasa vasorum and frequently present within the microvessel walls. In rare cases, intimal or adventitial lymphocytes were organized as small cell clusters containing up to 400 lymphoid cells (Fig. 1A). Immunofluorescence staining of plaque tissue sections by Fab′2 anti IgH (μ, γ, or α) reagents revealed bright cytoplasmic staining of occasional large cells pertaining to all three isotypic classes under study. In adventitial samples, the anti-α and anti-γ conjugates identified Ig-producing lymphoblasts mainly associated with the vasa vasorum walls (Fig. 1B). A similar staining pattern was obtained with the anti-CD19 reagent (Fig. 1B). In the five adventitial specimens studied by immunofluorescence, we found no IgM-producing cells.

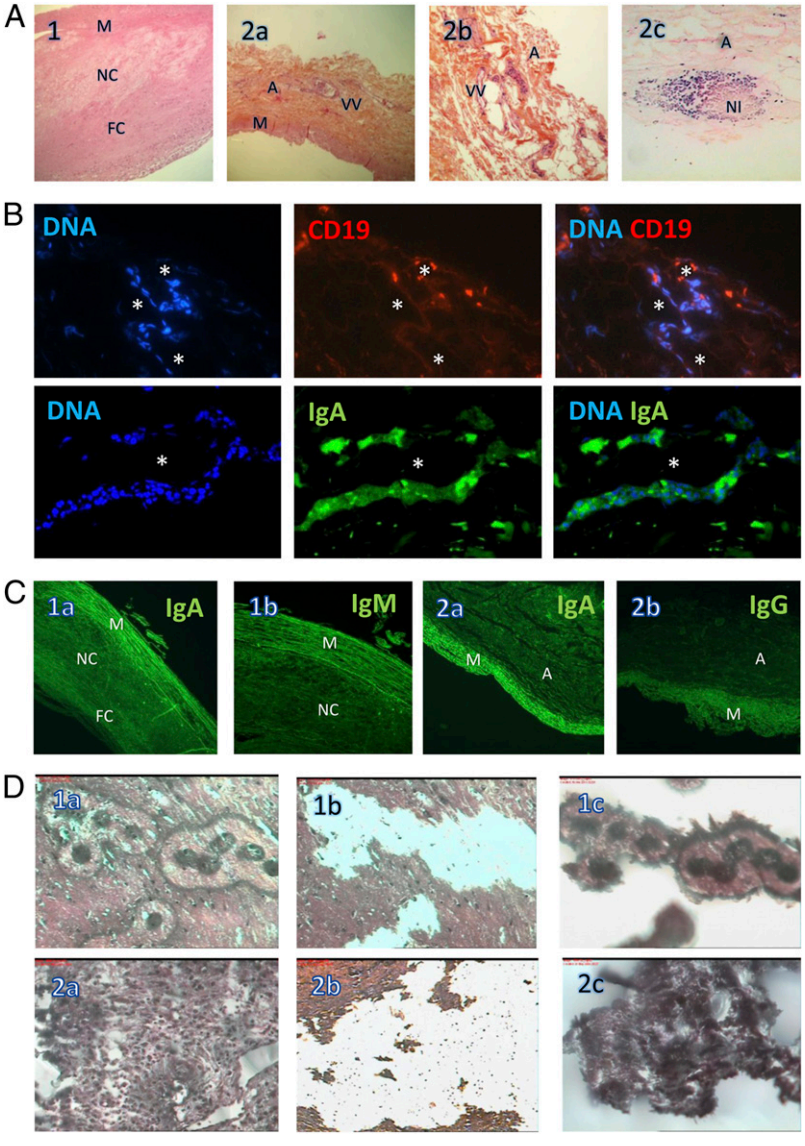

FIGURE 1. Histology and immunostaining of arterial wall lymphoid infiltrates, Ig depositions, and LCM (representative experiments). (**A**) H&E staining of arterial wall tissue sections. *1*, Plaque patient 22 10×; *2*, Adventitias: *2a*, patient 22 10×; *2b*, patient 21 20×; *2c*, patient 16 63×. A, adventitia; FC, fibrous cap; M, media; NC, necrotic core; NI, nodular infiltrate; VV, vasa vasorum. (**B**) $CD19^+$ and IgA-producing lymphoblasts in the vicinity of adventitial vasa vasorum. Patient 21, *upper row*: DNA, CD19, and overlay magnification ×20; *lower row*: DNA, IgA, and overlay magnification ×40. Asterisks indicate vasa vasorum lumen. (**C**) Immunoglobulin depositions in arterial walls. Magnification ×10. *1*, Plaques; *1a*, patient 20; *1b*, patient 22. *2*, Adventitias; *2a*, patient 21; *2b*, patient 22. Anti-CD7 and anti-CD19 fluorochrome-coupled reagents do not stain tunica media under similar experimental conditions. (**D**) Examples of LCM of patient 15 (*1*: *upper row*) and patient 14 (*2*: *lower row*) adventitial diffuse lymphoid infiltrates at different cell densities. Before (*a*) and after (*b*) laser shot; captured cells in cap (*c*).

Depositions of IgM, IgG, and IgA were found mainly in tunica media in all samples under study (Fig. 1C). Most specimens were brightly stained by anti-IgA and anti-IgG reagents. Ig deposits had a lamellar organization, and counterstaining with DAPI nuclear dye indicated that there was no Ig-producing cell in this layer. Western blots confirmed that IgH chains were major components in the protein extracts of atherosclerotic arterial walls (not shown).

B cells in arterial walls preferentially express IgA and IgG

In the arterial walls of a first group of 13 patients, an overall assessment of H chain isotype expression was achieved by RT-PCR amplification of Ig transcripts from whole-tissue extracts using J and C region primers. All adventitias but one contained Ig mRNAs, whereas three plaques completely lacked Ig expression and two contained only trace amounts of Ig transcripts (Fig. 2). IgG and IgA mRNAs were concomitantly expressed in nine plaque specimens, together with IgM in eight cases, and a single sample contained only a minute amount of γ H chain mRNAs. IgH expression patterns between individual patient adventitia and plaque specimens were frequently discordant (Fig. 2). Five adventitias contained μ H chain transcripts, whereas α H chain mRNAs were present in all Ig-expressing specimens and were the sole IgH transcripts in three cases (Fig. 2). In many instances, the JH-Cα amplification products appeared as doublets, owing to the difference in length between the α1 and α2 hinge regions, indicating that both isotypes were concomitantly produced. This finding was further confirmed by RT-PCR using α subclass specific primers and digestion of the amplification products with the PstI restriction enzyme that cleaves the CH1 α1 but not the CH1 α2 sequence (not shown). Nine adventitial specimens contained γ-chain transcripts (Fig. 2). Subclass-specific PCR primers identified the existence of γ1 transcripts in all of them, whereas γ2 mRNAs were found only in seven samples. Trace amounts of γ3 mRNAs were sometimes present, and there were no γ4 transcripts (not shown). Only three adventitia and three plaque extracts, in each case, contained low amounts of δ H chain mRNAs and there were no functional ε H chain transcripts (Fig. 2). Taken together, in a majority of samples, the absence of μ and/or δ mRNAs ruled out a possible blood cell contamination, and the isotype distribution was evocative of some degree of selection among resident B lymphocytes. Further insights on IgH expression were obtained by analyzing 10 LCM samples from arterial tissues of a second group of six patients. Plaque and adventitia lymphocytes isolated by LCM all expressed at least one H chain isotype. Ig α- and γ-chain transcripts were indeed predominant, and only two specimens contained μ mRNAs (Fig. 2). Of interest, different H chain isotypes were expressed by two independent nodular cell aggregates from patient 16: μ-type transcripts were exclusively found in the adventitial one, whereas a mixture of α and γ mRNAs was present in the intimal one (Fig. 2).

