Resistin-Like Molecule β Is Abundantly Expressed in Foam Cells and Is Involved in Atherosclerosis Development


Objective—Resistin-like molecule (RELM) β is a secretory protein homologous to resistin and reportedly contributes to local immune response regulation in gut and bronchial epithelial cells. However, we found that activated macrophages also express RELMβ and thus investigated the role of RELMβ in the development of atherosclerosis.

Approach and Results—It was demonstrated that foam cells in atherosclerotic lesions of the human coronary artery abundantly express RELMβ. RELMβ knockout (−/−) and wild-type mice were mated with apolipoprotein E–deficient background mice. RELMβ−/+ apolipoprotein E–deficient mice exhibited less lipid accumulation in the aortic root and wall than RELMβ+/- apolipoprotein E–deficient mice, without significant changes in serum lipid parameters. In vitro, RELMβ−/+ primary cultured peritoneal macrophages (PCPMs) exhibited weaker lipopolysaccharide-induced nuclear factor-kB classical pathway activation and inflammatory cytokine secretion than RELMβ+/-, whereas stimulation with RELMβ upregulated inflammatory cytokine expressions and increased expressions of many lipid transporters and scavenger receptors in PCPMs. Flow cytometric analysis revealed inflammatory stimulation–induced RELMβ in F4/80(+)/CD11c(+) PCPMs. In contrast, the expressions of CD11c and tumor necrosis factor were lower in RELMβ−/- PCPMs, but both were restored by stimulation with recombinant RELMβ.

Conclusions—RELMβ is abundantly expressed in foam cells within plaques and contributes to atherosclerosis development via lipid accumulation and inflammatory facilitation. (Arterioscler Thromb Vasc Biol. 2013;33:1986-1993.)

Key Words: atherosclerosis ■ inflammation ■ macrophage

Resistin was initially identified as an adipocyte-secreted factor that causes insulin resistance.1 Subsequent studies have suggested its association with type 2 diabetes mellitus,2 congestive heart failure,3 and coronary artery disease.4,5 After the discovery of resistin, 3 resistin-related proteins, termed resistin-like molecule (RELM) α, β (found in inflammatory zone 2, murine ten-cysteine protein 3, human ten-cysteine protein 2), and γ were identified in mice. These resistin family proteins share a cysteine-rich domain at their N terminus (Cxx11Cxx8CxxCxx2Cxx10CxxCxxCxx9CC), and the roles of RELMα, RELMβ, and RELMγ have been extensively studied.6–10 Unlike the situation in mice, resistin and RELMβ, but not RELMα and RELMγ, are present in humans.9,11

To date, expression of RELMβ has been reported to be limited to the gut or bronchi.12,13 RELMβ expression in the colon was reportedly induced by a high-fat diet,14 and RELMβ expression in the human colonic cell line LS174T was upregulated by saturated free fatty acid (SFA) or tumor necrosis factor-α (TNFα) stimulation.13 Thus, RELMβ seems to contribute to local immune system function in the gut by acting against bacteria and nematodes,7,12,14 and probably reflecting this function, RELMβ absence reportedly influences the microbiome composition.15 It was also documented that RELMβ augments interferon-γ–induced TNFα secretion in thioglycollate-isolated macrophages and infection-induced intestinal inflammation.16

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In terms of insulin resistance, the function of RELMβ might be similar to that of resistin. Peripheral infusion of RELMβ impaired insulin action in the liver. Transgenic mice expressing RELMβ in the liver reportedly exhibited insulin resistance with hyperinsulinemia, hyperglycemia, hyperlipidemia, and fatty liver when consuming a high-fat diet. Furthermore, glucose absorption in the intestinal tract was suggested to involve RELMβ. Based on these previous reports, we attempted to clarify the association of RELMβ expression levels in the intestinal tract with the pathophysiology of chronic inflammation in humans. During this investigation, unexpectedly, we found that considerable percentages of macrophages in gut connective tissue stained for the anti-RELMβ antibody, although staining intensities differed among individuals.

This finding led to the speculation that macrophages might possess the potential to express RELMβ when exposed to certain stimuli or conditions and raised the possibility that RELMβ contributes to atherosclerosis development. Herein, we present the first evidence showing the critical role of RELMβ in the development of atherosclerosis using human atherosclerotic coronary arteries and RELMβ knockout (−/−) mice, as well as in vitro data, suggesting possible molecular mechanisms underlying the processes of atherosclerosis induction.

**Materials and Methods**

Materials and Methods are available in the online-only Supplement.

**Results**

**Expression of RELMβ in Atherosclerotic Lesions**

The monoclonal antibodies against human RELMβ were generated by immunizing mice with amino acids 14 to 66 of RELMβ fused with glutathione S-transferase (Figure I in the online-only Data Supplement). As reported previously, epithelial cells, particularly goblet cells, were strongly stained in the intestine (Figure IIA in the online-only Data Supplement). However, some macrophages in the villi of the intestine contained considerable amounts of RELMβ (Figure IIB in the online-only Data Supplement).