Atherosclerotic arterial walls are populated by low numbers of B cell clones

We then examined the Ig VH and VL region repertoires of resident arterial B cells. Because IgH isotype production was rather homogeneous in intimal plaques, the samples under study were

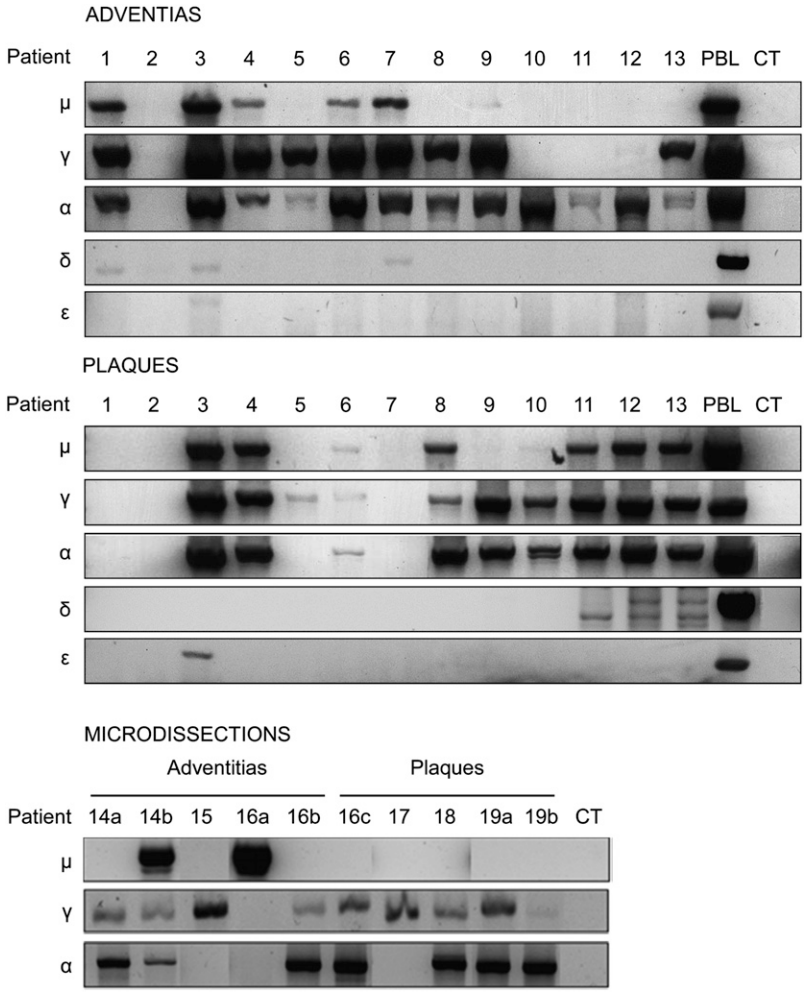

FIGURE 2. Expression of IgH isotypes in atherosclerotic lesions. Single round RT-PCR (32 cycles; adventitias and plaques) or nested RT-PCR (32 and 26 cycles; microdissections) using a forward JH primer with class-specific CH reverse primers. Microdissected cells in patient 16a and c samples were obtained from two independent adventitial and plaque nodular lymphocyte aggregates, whereas all other LCM specimens were representative of diffuse lymphoid infiltrates. Sequencing of patient 3 JH-CH ε PCR products identified amplification of sterile transcripts resulting from a cross-reaction between the JH primer and the germline sequences. RNAs extracted from normal individual PBL or absence of RNA template (CT) are respectively used as positive and negative controls. The empty lane present on original gels between these two controls has been removed. Because samples were anonymized during this study, gel images corresponding to microdissections in Figs. 2, 4B, and 6 have been recomposed from original gel photographs to achieve coherent numbering of patients' specimens.

chosen to be representative of the different H chain isotype distributions in adventitia (IgM + G + A, IgG + A, and IgA-only producers). With use of our RT-PCR amplification system of full-length VH regions, the total number of amplified bands detectable in each patient arterial sample ranged from 2 to 16 in adventitia and from 3 to 28 in plaque for the cumulated H chain isotypes (Fig. 3A). In a similar approach to assessing L chain repertoire of adventitial tissues, we found 0 to 7 bands per sample for κ L chains and 2 to 10 bands per sample for λ L chains (these numbers include consideration of some very weak bands) (Fig. 3B). For a given adventitia, numbers of H and L amplification products were generally in good correlation, with sometimes a slight excess of L chains that may be due either to a more efficient amplification of the shorter L chain mRNAs, to a certain degree of promiscuity in VL primers, or to the presence of nonfunctional transcripts (see below).

To assess their homogeneity, we cloned and sequenced a number of representative adventitial PCR products. The Ig H and L chain transcripts had an open reading frame throughout the entire V(D)J and constant regions (except for two independent λ L chain mRNAs from patient 5 that contained a frameshift mutation in CDR3, resulting in the appearance of a premature stop codon in the C region) and therefore could encode functional proteins. Iterative sequencing of 18 adventitial VH PCR products yielded a single sequence in 15 cases and 2 different sequences in 3 samples. In all cases, the amplified sequences strictly corresponded to the VH