Because foam cells in unstable plaques in the aorta would be derived from highly activated macrophages via many factors, an immunohistochemical analysis using 3A-6 anti-human RELMβ monoclonal antibody was performed on 10 autopsied human coronary arteries from subjects who had died of acute myocardial infarction (Figure 1). RELMβ was abundantly expressed in macrophages in atherosclerotic lesions of all 10 samples, without exception, and representative staining is shown in Figure 1A. The enlarged picture (Figure 1B) revealed RELMβ staining to be dot-like in the cytoplasm, likely reflecting the presence of RELMβ in secretory vesicles. The staining with anti-CD68 and anti-RELMβ antibodies was performed for tissues of atherosclerotic lesions, as well as tissues outside the aorta, using adjacent slides (Figure 1C). It was shown that enlarged macrophages in plaques are both CD68 and RELMβ positive, whereas RELMβ was not detected in the small CD68-positive cells in normal fat tissue around the artery (Figure 1C). In plaques, double staining by anti-CD68 (green) and anti-RELMβ (red) antibodies confirmed the RELMβ-expressing cells to be macrophages (Figure 1D).

**RELMβ+/− ApoE−/− Mice Showed Amelioration of Atherosclerotic Change Without Changes in Serum Lipid Profiles Compared With RELMβ+/− ApoE−/− Mice**

We generated RELMβ+/− mice with exon 2 to 4 deletions of the RELMβ gene using gene targeting technology (Figure III in the online-only Data Supplement). Then, we prepared RELMβ+/− mice with the C57BL6 background using marker-assisted breeding and examined the expressions of RELMβ in the colons of RELMβ+/+, +/-, and −/− mice. RELMβ expression in RELMβ+/− was very low under specific pathogen-free conditions but markedly increased under conventional conditions, whereas none was detected in RELMβ−/− mice under either condition. The colonic expression level in RELMβ+/− mice was significantly lower than that in RELMβ+/− mice, but was still readily detectable (Figure IVA in the online-only Data Supplement). However, PCPMs collected from RELMβ+/− expressed RELMβ abundantly when incubated with watanabe heritable hyperlipidemic (WHHL) rabbit serum but at a very low level when incubated with normal rabbit serum (Figure IVB in the online-only Data Supplement). The induction of RELMβ expression by WHHL rabbit serum was not detected by Western blotting of PCPMs from RELMβ+/− mice, similar to the results from RELMβ−/− mice, although the reason was unclear.

Then, RELMβ+/− mice were crossed with apolipoprotein E-deficient (ApoE−/−) mice to generate RELMβ+/− with the apoE−/− background. RELMβ+/−, +/−, +/+ with ApoE−/− background mice grew up without significant body weight gain. RELMβ was detected in atherosclerotic macrophages in the aortic roots of RELMβ+/− ApoE−/− mice by immunostaining, whereas those of RELMβ−/− ApoE−/− mice were unstained (Figure IVC and IVD in the online-only Data Supplement). There were no significant differences in lipid profiles (Figure IVE in the online-only Data Supplement) among the 3 RELMβ genotypes.

These mice were subjected to investigation of lipid accumulations in the aortic root (Figure 2A and 2C) at the ages of 3 and 6 months. Oil Red O staining of the aortic roots from RELMβ+/− mice with the ApoE−/− background showed significantly reduced lipid accumulation compared with their littermates. The area immunohistochemically stained with anti-macrophage antibodies in the aortic roots from 6-month-old RELMβ+/− ApoE−/− mice was also significantly reduced compared with their littermates. The change started from 3 months of age and was significant at 6 months.

Subsequently, the atherosclerotic lesions in the aortas of 12-month-old mice were subjected to Oil Red O staining (Figure 2B, 2D, and 2E). Quantification analysis revealed the ratios of areas with fat deposition to whole aortic wall areas to be significantly lower in RELMβ+/− ApoE−/− or RELMβ+/− ApoE−/− mice than in RELMβ+/− ApoE−/− mice (Figure 2D). The numbers of these areas in whole aortic areas were also lower in RELMβ+/− ApoE−/− mice (Figure 2E). RELMβ+/− ApoE−/− mice showed a significant reduction in the Oil Red O–stained area compared with RELMβ+/− ApoE−/− mice, but the reduction in the number of areas was not significant.

Furthermore, by crossing with low-density lipoprotein receptor (LDLR)−/− mice, RELMβ+/−, +/−, and +/+ mice with the LDLR−/− background were generated. These mice were fed...
It was demonstrated that RELM$\beta^{-/-}$ LDLR$^{-/-}$ mice showed marked amelioration of atherosclerotic lesions compared with RELM$\beta^{+/+}$ LDLR$^{-/-}$ mice, which is similar to that of ApoE$^{-/-}$ mice (Figure 2F).

RELM$\beta$ Promotes Macrophage Foam Cell Formation

The in vitro effect of RELM$\beta$ expression on macrophage foam cell formation was investigated (Figure 3A and 3B). PCPMs were obtained from RELM$\beta^{-/-}$ mice and their littermates 2 days after peritoneal injection of thioglycholate (TGC) and treated with 50$\mu$g/mL oxidized LDL, 50$\mu$g/mL VLDL, or 1% sera from 3-month-old WHHL rabbits. Incubation with oxidized LDL, VLDL, or WHHL rabbit serum induced significant lipid accumulation in PCPMs, and quantification of cellular lipids was performed by staining with AdipoRed assay reagent and adjusted for cell counts. RELM$\beta^{-/-}$ macrophages accumulated significantly smaller amount of lipids than RELM$\beta^{+/+}$ macrophages (Figure 3B*). In contrast, administration of 2$\mu$g/mL recombinant RELM$\beta$ increased lipid accumulation in RELM$\beta^{-/-}$ PCPMs (Figure 3B†), which was blocked by coincubation with 50$\mu$g/mL anti-RELM$\beta$ F(ab')2 antibody (Figure 3B#).