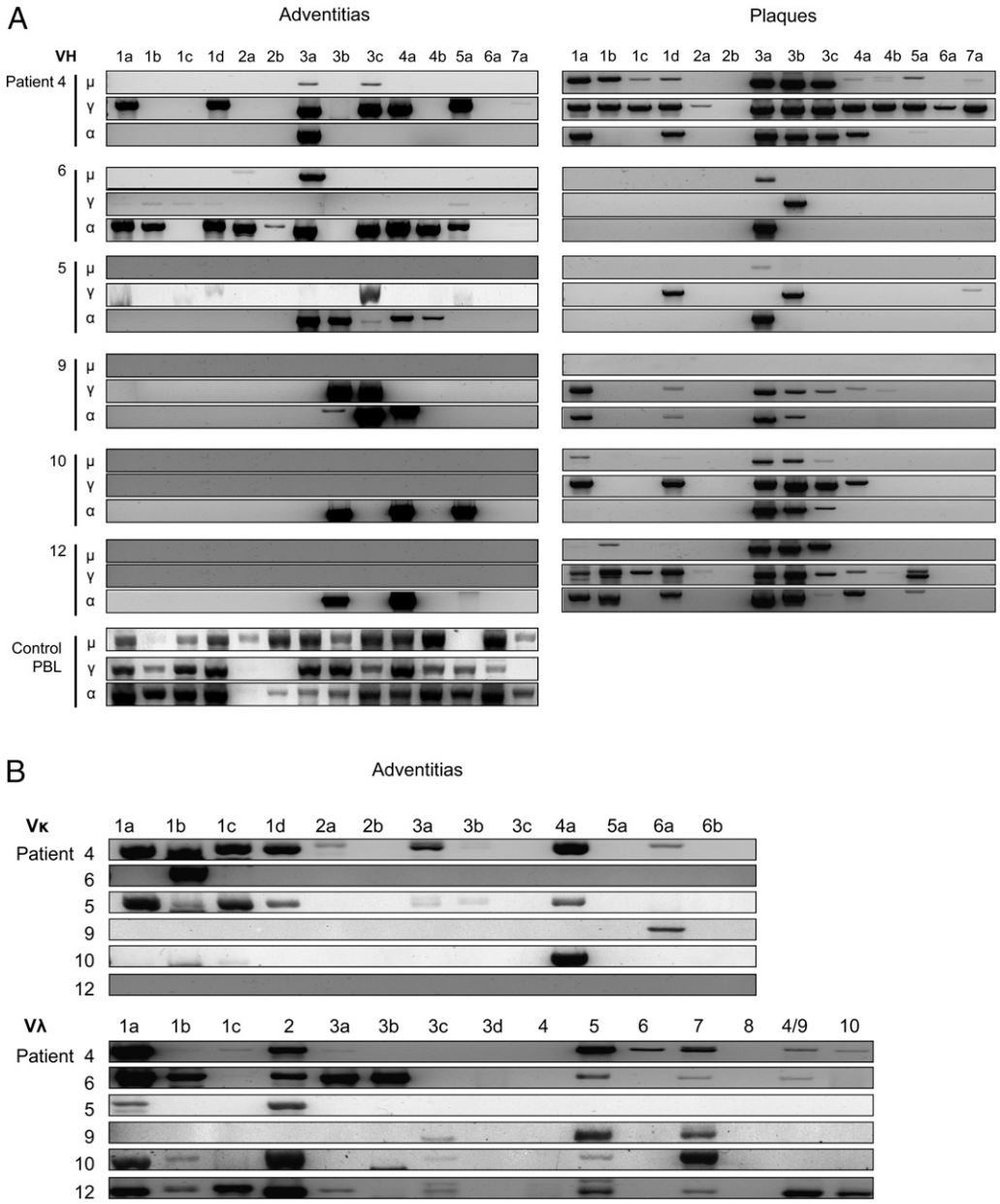

FIGURE 3. Arterial wall samples each contain a limited number of B cell clones. (**A**) Nested RT-PCR (32 and 26 cycles) using forward VH family–specific primers and reverse Cμ, Cγ, and Cα reverse primers. Templates are constituted by RNAs extracted from adventitias (*left panel*) and intimal plaques (*right panel*) representative of the different IgH isotype distributions in the outer arterial layer (2 in each group: IgM + G +A producers: patients 4 and 6, IgG + A producers: patients 5 and 9, IgA-only producers: patients 10 and 12). The same analysis performed on RNAs extracted from normal individual PBL is given for comparison. The presence of IgM and IgA transcripts in patient 5 samples is likely due to the better sensitivity of nested of VH-CH PCRs compared with the single-round JH-CH PCRs. (**B**) Analysis of L chain repertoire in adventitias by single-round RT-PCR (32 cycles) using forward Vκ or Vλ family–specific primers and respective Cκ or Cλ reverse primers. Patients are analyzed in the same order as in Fig. 3A.

(sub) family specified by the upstream oligonucleotide. A more limited evaluation of H chain PCR product complexity was achieved on randomly selected intimal VH3-CH bands from patient 4 and resulted in the retrieval of only a single sequence in each assay. Therefore, >80% of the VH amplification products were homogeneous, making the enumeration of DNA bands on agarose gels a fair estimation for the number of B cell clones actually present in the arterial wall samples. DNAs of 13 adventitial VL bands (4 κ and 9 λ) were also cloned and sequenced: 50% corresponded to a single sequence and 50% to two sequences. However, several duplicated sequences were explained by some promiscuity within VL oligonucleotides leading to the redundant amplification of certain L chain transcripts. In all adventitias but one (patient 5), there was a majority of Ig λ over Ig κ clones (overall ratio, 70.6% λ versus 29.4% κ). Taken together, these results indicate that each arterial wall sample contained a limited number of B cell clones.

Adventitial B cells preferentially express a limited set of hypermutated VH regions

When results from all patients under study were aggregated, the majority of expressed V regions belonged to the VH3, VH4, and VH5 gene families (Supplemental Fig. 2). Nevertheless, the observed frequencies were not significantly different from those expected from random gene usage. However, a preferential usage of a small number of specific individual family members accounted for the overrepresentation of VH3 sequences: The VH3-23 gene that is normally expressed by 6–7% of blood B cells (32) contributed to 30% of cumulated adventitial VH3 sequences and was present in the arterial wall samples of four of the six analyzed patients. VH3-66 was found in three instances and VH3-73 twice. Thus, more than one-half (58%) of the VH3-IgH sequences came from only three individual VH genes. Conversely, no particular DH or JH region appeared to be preferentially expressed.

Whereas only two μ H chain mRNAs contained unmodified VH, DH, and JH germline regions, all the other Ig transcripts featured extensive somatic modifications. In the γ, α, and one μ mRNAs, the number of mutations ranged from 7 to 39 per sequence (average, 21) for the sole VH portion. Somatic diversification was further extended by N and P insertions and numerous DH mutations (Supplemental Fig. 2). The VL regions were also targets for somatic mutations (7–21 per V region in κ-chains and 9–21 in functional λ-chains) (Supplemental Fig. 2).

Arterial wall B cells present hallmarks of local adaptive maturation and selection

Expression of AID was detected in three adventitias (whole-tissue extracts from patients 3 and 12 and some microdissected cells from patient 16) and two plaques (patients 4 and 6) (Fig. 4, Supplemental Fig. 3). Of note, in patient 16, AID was expressed in the adventitial diffuse cell infiltrate (sample 16b) but was not detected within B cell clusters producing IgM only (adventitial sample 16a) or IgG and IgA (plaque sample 16c). Transcripts resulting from a clonal H chain class switch event were evidenced in the tunica adventitia of patient 9: A fully identical VH-DH-JH sequence was

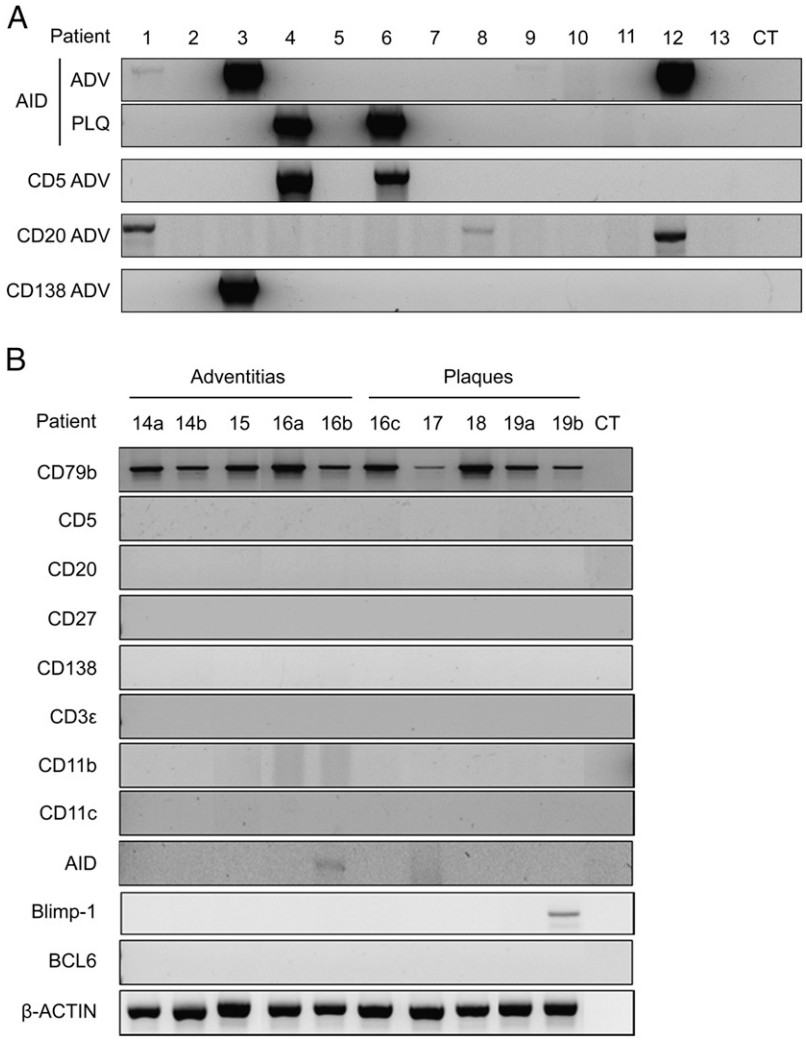

FIGURE 4. Markers of cellular differentiation in microdissected lymphoid cells. Nested RT-PCR (32 and 26 cycles) performed on total RNAs obtained from (**A**) whole adventitial (ADV) or plaque (PLQ) tissue extracts and (**B**) microdissected lymphoid cells, using specific primer pairs. Reactions resulting in undetectable amplification product were further amplified up to 50 cycles in the secondary rounds and remained negative (not shown). CT, Control reaction in the absence of RNA template.

associated either with a Cγ1 or with a Cγ2 region (Supplemental Fig. 4). In the same sample, two clonally related IgA1 mRNAs featured a common CDR 3 sequence resulting from a VH3-23-DH2-15-JH4 rearrangement whose formation has necessitated the incorporation of 13 nontemplate nucleotides and 2 mutations in the D region. However, they were representative of two divergent subclones having accumulated independent mutations in FRs and CDR 1 and 2 regions (23 differences leading to 13 aa replacements; Supplemental Fig. 4). Two different IgA1 transcripts from patients 4 and 9 shared the same nucleotide sequence in their VH3-23 portion, including seven identical mutations in CDR2 and a germline CDR1. Yet their CDR3 regions were dissimilar, using two different DH regions (Supplemental Fig. 4). Within L chain transcripts of different patients, it was also possible, in two cases, to identify common CDR3s either at the DNA or at the protein level (Supplemental Fig. 4). In both instances, the V genes that contributed the final CDR3 sequences were different.

In a limited number of patients, using oligonucleotides specific to individual CDR3 sequences as clonotypic identifiers, we could design RT-PCRs that allowed detection of the traffic of certain lymphocyte clones between adventitias and available draining lymph nodes (Fig. 5). We were able to reclone, from patient 6 lymph node RNAs, a number of VDJ cDNAs corresponding to the 06_59A and 06_60A prototypes already identified in adventitia. Whereas all the 06_59A related sequences remained fully identical, members of the 06_60A family presented signs of ongoing clonal maturation (Supplemental Fig. 4). Of note, the inserted Arg^{60} in somatically diversified 06_60A family sequences is specified by different codons that may indicate a strong selective pressure for the maintenance of this mutation. Using this approach, we also found that plaque and adventitia repertoires were essentially different (Fig. 5 and data not shown), thus confirming the observed difference in H chain isotype expression.

Most adventitial B lymphocytes are representative of late stages of differentiation and express proinflammatory cytokines

Immunohistochemical staining of RCL2-fixed arterial wall tissue sections by anti-CD3 and anti-CD20 Abs revealed 0.5–2% and $<$ 1% positive cells, respectively, in plaque samples and even lower percentages in adventitia, whereas no cell reacted with anti-CD138 in both arterial layers (data not shown). When compared with the pattern obtained on formalin-fixed tissues, anti-CD19 or anti-IgH staining of RCL2-treated specimens appeared rather inefficient, identifying only a small proportion of the potentially positive resident lymphocytes. In addition, for there was some uncertainty about arterial wall B lymphocyte surface CD marker detection by immunohistochemical techniques (11, 33, 34) and because anti-Ig reagent use could also identify non-B cells bearing Ig-loaded FcRs and was complicated by the widespread presence of Ig deposits, we decided to microdissect cells in lymphoid infiltrates by simply selecting them on the basis of morphological criteria. The LCM specimens (five adventitias and five plaques) corresponding to 100–2500 cell equivalents were surprisingly homogeneous in term of lineage marker expression: Samples all contained transcripts coding for Igs (Fig. 2) and the short isoform of CD79b, whereas CD3ε, CD11b, or CD11c mRNAs were under the threshold of detection in our reactions (Fig. 4). This finding indicated a predominance of B lymphocytes within the LCM samples because T and monocytic cell lineage markers (CD3ε and CD11b transcripts) could be detected in the arterial wall whole-tissue extracts (Supplemental Fig. 3). CD20 transcripts were not detected in the captured cells (Fig. 4) in accordance with the occasional CD20 mRNA expression in adventitial total extracts (3 of 13; Supplemental Fig. 3). Moreover, this finding was confirmed by immunohistochemistry experiments showing a very low percentage of lymphocytes reacting with the anti-CD20 Ab in the corresponding samples (not shown). However, CD20 mRNAs were expressed in the total extracts of 7 of 13 plaque specimens (Supplemental Fig. 3), indicating that some sampling could be linked to the LCM protocol (see *Discussion*). CD138 mRNAs were not found in LCM lymphocytes, a confirmatory result of data obtained on total arterial wall samples showing that expression of this molecule was infrequent in atherosclerotic lesions (Fig. 4, Supplemental Fig. 3). CD5 and CD27 transcripts were also absent from microdissected mononuclear cells (Fig. 4), whereas they were likely contributed by other cell types in total arterial extracts (Supplemental Fig. 3). Finally, B cell differentiation reciprocal and antagonistic transcription factors BCL6 (B-cell lymphoma 6) and Blimp-1 (B lymphocyte–induced maturation protein 1) were not expressed by LCM cells (with one exception for the latter). In summary, adventitial B cells mostly express switched IgH isotypes with a hypermutated V region, and their phenotype is compatible with their classification as plasmablasts.

Within the complex array of cytokine transcripts present in whole-tissue extracts (Supplemental Fig. 3), LCM of arterial wall lymphocytes allowed identification of a more restricted pattern of expression. Several adventitial and plaque LCM samples that featured B cell–related mRNAs also contained transcripts coding for the proinflammatory cytokines IL-6, GM-CSF, and TNF-α (Fig. 6). Conversely, IL-1β, IL-2, IL-4, IL-10, IL-12, IFN-γ, M-CSF, TGF-β, lymphotoxin A, and lymphotoxin B mRNAs were never detected within microdissected cells (Fig. 6 and data not shown).

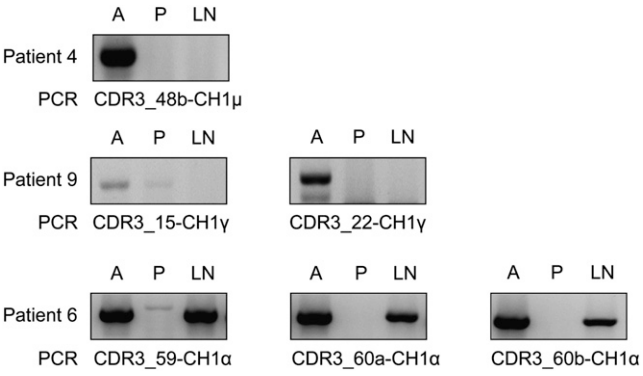

FIGURE 5. B lymphocyte traffic between adventitia and draining lymph nodes. Single-round RT-PCR (32 cycles) was performed on adventitia, plaque, and available autologous draining lymph node, using forward oligonucleotides specific to individual CDR3 sequences and reverse class-specific Cμ, Cγ, or Cα primers. A, Adventitia; LN, lymph node; P, plaque.

Discussion

In atherosclerosis, lymphocyte infiltration in the adventitia has been known for a long time (35, 36), but description of its B cell component is more recent (7–13). Adoptive transfer experiments showed that vascular wall B lymphocytes constitutively home within arterial regions prone to lesion development (6, 7, 15, 28), indicating a high degree of specialization. However, many properties of these resident B cells remain to be described. Herein, we addressed the question of local Ig production for all H chain classes. Of interest, IgA-producing lymphocytes are an integral feature of the local immune response and are predominant in adventitia, where they are frequently associated with IgG-expressing cells, whereas IgM-producing cells are often missing. Of note, elevated levels of serum IgA and C4 were independently associated with severe atherosclerosis (corresponding to the clinical status of

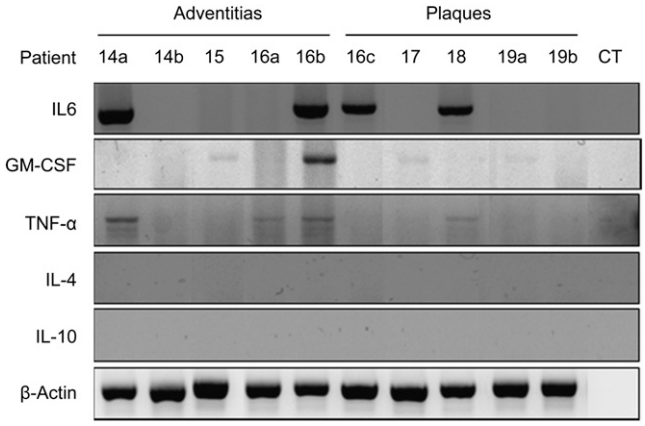

FIGURE 6. Arterial wall B lymphocytes preferentially express proinflammatory cytokines. Nested RT-PCR (32 and 26 cycles) performed on total RNAs obtained from LCM arterial wall lymphoid cells, using specific primer pairs. IL-4 and IL-10 PCRs are shown as representative negative results. CT, Control reaction in the absence of RNA template.