Next, 1,1-dioctadecyl-3,3,3,3-tetramethylindocarbocyanine (Dil)-acyl LDL uptake for 4 hours was assayed and then adjusted by cell numbers (Figure 3C). 1,1-dioctadecyl-3,3,3,3-tetramethylindocarbocyanine (Dil)-acyl LDL uptake into RELM$\beta^{-/-}$ PCPMs was significantly lower than that into RELM$\beta^{+/+}$ PCPMs. Similarly, [3H]-cholesterol efflux by high-density lipoprotein uptake was slightly but significantly decreased by RELM$\beta$ deficiency (Figure 3D).

Alterations in the expressions of lipoprotein receptors, scavenger receptors (SRs), and lipid transporters were investigated (Figure 3E). Absence of RELM$\beta$ significantly reduced protein levels of SR-A1 and VLDL receptor. SR-A2 and Lox-1 mRNA levels in the RELM$\beta^{+/+}$ PCPMs were markedly elevated by stimulation with lipopolysaccharide (LPS), and the degree of LPS-induced increase was markedly attenuated in RELM$\beta^{-/-}$ PCPMs. Similarly, [3H]-cholesterol efflux by high-density lipoprotein uptake was decreased but significantly decreased by RELM$\beta$ deficiency (Figure 3D).
PCPMs. The effects of recombinant RELMβ stimulation of the J774.1 cell line were generally similar to the data obtained for RELMβ−/− PCPMs compared with RELMβ−/− PCPMs, with some exceptions for CD36, LDLR, and SRB1 (Figure V in the online-only Data Supplement).

**RELΜβ Enhances the Expressions of Inflammatory Cytokines and the Nuclear Factor-κB Pathway With LPS Stimulation in Macrophages**

To reveal the proinflammatory effects of RELMβ on macrophages, LPS-induced mRNA expressions of inflammatory cytokines in PCPMs from RELMβ+/+ mice and their littermates 2 days after TGC peritoneal injection were examined by quantitative polymerase chain reaction (Figure 4A). The inductions of TNFα, interleukin (IL)-1β, and IL-6 by incubation with 10 ng/mL LPS for 4 hours were very high in PCPMs from RELMβ+/+ mice, and these inductions were significantly blunted in the absence of RELMβ. In addition, inductions of inflammatory cytokine secretions by recombinant human RELMβ (hRELMβ) administration were investigated in phorbol 12-myristate 13-acetate–differenitated human cell lines THP-1 and U-937 (Figure VIA and VIB in the online-only Data Supplement). Supernatants from THP-1 or U-937 cell culture treated with 3 g/mL hRELMβ or human resistin for 24 hours were collected, and concentrations of TNFα, IL-1β, and IL-6 were determined using a Bioplex kit. hRELMβ markedly increased the secretions of TNFα, IL-1β, and IL-6. In contrast, resistin had no effects on these cytokine secretions.

Next, LPS-induced nuclear factor (NF)-κB activation was investigated. After stimulation with 100 ng/mL LPS, time-dependent changes in the protein expressions and phosphorylation levels of NF-κB and IκB kinase-α/β were compared between the PCPMs from RELMβ+/+ mice and their littermates (Figure 4B). Degradation of IκB by 100 nM LPS in the presence of cycloheximide was also investigated. Although protein expression levels of NF-κB and IκB kinase-α/β did not differ between PCPMs from RELMβ+/+ mice and their littermates, phosphorylation levels of NF-κB and IκB kinase-α/β were significantly lower in the RELMβ−/− than in the RELMβ+/+.
PCPMs. IκB degradation by LPS stimulation was also restored in the absence of RELMβ at 60 minutes in the presence of cycloheximide, thus IκB degradation by LPS was delayed in RELMβ−/− macrophages. These data suggest that RELMβ exerts an enhancing effect on LPS-induced NF-κB activation.

RELMβ Is Expressed in CD11c-Positive Cells, and the Absence of RELMβ Blunted the Inflammatory Response

Peritoneal macrophages from RELMβ+/+ and RELMβ−/− mice were collected from RPMI1640 medium 2 days after addition of PBS, 10% proteose peptone, or 3% TGC injection. Cells were stained with F4/80, CD11c, CD206, and RELMβ and then analyzed by flow cytometry (Figure VIIA and VIIB in the online-only Data Supplement). RELMβ (+) cells were mostly F4/80(+) CD11c (+). In both F4/80 (+) CD11c (+) cells and a small population of F4/80 (+) CD206 (+) cells, RELMβ-positive cells were inducible when stimulated with pepton or TGC to induce aseptic inflammation in the peritoneum. Absence of RELMβ significantly reduced the CD11c (+) cells, as well as CD206 (+) cells, induced by pepton/TGC (Figure VIIB in the online-only Data Supplement).

Next, we investigated whether extracellular administration of RELMβ affects the M1/M2 markers of PCPMs and whether extracellular administration of neutralizing antibody can block the effects of RELMβ on M1/M2 markers. The peritoneal macrophages from RELMβ+/, +/−, and −/− mice were collected after stimulation with or without TGC injection, and the PCPMs obtained were incubated with 100 ng/mL LPS for 4 hours. TGC treatment markedly increased expressions of CD11c, TNFα, and CD206 in RELMβ−/− macrophages, whereas IL-10 decreased the expressions of these macrophages (Figure VIII* in the online-only Data Supplement). The effects of TGC on CD11c, TNFα, CD206, and IL-10 were significantly suppressed in RELMβ-positive cells when stimulated with pepton or TGC to induce aseptic inflammation in the peritoneum. Absence of RELMβ significantly reduced the CD11c (+) cells, as well as CD206 (+) cells, induced by pepton/TGC (Figure VIIB in the online-only Data Supplement).
the RELMβ−/− macrophages (Figure VIII† in the online-only Data Supplement), whereas RELMβ administration to these macrophages partially restored the effects of TGC (Figure VIII‡ in the online-only Data Supplement). Furthermore, the effects of endogenous RELMβ expression or extracellular administration of RELMβ were blocked by coincubation with anti-RELMβ F(ab′)2 antibody (Figure VIII# in the online-only Data Supplement).

RELMβ Is Upregulated by Stimulation With Saturated Fatty Acids in Human Macrophage Cell Lines

The regulation of RELMβ expression in the human macrophage cell lines THP-1 and U-937 was investigated using real-time polymerase chain reaction. RELMβ expression levels in these cell lines were very low under basal conditions but showed marked induction when incubated with 0.2 mmol/L SFA, such as stearic and palmitic acids, for 16 hours. Unsaturated fatty acids were less effective for RELMβ induction. In contrast, resistin expression levels were not altered by either SFA (Figure IXA and IXB in the online-only Data Supplement). In addition, the degrees of SFA-induced TNFα and IL-6 expressions were significantly lower in RELMβ−/− than in RELMβ+/+ PCPMs (Figure IXC in the online-only Data Supplement).

Discussion

RELMβ expression was formerly thought to be limited to epidermal, particularly goblet, cells of the small and large intestines and bronchial tracts.9,12 In these tissues, RELMβ reportedly contributes to protection against infections with parasitic worms or bacteria and also functions to maintain barrier integrity.14,20 In agreement with such functions, RELMβ expression in the gut is reportedly induced on exposure to a conventional environment after being in a germ-free environment.21 Furthermore, RELMβ has been suggested to be involved in a variety of human inflammatory gastrointestinal conditions, including allergic gastroenteropathies,20 airway remodeling,22 and pulmonary hypertension.23

In contrast to the aforementioned reports, the first surprising finding of this study was the high expression of RELMβ in the foam cells of atherosclerotic lesions, which was demonstrated in both human autopsy samples and the aortas of ApoE−/− and LDLR−/− mice. RELMβ detection in atherosclerotic lesions was limited to the large, foam cell macrophages in plaques, with none being found in the small CD68-positive macrophages scattered in the surrounding normal adipose tissue. In this study, it was shown that very LDL-rich WHHL serum in murine PCPMs and SFA in human macrophage cell lines markedly upregulated the expression of RELMβ. Thus, in contrast to the continuous expression of resistin in macrophages, RELMβ expression in macrophages is likely to be induced by certain stimulants, such as specific pathological states.

To examine the contribution of RELMβ to the pathogenesis of atherosclerosis, we generated RELMβ−/− mice with the ApoE−/− or LDLR−/− background. Indeed, these mice showed significantly less lipid accumulation in the aortic root and aortic wall than RELMβ+/+ with ApoE−/− or LDLR−/− mice. Absence of RELMβ does not result in significant changes in serum lipid profiles, which indicates that macrophage-derived RELMβ directly contributes to lipid accumulation in macrophages and the development of atherosclerosis.

It is well known that atherosclerosis develops through multiple processes, among which foam cell formation is a key event, because it leads to the secretion of inflammatory cytokines24 and plaque instability.25 It was revealed in vitro that
RELMβ induced macrophages to induce NF-κB signaling and express inflammatory cytokines, lipid uptake, and also promoted their transformation into foam cells. NF-κB signaling is reportedly involved in not only inflammatory responses but also foam cell formation.

In this study, it was demonstrated that RELMβ induces the transformation of macrophages into foam cells. Furthermore, cellular mechanisms lead to foam cell transformations, such as lipid uptake, metabolism, efflux, and, governed by their respective SRs, expressions of lipases, hydroxylase, and ATP binding cassette transporters. It was previously documented that intraperitoneal injection of RELMβ enlarged murine peritoneal macrophages. We speculated that lipid accumulation would be the explanation for this observation and then demonstrated that RELMβ−/− PCPs accumulated smaller amounts of lipid when incubated with various lipoproteins. In the lipid uptake assay, RELMβ−/− showed diminished lipoprotein uptake, but lipid efflux was also diminished by RELMβ deficiency. Extracellular recombinant RELMβ administration to RELMβ−/− PCPs and J774.1 cells results in expression changes of SRs and lipid transporters, such as lipoprotein receptors (LDLR, VLDL receptor) and class A (SR-A1) and B (CD36) SRs. Class A is a group of receptors for oxidized LDL and acLDL. Cholesterol efflux and high-density lipoprotein–dependent lipid transporters (SR-B1, ATP binding cassette A1) were downregulated in RELMβ−/− macrophages, whereas lipid uptake, especially of modified LDL and VLDL, was phenotypically predominant.

RELMβ activates the classical M1 macrophage marker CD11c and inflammatory cytokines, and absence of RELMβ reduces inducible CD11c-positive and CD206-positive cells. In contrast, major portion of inflammation-induced CD11c− or CD206-positive cells are RELMβ positive. CD11c-positive cells are reportedly important for foam cell formation and constitute a major cell population in atherosclerotic plaque. RELMβ is essential for the induction of CD11c-positive cells, and a direct effect was demonstrated by administration of RELMβ. The number of CD206-positive macrophages is paradoxically increased by peritoneal TGC injection, although IL-10, an anti-inflammatory cytokine, is decreased. The latter effect is partially reversed by neutralization of extracellular RELMβ.

CD206-positive, alternatively activated M2 macrophages are generally anti-inflammatory, but also have a role in foam cell formation. Induction of CD206-positive cells is speculated to provide a degree of compensation but is not sufficient to overcome the inflammatory phenotype, and RELMβ in CD206-positive cells suggests inhibition of IL-10 expression.