patients studied herein), in multivariate analysis during a retrospective study, whereas serum IgG and IgM were not (37). IgA is definitely the dominant isotype produced by mammalian organisms but is mainly found in mucosal tissues; its presence in the arterial wall is more surprising. Whether IgA achieves, in this peculiar location, immune protection while avoiding deleterious inflammation and local tissue damage, as it does in the gut, remains to be determined. Both IgA1 and IgA2 are produced in arterial walls, and distribution of $\alpha 1$ ($n = 10$) and $\alpha 2$ ($n = 2$) sequences in adventitia transcripts is close to that observed in blood, where IgA1 represents the major (90%) IgA subclass (38). Arterial wall resident immune response associates production of IgG1 (the prototypic isotype of immune responses to T-dependent protein Ags; Ref. 39) and IgG2 (the major isotype elicited by T-independent polysaccharide Ags). These IgG subclasses also differ by their cytophilic properties. B cell maturation toward production of IgG1, IgG2, or IgA each involves different cytokine microenvironments requiring IL-4, IFN-γ, and TGF-β, respectively, and genes encoding these cytokines were actively transcribed in the arterial walls under study (Supplemental Fig. 3).

IgG, IgA, and IgM have been found in protein eluates from human atherosclerotic lesions (40) and arterial wall Igs may by derived in part from local biosynthesis, as evidenced by metabolic labeling (41). By immunofluorescence, we have found deposits of the three main Ig classes mainly within arterial tunica media, whereas others studies in animal models have found Ig depositions with roughly the same localization (7) or in the acellular base of the lesion with a reciprocal relationship to $CD68^+$ macrophages (42). Other reports have demonstrated a higher Ig content within intimal plaque than in tunica media (40, 43). Besides technical issues related to the modes of Ig detection, variations in the anatomic localization of arterial specimens (abdominal aorta versus carotid), differences may also arise in relation to the evolutive stage of the disease because we observed, in a group of organ donors, that milder arterial lesions had less prominent Ig deposits in the media (not shown; M. Hamze, C. Desmetz, and P. Guglielmi, unpublished observations).

Diversity of Ig expression within the arterial wall has been evaluated only in humans but was differently appreciated. Walton et al. (10) found a polyclonal BCR repertoire in 24 of 25 cases of abdominal aneurysms. In contrast, Burioni et al. (44) demonstrated an oligoclonal expansion and evolution of local IgG1/κ-producing intimal lymphocytes, interpreted as signs of Ag-driven maturation. Interestingly, VH3-23 and VH3-73 were the most represented VH genes in 4 of the 6 intimal plaques examined in this latter study, but their CDR3 regions generated by the recombination process differed from those we found in adventitias. We show herein that low numbers of B cell clones populate the adventitial specimens. However, this conclusion needs to be balanced by taking in account the patchy nature of lymphocyte infiltration in arterial lesions. Moreover, because structure and inflammatory cell composition of the diseased arterial wall may differ according to anatomic location (15), extrapolation of results to a whole organism has to be made with caution. The question of clonality of resident T cells in atherosclerotic lesions has also been addressed, with contrasting results. Initial data pointed to a polyclonal origin for T cells in plaques (45, 46), but more recent studies demonstrated that resident T cells were locally activated by OxLDL and heat shock protein, using a restricted TCR repertoire (47, 48).

BCR sequence analysis indicated that only a minority of adventitial B cells used germline VDJ regions and could therefore be classified as innate-like B lymphocytes. Accordingly, LCM isolated B cells did not feature the CD5 and CD27 markers present, respectively, on B1a and human marginal zone cell subpopulations. By far, mutated VDJ sequences identified a great proportion of resident B cells as fully differentiated B2 lymphocytes expressing switched isotypes. However, many of these B cells were not yet committed toward a memory or plasma cell phenotype because they respectively lacked CD27 and BCL-6 or CD138 and Blimp-1 expression. The absence of CD20 expression by adventitial B cells producing inflammatory cytokines may allow their classification as plasmablasts or early plasma cells (49).

Evidence of local differentiation of B lymphocytes gathered by the current study includes recurrent preferential use of certain VH genes, clonal diversification by additional somatic mutations, similarities in CDR sequences between independent B cells, clonal H chain switch, and inversion of the λ/κ ratio of L chain use. AID that mediates somatic hypermutation and H chain class switch is, at first glance, inconstantly present in arterial wall samples. However, this enzyme is normally expressed during limited steps of B cell differentiation, and its detection in samples that are snapshots of long-lasting lesions indicates that it likely plays a role in the natural history of the disease. Taken together, our results suggest the existence of an adaptive selection, and it is tempting to speculate that resident adventitial B lymphocyte differentiation is an Ag-driven process. Indeed, preliminary experiments in our laboratory with genetically engineered reconstructed adventitial Abs indicate that they react with discrete components of arterial wall cell extracts. It is interesting that a reconstructed Ab fragment, originally produced in atherosclerotic plaque, was shown to react with human transgelin type 1 expressed by arterial fibrocyte-like cells, and to cross-react with outer membrane proteins of *Proteus mirabilis* and *Klebsiella pneumoniae* (50).

B cells traffic regionally between adventitia and cervical lymph nodes. Despite limitations due to the human model (only a restricted portion of the arterial wall and a single lymph node can be examined per patient) and the low number of lymphocytes under study, clonally related B cells were easily found in different anatomic locations. It remains to be determined if B cells expressing isotypes other than IgA also circulate and if vascular wall lymphocytes can home in more distant lymphoid organs. In an individual arterial lesion, both CH and VH region expression differed between plaque and adventitia, confirming the limited inflammatory cell traffic observed between these compartments in mouse atherosclerosis (15).

Animal models have shown that B lymphocytes affect atherosclerosis physiopathology by different mechanisms. Natural

anti-OxLDL IgM produced by B1a cells attenuate, whereas B2 cells (directly or indirectly) promote atherosclerosis (5, 6, 26). However, adventitial B lymphocytes of young mice may be also early responders to atherogenic signals, limiting macrophage accumulation in intimal plaque through local production of anti-inflammatory cytokines (28). Results herein were obtained in aged patients having advanced end-stage lesions and suggest a different adaptation of B lymphocytes to this different context. Human arterial wall B cells produce GM-CSF, which is known to be a regulator of lesional dendritic cell accumulation and differentiation (51). GM-CSF is one of the general determinants of macrophage polarization toward the proinflammatory M1 (classical inflammatory macrophage) phenotype (52, 53) and is also clearly associated with IL-17–producing Th17 cell pathogenicity (54). However, there is yet no unambiguous demonstration of an instrumental role for Th17 lymphocytes in atherosclerosis pathophysiology, and their involvement is still unclear. Resident B cells produce IL-6 and TNF-α. Elevated serum levels of these cytokines are generally found in patients having a poor prognosis or more severe arterial lesions (55, 56). Animal models designed to decipher the role of IL-6, TNF-α, and GM-CSF in atherosclerosis have not yet been fully conclusive because experimental settings (feeding diet, location of the lesions, and sex of the animals) largely determine the outcome of lesion evolution (57–64). In this study we show that IL-6, TNF-α, and GM-CSF production is inconstant but characteristic of resident B cells, whereas the lack of expression of the other tested cytokines is a permanent feature. Whether the observed differences also reflect discrete stages of arterial lesion evolution remains to be determined. Indeed, different cell types can synthesize these cytokines, but IL-6–producing B cells were recently demonstrated to be major contributors to the pathogenesis of well-known T cell–mediated autoimmune conditions (65). Finally, the pattern of cytokine production by resident B cells described in this article does not fit well with the classification of effector B (Be) lymphocytes (66) in Be1 B cells (producing the proinflammatory Th1 type cytokines IFN-γ, IL-2, and IL-12) and Be2 B cells (producing the Th2-type cytokines IL-4, IL-6, and IL-10). Rather, resident B lymphocytes have an activated phenotype close to the one observed after in vitro B cell combined stimulation of the CD40 and BCR pathways (67).