Taking into consideration that macrophages themselves produce RELMβ and that serum RELMβ (on the order of several nanograms per milliliter in mice) concentrations would not reach those necessary to function in macrophages, it is possible that RELMβ produced by foam cells functions in macrophages in either a paracrine or an autocrine manner. We demonstrated that extracellular RELMβ can induce inflammation, lipid accumulation, and gene regulations by recombinant RELMβ administration and neutralization of inflammation by its blocking antibody.

Our results strongly suggest that RELMβ, which is abundantly expressed in the foam cells of atherosclerotic lesions, functions in both autocrine and paracrine manners in M1/M2 macrophages, endothelial cells, and fibroblasts (data not shown), thereby contributing to atherosclerosis development and plaque instability (Figure X in the online-only Data Supplement). Thus, an agent suppressing RELMβ expression or an antagonist of the as yet unidentified receptor might be used to prevent or treat atherosclerosis. In addition, serum RELMβ concentrations might serve as a marker for judging the degree of atherosclerosis. Further study, particularly for identification of the RELMβ receptor and to assess the value of measuring the serum RELMβ concentration, is needed.

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A. Kushiyama designed the research, performed experiments, and wrote the article; N. Oue, Y. Nakatsu, H. Ono, T. Fukushima, H. Kamata, T. Kikuchi, M. Fujishiro, K. Nishiyama, H. Aburatani, S. Kushiyama, M. Izuika, N. Taki, J. Encinas, K. Sentani, N. Ogomuki, A. Ogura, and W. Yasui performed experiments; H. Sakoda, F. Nishimura, S. Kawazu, H. Katagiri, Y. Higashi, and H. Kurihara designed the research; and T. Asano designed the research and wrote the article. We thank Masako Fujita, Yuriko Muta, and Hirokazu Sato for technical assistance.

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Disclosures

None.

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**Significance**

This study demonstrated, for the first time, the expression and involvement of resistin-like molecule (RELM) beta derived from macrophages in atherosclerotic lesions in both human tissues and mice. Deficiency of RELMbeta expression reduces the size of lesions composed of macrophages and lipid accumulation in atherosclerotic model mice, without altering serum lipid profiles. RELMbeta directly induces lipid cycling and results in foam cell formation. Furthermore, RELMbeta is expressed only in activated inflammatory macrophages and activates both classical and alternative pathways. The lipopolysaccharide effect on inflammatory cytokine expression is enhanced by RELMbeta, and it is suggested that the presence of RELMbeta promotes the nuclear factor-kappaB pathway. Interventions aimed at preventing the effects of RELMbeta might be the key to inhibiting atherosclerosis development.
Resistin-Like Molecule β Is Abundantly Expressed in Foam Cells and Is Involved in Atherosclerosis Development

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SUPPLEMENTAL MATERIALS

Resistin like molecule β is abundantly expressed in foam cells and is involved in atherosclerosis development

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Alignment of amino acid sequences for human RELMβ and resistin, and peptides for generating monoclonal antibodies against human RELMβ. Balb/c mice were immunized with amino acids 14-66 of RELMβ fused with GST. Among the isolated monoclonal antibodies, we selected two, 1C1-A and 3A-6, which can be used for immunoblotting and immunostaining. These antibodies did not cross-react with resistin (data not shown), as predicted by amino acids 14-66 of RELMβ not being conserved in the sequence of resistin.
Supplementary Fig. II
Immunohistochemistry of the human colon with 3A-6 antibody. A. Normal colon tissue was routinely embedded in paraffin. Four-μm-thick slices obtained from these samples were immunostained with anti-hRELMβ antibody. Bars in panel A indicate 100μm. B. Arrow indicates a RELMβ positive macrophage. These staining reactions were blunted by co-incubation with recombinant antigen (data not shown), suggesting this staining to be specific.
Supplementary Fig. III

Construction of RELMβ gene targeting vector. The Lambda KOS phage library was screened by PCR using exon 2-specific primers. pKOS-39 was isolated, then transfected into yeast, and clones that had undergone homologous recombination to replace exons 2-4 were isolated. The linearized targeting vector was electroporated into 129/SvEv\textsuperscript{Br}d (Lex-1) ES cells. G418/FIAU-resistant ES cell clones were isolated, and correctly targeted clones were identified and confirmed by Southern analysis.
RELMβ promoted atherosclerosis development in ApoE -/- mice.

A. RELMβ expression in the colons of RELMβ +/+ mice under specific pathogen free conditions and RELMβ +/+, +/- and -/- mice under conventional circumstances. B. RELMβ expression in PCPMs of RELMβ +/+ treated with control rabbit serum, and PCPMs of +/+, +/- and -/- mice treated with WHHL serum. Bands in the upper panel from western blotting represent RELMβ expression, the lower panel β-actin expression. C. RELMβ expression by macrophages in the aortic root. Aortic roots from RELMβ +/- ApoE -/- mice were routinely embedded in OTC compound. Five-μm-thick slices of the aortic root were processed for immunohistochemical staining using anti-mRELMβ. Hematoxylin staining was used to detect the nuclei. D. RELMβ absence in RELMβ -/- ApoE -/- mouse aortic root. Scales in panels C and D indicate 50μm. E. Serum investigation of lipid profiles. Bars indicate means±SD.
Supplementary Fig. V.

Stimulation with mRELMβ enhances macrophage foam cell formation with effects on expressions of lipoprotein receptors and lipid transporters. J774.1 cells were incubated with or without 100ng/ml mRELMβ or 10ng/ml LPS for 16 hours. Thirty micrograms of cellular protein were immunoblotted. A. Representative bands are presented. B. Quantification of triplicate test results is presented. Note that effects of mRELMβ administration are almost the opposite of those obtained in the absence of RELMβ as shown in Fig. 5E. Bars indicate means±SEM. *Statistical significance at p<0.05
Supplementary Fig. VI. RELMβ and LPS but not resistin upregulated inflammatory cytokine secretions from macrophages

A. The concentrations of TNFα, IL-1β and IL-6 in the culture media from THP-1 cells treated with or without 3μg/ml hRELMβ or 3μg/ml human resistin for 24 hours were measured using Bioplex. B. The media from the U-937 cell cultures treated with or without RELMβ or resistin for 4 hours were collected and the concentrations of TNFα, IL-1β and IL-6 were determined using Bioplex. (**P<0.01). Bars indicate means±SD. **Statistical significance at p<0.01.
Supplementary Fig. VII. Peritoneal macrophages from RELMβ +/+ and -/- mice were collected by RPMI1640 medium supplementation or not with 10% proteose pepton (pepton) or 3% thioglycolate (TGC). Cells were stained for F4/80, CD11c, CD206 and RELMβ, and then analyzed by flowcytometry. F4/80 (+) CD11c (+) cells were mostly RELMβ (+), and a small but significant population of F4/80 (+) CD206 (+) cells was also RELMβ (+). Both populations of RELMβ positive cells were inducible when stimulated by pepton or TGC to induce aseptic inflammation in the peritoneum. Absence of RELMβ significantly reduced pepton/TGC induction of CD11c (+) cells and also blunted that of CD206 (+) cells.
Supplementary Fig. VIII. Differences in the expressions of M1 and M2 macrophage markers among RELMβ genotypes (+/+, +/-, or -/-), extracellular administration of mRELMβ and extracellular administration of mRELMβ neutralizing antibody

PCPMs were collected 2 days after phosphate-buffered saline injection, supplemented or not with 3% TGC. Then, the cells were incubated with 100ng/ml LPS for 4 hours. Relative mRNA expression to that of β-actin was expressed as 100% for RELMβ +/- and TGC(+). Bars represent means±SD. n=6-9. *statistically significant (p<0.05) for TGC induction of mRNA expression. †statistically significant (p<0.05) for RELMβ absence. ‡statistically significant for mRELMβ administration. #statistically significant (p<0.05) for mRELMβ neutralization by anti-RELMβ F(ab’)2 antibody.
Supplementary Fig. IX. RELMβ expression is increased by stimulation with fatty acids, and free fatty acid (FFA)-induced inflammatory cytokine expressions were enhanced by extracellular RELMβ. A. THP-1 cells were incubated with 0.2 mM of the indicated fatty acid for 16 hours. The mRNA amounts of RELMβ, resistin and β-actin cDNA were quantified by qPCR. B. U-937 cells were incubated with 0.2mM of the indicated fatty acid for 16 hours. The same processes as those in Figure 3A were performed. *statistically significant (p<0.05) compared with control. C. PCPMs were incubated with 0.2mM stearic acid for 16 hours and TNFα, IL-6, and β-actin mRNA expressions were quantified by qPCR. Fold changes in the expressions of TNFβ and IL-6 mRNA by PCPMs, to which FFA had been added, from RELMβ +/+ mice were determined in triplicate. PCPMs, with RELMβ +/+,-/+ and -/- phenotypes, were co-incubated with 2 μg/ml mRELMβ, or -/- cells were co-incubated with both 2 μg/ml of recombinant mRELMβ and 50μg/ml of anti-mRELMβ F(ab')2 antibody. The results are presented as means±SE, from three independent experiments. *statistically significant (p<0.05) for stearic acid (+) RELMβ -/- compared to stearic acid (+) RELMβ +/+. #statistically significant (p<0.05) for stearic acid (+) RELMβ -/- compared to stearic acid (+) anti-RELMβ F(ab')2 antibody.
Supplementary Fig. X

Scheme illustrating the involvement of RELMβ in the development of atherosclerosis

1) SFA or inflammatory signals stimulate RELMβ expression in macrophages.
2) RELMβ expressing macrophages increase lipid uptake, develop into foam cells, inflammatory cytokine secretion increases, enhancing LPS effects. RELMβ induces neovascularization of endothelial cells and cellular migration of invading cells.
3) These RELMβ mediated effects lead to atherosclerotic plaque development and induce plaque instability.
METHODS and MATERIALS

Reagents

Recombinant m- and h-RELMβ proteins were purchased from Peprotech (NJ, USA). Lipopolysaccharide (LPS) from Escherichia coli 0111:B4 was purchased from Sigma-Aldrich Japan. Serum of 3-month-old Watanabe heritable hyperlipidemic (WHHL) rabbits was purchased from Oriental Yeast (Tokyo, Japan). Human oxLDL (Biomedical Technologies, MA, USA, #BT-910), human HDL (Calbiochem, CA, USA, #437641), VLDL (Sigma-Aldrich, MO, USA, #L7527), human acetylated (ac) LDL (Kalen Biomedical, MD, USA, #770201), and Dil conjugated AcLDL (Biomedical Technologies, #BT-902) were also purchased. (1,2,−3H)-cholesterol was purchased from PerkinElmer (NJ, USA, NET139250UC(9.25 MBq)). All reagents were of analytical grade.