Data herein are indeed compatible with B cells being a major component of the adventitial lymphocyte population within the severe carotid lesions of many patients, in agreement with the observations indicating that B cell parietal infiltration increases with progression of atherosclerosis (11, 15). The tertiary lymphoid tissue that develops in chronically rejecting heart allografts are predominantly B cell in origin or have compartmentalized B/T areas (68). AID and switched isotypes are expressed in the lymphoid structures within those grafted hearts. B lymphocytes also formed a prominent part of the inflammatory cells in renal transplants (69) or kidney diseases (70). A fundamental pathogenic role for B cells was demonstrated in human diseases such as type 2 diabetes or periodontal disease (71) and in obesity-associated insulin resistance and glucose intolerance (72). Our results strongly suggest that B cells may be also important contributors to the physiopathology of human atherosclerosis.

Reduction of arterial lesion burden by anti-CD20 ablation of B lymphocytes in mouse atherosclerosis has raised the question of its possible use for disease management in humans. Our data indicate that resident B cells, producing potentially deleterious cytokines, may represent interesting therapeutic targets. Apart from technical detection threshold effects, the heterogeneity in CD20 expression between the different samples may be explained by 1) the presence of different B cell subpopulations in intimal plaque and tunica adventitia, 2) the lack of representativeness of a given specimen with regard to the total atherosclerosis burden of the corresponding patient, 3) the stages of evolution of the lesions, 4) the possible heterogeneity of atherosclerosis pathophysiology between patients, and 5) the combination of all these elements. Therefore, further understanding of B cell involvement in disease progression, based on the study of large groups of patients, is still necessary to efficiently use selective B cell ablative therapy in atherosclerosis.

Acknowledgments

We thank Nathalie Bros from the Biothèque du Centre Hospitalier Universitaire de Nîmes for excellent technical assistance, the Réseau d'Histologie Expérimentale de Montpellier histology facility for processing arterial tissues, Vicky Diakou from Montpellier RIO Imaging for expert assistance in imaging, and Hans Yssel for critical reading of this manuscipt.

Disclosures

The authors have no financial conflicts of interests.

References

1. Weber, C., A. Zernecke, and P. Libby. 2008. The multifaceted contributions of leukocyte subsets to atherosclerosis: lessons from mouse models. *Nat. Rev. Immunol.* 8: 802–815.
2. Smith, J. D., E. Trogan, M. Ginsberg, C. Grigaux, J. Tian, and M. Miyata. 1995. Decreased atherosclerosis in mice deficient in both macrophage colony-stimulating factor (op) and apolipoprotein E. *Proc. Natl. Acad. Sci. USA* 92: 8264–8268.
3. Hansson, G. K., and A. Hermansson. 2011. The immune system in atherosclerosis. *Nat. Immunol.* 12: 204–212.
4. Mallat, Z., A. Gojova, V. Brun, B. Esposito, N. Fournier, F. Cottrez, A. Tedgui, and H. Groux. 2003. Induction of a regulatory T cell type 1 response reduces the development of atherosclerosis in apolipoprotein E-knockout mice. *Circulation* 108: 1232–1237.
5. Ait-Oufella, H., O. Herbin, J.-D. Bouaziz, C. J. Binder, C. Uyttenhove, L. Laurans, S. Taleb, E. Van Vré, B. Esposito, J. Vilar, et al. 2010. B cell depletion reduces the development of atherosclerosis in mice. *J. Exp. Med.* 207: 1579–1587.
6. Kyaw, T., C. Tay, A. Khan, V. Dumouchel, A. Cao, K. To, M. Kehry, R. Dunn, A. Agrotis, P. Tipping, et al. 2010. Conventional B2 B cell depletion ameliorates whereas its adoptive transfer aggravates atherosclerosis. *J. Immunol.* 185: 4410–4419.
7. Galkina, E., A. Kadl, J. Sanders, D. Varughese, I. J. Sarembock, and K. Ley. 2006. Lymphocyte recruitment into the aortic wall before and during development of atherosclerosis is partially L-selectin dependent. *J. Exp. Med.* 203: 1273–1282.
8. Jonasson, L., J. Holm, O. Skalli, G. Bondjers, and G. K. Hansson. 1986. Regional accumulations of T cells, macrophages, and smooth muscle cells in the human atherosclerotic plaque. *Arteriosclerosis* 6: 131–138.
9. Munro, J. M., J. D. van der Walt, C. S. Munro, J. A. C. Chalmers, and E. L. Cox. 1987. An immunohistochemical analysis of human aortic fatty streaks. *Hum. Pathol.* 18: 375–380.
10. Walton, L. J., J. T. Powell, and D. V. Parums. 1997. Unrestricted usage of immunoglobulin heavy chain genes in B cells infiltrating the wall of atherosclerotic abdominal aortic aneurysms. *Atherosclerosis* 135: 65–71.
11. Houtkamp, M. A., O. J. de Boer, C. M. van der Loos, A. C. van der Wal, and A. E. Becker. 2001. Adventitial infiltrates associated with advanced atherosclerotic plaques: structural organization suggests generation of local humoral immune responses. *J. Pathol.* 193: 263–269.
12. Moos, M. P. W., N. John, R. Gräbner, S. Nossmann, B. Günther, R. Vollandt, C. D. Funk, B. Kaiser, and A. J. R. Habenicht. 2005. The lamina adventitia is the major site of immune cell accumulation in standard chow-fed apolipoprotein E-deficient mice. *Arterioscler. Thromb. Vasc. Biol.* 25: 2386–2391.
13. Watanabe, M., A. Sangawa, Y. Sasaki, M. Yamashita, M. Tanaka-Shintani, M. Shintaku, and Y. Ishikawa. 2007. Distribution of inflammatory cells in adventitia changed with advancing atherosclerosis of human coronary artery. *J. Atheroscler. Thromb.* 14: 325–331.
14. Aubry, M. C., D. L. Riehle, W. D. Edwards, H. Maradit-Kremers, V. L. Roger, T. J. Sebo, and S. E. Gabriel. 2004. B-Lymphocytes in plaque and adventitia of coronary arteries in two patients with rheumatoid arthritis and coronary atherosclerosis: preliminary observations. *Cardiovasc. Pathol.* 13: 233–236.
15. Gräbner, R., K. Lötzer, S. Döpping, M. Hildner, D. Radke, M. Beer, R. Spanbroek, B. Lippert, C. A. Reardon, G. S. Getz, et al. 2009. Lymphotoxin beta receptor signaling promotes tertiary lymphoid organogenesis in the aorta adventitia of aged ApoE-/- mice. *J. Exp. Med.* 206: 233–248.
16. Major, A. S., S. Fazio, and M. F. Linton. 2002. B-lymphocyte deficiency increases atherosclerosis in LDL receptor-null mice. *Arterioscler. Thromb. Vasc. Biol.* 22: 1892–1898.

17. Caligiuri, G., A. Nicoletti, B. Poirier, and G. K. Hansson. 2002. Protective immunity against atherosclerosis carried by B cells of hypercholesterolemic mice. *J. Clin. Invest.* 109: 745–753.
18. Binder, C. J., K. Hartvigsen, M. K. Chang, M. Miller, D. Broide, W. Palinski, L. K. Curtiss, M. Corr, and J. L. Witztum. 2004. IL-5 links adaptive and natural immunity specific for epitopes of oxidized LDL and protects from atherosclerosis. *J. Clin. Invest.* 114: 427–437.
19. Palinski, W., E. Miller, and J. L. Witztum. 1995. Immunization of low density lipoprotein (LDL) receptor-deficient rabbits with homologous malondialdehyde-modified LDL reduces atherogenesis. *Proc. Natl. Acad. Sci. USA* 92: 821–825.
20. Zhou, X. H., G. Caligiuri, A. Hamsten, A. K. Lefvert, and G. K. Hansson. 2001. LDL immunization induces T-cell-dependent antibody formation and protection against atherosclerosis. *Arterioscler. Thromb. Vasc. Biol.* 21: 108–114.
21. Palinski, W., R. K. Tangirala, E. Miller, S. G. Young, and J. L. Witztum. 1995. Increased autoantibody titers against epitopes of oxidized LDL in LDL receptor-deficient mice with increased atherosclerosis. *Arterioscler. Thromb. Vasc. Biol.* 15: 1569–1576.
22. Cyrus, T., D. Praticò, L. Zhao, J. L. Witztum, D. J. Rader, J. Rokach, G. A. FitzGerald, and C. D. Funk. 2001. Absence of 12/15-lipoxygenase expression decreases lipid peroxidation and atherogenesis in apolipoprotein e-deficient mice. *Circulation* 103: 2277–2282.
23. Tsimikas, S., W. Palinski, and J. L. Witztum. 2001. Circulating autoantibodies to oxidized LDL correlate with arterial accumulation and depletion of oxidized LDL in LDL receptor-deficient mice. *Arterioscler. Thromb. Vasc. Biol.* 21: 95–100.
24. Rossi, G. P., M. Cesari, R. De Toni, M. Zanchetta, G. Maiolino, L. Pedon, C. Ganzaroli, P. Maiolino, and A. C. Pessina. 2003. Antibodies to oxidized low-density lipoproteins and angiographically assessed coronary artery disease in white patients. *Circulation* 108: 2467–2472.
25. Tsimikas, S., E. S. Brilakis, R. J. Lennon, E. R. Miller, J. L. Witztum, J. P. McConnell, K. S. Kornman, and P. B. Berger. 2007. Relationship of IgG and IgM autoantibodies to oxidized low density lipoprotein with coronary artery disease and cardiovascular events. *J. Lipid Res.* 48: 425–433.
26. Kyaw, T., C. Tay, S. Krishnamurthi, P. Kanellakis, A. Agrotis, P. Tipping, A. Bobik, and B.-H. Toh. 2011. B1a B lymphocytes are atheroprotective by secreting natural IgM that increases IgM deposits and reduces necrotic cores in atherosclerotic lesions. *Circ. Res.* 109: 830–840.
27. Kyaw, T., P. Tipping, B.-H. Toh, and A. Bobik. 2011. Current understanding of the role of B cell subsets and intimal and adventitial B cells in atherosclerosis. *Curr. Opin. Lipidol.* 22: 373–379.
28. Doran, A. C., M. J. Lipinski, S. N. Oldham, J. C. Garmey, K. A. Campbell, M. D. Skaflen, A. Cutchins, D. J. Lee, D. K. Glover, K. A. Kelly, et al. 2012. B-cell aortic homing and atheroprotection depend on Id3. *Circ. Res*. 110: e1–12. doi: 10.1161.
29. Delfour, C., P. Roger, C. Bret, M. L. Berthe, P. Rochaix, N. Kalfa, P. Raynaud, F. Bibeau, T. Maudelonde, and N. Boulle. 2006. RCL2, a new fixative, preserves morphology and nucleic acid integrity in paraffin-embedded breast carcinoma and microdissected breast tumor cells. *J. Mol. Diagn.* 8: 157–169.
30. Masir, N., M. Ghoddoosi, S. Mansor, F. Abdul-Rahman, C. S. Florence, N. A. Mohamed-Ismail, M.-R. Tamby, and N. H. Md-Latar. 2012. RCL2, a potential formalin substitute for tissue fixation in routine pathological specimens. *Histopathology* 60: 804–815.
31. Lefranc, M.-P., V. Giudicelli, C. Ginestoux, J. Jabado-Michaloud, G. Folch, F. Bellahcene, Y. Wu, E. Gemrot, X. Brochet, J. Lane, et al. 2009. IMGT (R), the international ImMunoGeneTics information system (R). *Nucleic Acids Res*. 37: D1006–D10012. doi: 10.1093.
32. Glanville, J., W. Zhai, J. Berka, D. Telman, G. Huerta, G. R. Mehta, I. Ni, L. Mei, P. D. Sundar, G. M. R. Day, et al. 2009. Precise determination of the diversity of a combinatorial antibody library gives insight into the human immunoglobulin repertoire. *Proc. Natl. Acad. Sci. USA* 106: 20216–20221.
33. Zhou, X., and G. K. Hansson. 1999. Detection of B cells and proinflammatory cytokines in atherosclerotic plaques of hypercholesterolaemic apolipoprotein E knockout mice. *Scand. J. Immunol.* 50: 25–30.
34. Katsuda, S., H. C. Boyd, C. Fligner, R. Ross, and A. M. Gown. 1992. Human atherosclerosis. III. Immunocytochemical analysis of the cell composition of lesions of young adults. *Am. J. Pathol.* 140: 907–914.
35. Gerlis, L. M. 1956. The significance of adventitial infiltrations in coronary atherosclerosis. *Br. Heart J.* 18: 166–172.
36. Schwartz, C. J., and J. R. Mitchell. 1962. Cellular infiltration of the human arterial adventitia associated with atheromatous plaques. *Circulation* 26: 73–78.
37. Muscari, A., C. Bozzoli, C. Gerratana, F. Zaca', C. Rovinetti, D. Zauli, M. La Placa, and P. Puddu. 1988. Association of serum IgA and C4 with severe atherosclerosis. *Atherosclerosis* 74: 179–186.
38. Kett, K., P. Brandtzaeg, J. Radl, and J. J. Haaijman. 1986. Different subclass distribution of IgA-producing cells in human lymphoid organs and various secretory tissues. *J. Immunol.* 136: 3631–3635.
39. Stavnezer, J., and C. T. Amemiya. 2004. Evolution of isotype switching. *Semin. Immunol.* 16: 257–275.
40. Vlaicu, R., H. G. Rus, F. Niculescu, and A. Cristea. 1985. Immunoglobulins and complement components in human aortic atherosclerotic intima. *Atherosclerosis* 55: 35–50.
41. Hollander, W., M. A. Colombo, B. Kirkpatrick, and J. Paddock. 1979. Soluble proteins in the human atherosclerotic plaque. With spectral reference to immunoglobulins, C3-complement component, alpha 1-antitrypsin and alpha 2-macroglobulin. *Atherosclerosis* 34: 391–405.
42. Lewis, M. J., T. H. Malik, M. R. Ehrenstein, J. J. Boyle, M. Botto, and D. O. Haskard. 2009. Immunoglobulin M is required for protection against atherosclerosis in low-density lipoprotein receptor-deficient mice. *Circulation* 120: 417–426.
43. Ylä-Herttuala, S., W. Palinski, S. W. Butler, S. Picard, D. Steinberg, and J. L. Witztum. 1994. Rabbit and human atherosclerotic lesions contain IgG that recognizes epitopes of oxidized LDL. *Arterioscler. Thromb.* 14: 32–40.