Cell culture

Primary cultured peritoneal macrophages (PCPMs) from mice were collected 4 days after peritoneal 10% proteose pepton (pepton) or 3% thioglycolate (TGC) injection, as described previously 1, purified using MSP-P (JIMRO, Gunma, Japan), and cultured in RPMI1640 supplemented with 10% fetal calf serum. J774.1, murine monocyte/macrophage cell lines, and THP-1 and U-937, human monocyte/macrophage cell lines, J774.1, THP-1 and U-937, were cultured in RPMI 1640 (Sigma-Aldrich) medium supplemented with 10% fetal calf serum (Invitrogen, CA, USA). All media contained Penicillin 100U/ml and Streptomycin 100μg/ml (Invitrogen) and all cells were cultured at 37°C in 5% CO₂.

Antibody List

The affinity-purified antibodies against murine RELMβ (mRELMβ) were prepared as previously described 2. Anti-mRELMβ F(ab')2 antibody was prepared using a F(ab')2 preparation kit (Thermo Scientific, IL, USA) to block the effects of extracellular RELMβ. The aim of using the F(ab')2 antibody is to prevent macrophage activation via the Fc receptor portion. The monoclonal antibodies against human RELMβ (3A6 and 1C1) were prepared using amino acids 14-66 of RELMβ.

Two of the isolated monoclonal antibodies, 1C1-A and 3A-6, were revealed to be applicable to immunoblotting and immunostaining, and in this study, mainly 3A-6 was used. Primary antibodies for western blotting and immuno-fluorescent staining were purchased, as follows; low density lipoprotein receptor (LDLR) (Cayman Chemical, MI, USA, #1007665), very low density lipoprotein (VLDL) R, scavenger receptor (SR)-A1 (R&D Systems, MN, USA, #AF2258, 1797), CD36 (Lifespan Bioscience, WA, USA, #LS-B662/10019), SR-B1, -B2, ATP-binding cassette (ABC)G1 (Novus Biologicals, CO, USA, #NB400-101, 102, 132), ABCA1 (Thermo Scientific, MA, USA, #PA1-16789), anti-macrophage (Abcam #56297, Cambridge, UK). The NFκB Pathway Sampler Kit was purchased from Cell Signaling
Technology (MA, USA, #9936). Normal rabbit IgG for generating the control F(ab’)2 antibody was purchased from MBL (Nagoya, Japan #PM035).

For flowcytometry, rat anti-mouse CD16/32 antibody (Ab) (BD Pharmingen, NJ, USA, #553142), anti-CD11c antibody-PE conjugated Ab (Abcam #ab86901), Alexa Fluor 488 anti-mouse CD206 Ab (Biolegend, CA, USA, #BL141710), anti-F4/80-PE/Cy5 conjugated Ab (eBioscience, CA, USA, #154801), and anti-rabbit Ab-PE/Cy7 conjugated Ab (Santa Cruz, #SC-3845) were used.

**Human tissue samples**

Tissue samples of the coronary artery and colon were obtained at autopsy from 6 men (age range, 74-88 years) and 4 women (age range, 72-92 years) diagnosed with acute myocardial infarction. These patients had been treated at the Hiroshima University Hospital or an affiliated hospital. Written informed consent was obtained from an authorized representative. For strict privacy protection, identifying information for all samples was removed before analysis. This procedure was in accordance with the Ethical Guidelines for Human Genome/Gene Research of the Japanese Government.

Routinely embedded paraffin sections were incubated either with a mouse monoclonal anti-hRELMβ antibody (1C1-A or 3A-6) and/or anti-CD68 antibody (a macrophage marker, Dako Cytomation) and then visualized employing the Dako Envision+ Mouse Peroxidase Detection System (Dako Cytomation, Carpinteria, CA, USA), or with 3A-6 and CD86 antibody pre-labeled with Alexafluor 546 and 488, respectively.

**Immunohistochemical analysis for human RELMβ**

For immunohistochemical analysis, we used archival formalin-fixed, paraffin-embedded tissues. Immunohistochemical analysis was performed with a Dako Envision+ Mouse Peroxidase Detection System (Dako Cytomation, Carpinteria, CA, USA). Antigen retrieval was performed by microwave heating in citrate buffer (pH 6.0) for 30 minutes. Peroxidase activity was blocked with 3% H2O2-methanol for 10 minutes, and sections were incubated with normal goat serum (Dako Cytomation) for 20 minutes to block nonspecific antibody binding sites. Sections were incubated with a mouse monoclonal anti-hRELMβ antibody (1C1-A or 3A-6) or anti-CD68 antibody (a macrophage marker, Dako Cytomation) for 1 hour at room temperature, followed by incubation with Envision+ anti-mouse peroxidase for 1 hour. For color reaction, sections were incubated with the DAB Substrate-Chromogen Solution (Dako Cytomation) for 10 minutes. Sections were counterstained with 0.1% hematoxylin. Negative controls were created by omission of the primary antibody.

For double-immunofluorescence staining, the anti-hRELMβ antibody (3A-6) and anti-CD68 antibody were pre-labeled with Alexafluor 546 and 488, respectively, using the
Zenon Labeling Kit (Invitrogen), and confocal imaging was performed using a Zeiss confocal microscope (Carl Zeiss, Thornwood, NY, USA).