44. Burioni, R., F. Canducci, D. Saita, M. Perotti, N. Mancini, D. De Marco, N. Clementi, A. Chieffo, M. Denaro, D. Cianflone, et al. 2009. Antigen-driven evolution of B lymphocytes in coronary atherosclerotic plaques. *J. Immunol.* 183: 2537–2544.
45. Stemme, S., L. Rymo, and G. K. Hansson. 1991. Polyclonal origin of T lymphocytes in human atherosclerotic plaques. *Lab. Invest.* 65: 654–660.
46. Swanson, S. J., A. Rosenzweig, J. G. Seidman, and P. Libby. 1994. Diversity of T-cell antigen receptor V beta gene utilization in advanced human atheroma. *Arterioscler. Thromb.* 14: 1210–1214.
47. Paulsson, G., X. H. Zhou, E. Törnquist, and G. K. Hansson. 2000. Oligoclonal T cell expansions in atherosclerotic lesions of apolipoprotein E-deficient mice. *Arterioscler. Thromb. Vasc. Biol.* 20: 10–17.
48. Rossmann, A., B. Henderson, B. Heidecker, R. Seiler, G. Fraedrich, M. Singh, W. Parson, M. Keller, B. Grubeck-Loebenstein, and G. Wick. 2008. T-cells from advanced atherosclerotic lesions recognize hHSP60 and have a restricted T-cell receptor repertoire. *Exp. Gerontol.* 43: 229–237.
49. Oracki, S. A., J. A. Walker, M. L. Hibbs, L. M. Corcoran, and D. M. Tarlinton. 2010. Plasma cell development and survival. *Immunol. Rev.* 237: 140–159.
50. Canducci, F., D. Saita, C. Foglieni, M.R. Piscopiello, R. Chiesa, A. Colombo, D. Cianflone, A. Maseri, M. Clementi, and R. Burioni. 2012. Cross-reacting antibacterial auto-antibodies are produced within coronary atherosclerotic plaques of acute coronary syndrome patients. *PLoS One* 7: e42283. doi: 10.1371.
51. Zhu, S.-N., M. Chen, J. Jongstra-Bilen, and M. I. Cybulsky. 2009. GM-CSF regulates intimal cell proliferation in nascent atherosclerotic lesions. *J. Exp. Med.* 206: 2141–2149.
52. Mantovani, A., A. Sica, and M. Locati. 2007. New vistas on macrophage differentiation and activation. *Eur. J. Immunol.* 37: 14–16.
53. Brochériou, I., S. Maouche, H. Durand, V. Braunersreuther, G. Le Naour, A. Gratchev, F. Koskas, F. Mach, J. Kzhyshkowska, and E. Ninio. 2011. Antagonistic regulation of macrophage phenotype by M-CSF and GM-CSF: implication in atherosclerosis. *Atherosclerosis* 214: 316–324.
54. Peters, A., Y. Lee, and V. K. Kuchroo. 2011. The many faces of Th17 cells. *Curr. Opin. Immunol.* 23: 702–706.
55. Harris, T. B., L. Ferrucci, R. P. Tracy, M. C. Corti, S. Wacholder, W. H. Ettinger, Jr., H. Heimovitz, H. J. Cohen, and R. Wallace. 1999. Associations of elevated interleukin-6 and C-reactive protein levels with mortality in the elderly. *Am. J. Med.* 106: 506–512.
56. Skoog, T., W. Dichtl, S. Boquist, C. Skoglund-Andersson, F. Karpe, R. Tang, M. G. Bond, U. de Faire, J. Nilsson, P. Eriksson, and A. Hamsten. 2002. Plasma tumour necrosis factor-alpha and early carotid atherosclerosis in healthy middle-aged men. *Eur. Heart J.* 23: 376–383.
57. Huber, S. A., P. Sakkinen, D. Conze, N. Hardin, and R. Tracy. 1999. Interleukin-6 exacerbates early atherosclerosis in mice. *Arterioscler. Thromb. Vasc. Biol.* 19: 2364–2367.
58. Schieffer, B., T. Selle, A. Hilfiker, D. Hilfiker-Kleiner, K. Grote, U. J. F. Tietge, C. Trautwein, M. Luchtefeld, C. Schmittkamp, S. Heeneman, et al. 2004. Impact of interleukin-6 on plaque development and morphology in experimental atherosclerosis. *Circulation* 110: 3493–3500.
59. Ohta, H., H. Wada, T. Niwa, H. Kirii, N. Iwamoto, H. Fujii, K. Saito, K. Sekikawa, and M. Seishima. 2005. Disruption of tumor necrosis factor-alpha gene diminishes the development of atherosclerosis in ApoE-deficient mice. *Atherosclerosis* 180: 11–17.
60. Schreyer, S. A., C. M. Vick, and R. C. LeBoeuf. 2002. Loss of lymphotoxin-alpha but not tumor necrosis factor-alpha reduces atherosclerosis in mice. *J. Biol. Chem.* 277: 12364–12368.
61. Schreyer, S. A., J. J. Peschon, and R. C. LeBoeuf. 1996. Accelerated atherosclerosis in mice lacking tumor necrosis factor receptor p55. *J. Biol. Chem.* 271: 26174–26178.
62. Shaposhnik, Z., X. Wang, M. Weinstein, B. J. Bennett, and A. J. Lusis. 2007. Granulocyte macrophage colony-stimulating factor regulates dendritic cell content of atherosclerotic lesions. *Arterioscler. Thromb. Vasc. Biol.* 27: 621–627.
63. Ditiatkovski, M., B.-H. Toh, and A. Bobik. 2006. GM-CSF deficiency reduces macrophage PPAR-gamma expression and aggravates atherosclerosis in ApoE-deficient mice. *Arterioscler. Thromb. Vasc. Biol.* 26: 2337–2344.
64. Haghighat, A., D. Weiss, M. K. Whalin, D. P. Cowan, and W. R. Taylor. 2007. Granulocyte colony-stimulating factor and granulocyte macrophage colony-stimulating factor exacerbate atherosclerosis in apolipoprotein E-deficient mice. *Circulation* 115: 2049–2054.
65. Barr, T. A., P. Shen, S. Brown, V. Lampropoulou, T. Roch, S. Lawrie, B. Fan, R. A. O'Connor, S. M. Anderton, A. Bar-Or, et al. 2012. B cell depletion therapy ameliorates autoimmune disease through ablation of IL-6-producing B cells. *J. Exp. Med.* 209: 1001–1010.
66. Harris, D. P., L. Haynes, P. C. Sayles, D. K. Duso, S. M. Eaton, N. M. Lepak, L. L. Johnson, S. L. Swain, and F. E. Lund. 2000. Reciprocal regulation of polarized cytokine production by effector B and T cells. *Nat. Immunol.* 1: 475–482.
67. Burdin, N., C. Van Kooten, L. Galibert, J. S. Abrams, J. Wijdenes, J. Banchereau, and F. Rousset. 1995. Endogenous IL-6 and IL-10 contribute to the differentiation of CD40-activated human B lymphocytes. *J. Immunol.* 154: 2533–2544.
68. Motallebzadeh, R., S. Rehakova, T. M. Conlon, T. S. Win, C. J. Callaghan, M. Goddard, E. M. Bolton, N. H. Ruddle, J. A. Bradley, and G. J. Pettigrew. 2012. Blocking lymphotoxin signaling abrogates the development of ectopic lymphoid tissue within cardiac allografts and inhibits effector antibody responses. *FASEB J.* 26: 51–62.

69. Segerer, S., and D. Schlöndorff. 2008. B cells and tertiary lymphoid organs in renal inflammation. *Kidney Int.* 73: 533–537.
70. Heller, F., M. T. Lindenmeyer, C. D. Cohen, U. Brandt, D. Draganovici, M. Fischereder, M. Kretzler, H.-J. Anders, T. Sitter, I. Mosberger, et al. 2007. The contribution of B cells to renal interstitial inflammation. *Am. J. Pathol.* 170: 457–468.
71. Nikolajczyk, B. S. 2010. B cells as under-appreciated mediators of non-autoimmune inflammatory disease. *Cytokine* 50: 234–242.
72. Winer, D. A., S. Winer, L. Shen, P. P. Wadia, J. Yantha, G. Paltser, H. Tsui, P. Wu, M. G. Davidson, M. N. Alonso, et al. 2011. B cells promote insulin resistance through modulation of T cells and production of pathogenic IgG antibodies. *Nat. Med.* 17: 610–617.