Animals

This study was approved by the Ethics Committee of the Institute for Adult Diseases, Asahi Life Foundation. All animal experiments were conducted in accordance with the Guidelines for the Care and Use of Laboratory Animals of the same institution. ApoE -/- mice (B6.129P2-Apoltm1Unc/J) and LDLR-/- mice were purchased from Charles River Co (MA, USA). Mice were maintained under conventional conditions, unless otherwise indicated, and a 12-hour light/dark cycle with free access to food and water. High cholesterol diet (20.1% fat, 1.25% cholesterol) was purchased from Research Diet Inc. (NJ, USA, #D12801C) and fed to LDLR -/- mice for 8 weeks. The water was replaced every 2 days. Food was withdrawn 12 hours before the experiment.

Generation of RELMβ -/- mice

The RELMβ mutant mice were generated (Supplementary Fig. III) in collaboration with Lexicon Pharmaceuticals, Inc. (The Woodlands, TX, USA).

The RELMβ targeting vector was derived using the Lambda KOS system. The Lambda KOS phage library, arrayed into 96 super-pools, was screened by PCR using exon 2-specific primers for RELMβ-2 (Supplementary Table).

The PCR-positive phage super-pools were plated and screened by filter hybridization using the 347 bp amplicon derived from primers RELMβ-2 as a probe. Two pKOS genomic clones, pKOS-39 and pKOS-59, were isolated from the library screen and confirmed by sequence and restriction analyses. Gene-specific arms using RELMβ-3 primers (The primer list is in the Supplementary Table) were appended by PCR to a yeast selection cassette containing the URA3 marker.

The yeast selection cassette and pKOS-39 were co-transformed into yeast, and clones that had undergone homologous recombination to replace a 1713 bp region containing exons 2-4 with the yeast selection cassette were isolated. The yeast cassette was subsequently replaced with a LacZ/Neo selection cassette to complete the RELMβ targeting vector.

The Not I linearized targeting vector was electroporated into 129/SvEvbrd (Lex-1) ES cells. G418/FIAU resistant ES cell clones were isolated, and correctly targeted clones were identified and confirmed by Southern analysis using a 493 bp 5' external probe (26/21), generated by PCR using primers RELMβ-4, and a 479 bp 3' internal probe (22/24), amplified by PCR using primers RELMβ-22 and -24.
Southern analysis using probe 26/21 detected a 7.8 Kb wild type band and a 3.4 Kb mutant band in ApaL1 digested genomic DNA while probe 22/24 detected a 17.2 Kb wild type band and a 9.0 Kb mutant band in XhoI digested genomic DNA. One targeted ES cell clone was identified and microinjected into C57BL/6 (albino) blastocysts to generate chimeric animals which were bred to C57BL/6 (albino) females, and the resulting heterozygous offspring were interbred to produce homozygous RELMβ deficient mice. Mice heterozygous for the deleted exon2 were bred to generate homozygous knockout mice.

The genetic background was then changed to C57BL/6 by a marker-assisted speed congenic strategy. B6 background RELMβ -/- mice were crossed with ApoE -/- or LDLR -/- mice to generate RELMβ -/- mice with ApoE -/- or LDLR -/- background. Generation of RELMβ -/- mice

Preparation of murine tissue samples
At the indicated ages, the mice were euthanized. The heart and entire aorta were removed en bloc, then formalin-fixed. Samples were rinsed with phosphate-buffered saline (PBS) and aortic roots were routinely embedded in OCT compound (Sakura Finetek Japan, Tokyo, Japan). Five-μm-thick slices of the aortic root were obtained sequentially. The aortic tree was incised longitudinally, and then rinsed with PBS.

Histological analyses of mice
The aortic root slices and opened aortic trees were subjected to oil red O staining, as previously described. Hematoxylin staining was used to detect the nuclei. In addition, these samples were processed for immunofluorescence staining using anti-macrophage antibody (Abcam). Alexa-Fluor 488 anti-rat IgG was used as the secondary antibody. Digital images of lesions were obtained with a Nikon Eclipse Ti microscope. Areas of lipid accumulation were histomorphometrically analyzed using MultiGauge ver. 3.1 (FujiFilm, Tokyo, Japan), according to the manufacturer’s instructions. The ratios of lesion area or number stained by oil red O, to the whole aortic wall area, were calculated as previously described.

Serum investigation
Serum triglyceride, cholesterol and free fatty acids were assayed with Triglyceride E test Wako, Cholesterol E test Wako, and NEFA C test Wako (Wako Chemicals, Osaka, Japan), respectively, according to the manufacturer’s instructions.

Quantification of lipid accumulation in macrophages
PCPMs were cultured on 96-well plates for lipid accumulation assays as previously described. After incubation with 50mg/ml oxLDL, 50mg/ml VLDL, or 1% Watanabe heritable
hyperlipidemic (WHHL) rabbit serum for 48h, the cells were stained with AdipoRed™ assay reagent (Nile Red) with DAPI counter-staining for nuclei, and then subjected to lipid accumulation quantification using an ARVO MX fluorimeter (Perkin Elmer, MA, USA), according to the manufacturer’s instructions. Lipid accumulation was adjusted for cell counts.

1,1-dioctadecyl-3,3,3,3–tetramethylindocarbocyanine (Dil)-acLDL uptake assay

The Dil-acLDL assay was performed as previously described with slight modification. PCPMs were incubated with 10 mg/mL Dil-acLDL and 1μg/ml DAPI for 4 hours at 37°C. After the cells were counted, they were washed, Dil was then extracted with isopropyl alcohol, and relative fluorescence intensity was determined at 524 nm (excitation) and at 567 nm (emission). Experiments were performed 3 times, and representative values are shown as means±SEM.

Cholesterol efflux measurements

Cholesterol efflux was measured as previously described. PCPMs were incubated with 100 μg/mL acLDL and 1.2 μCi/ml 1,2,−3H)-cholesterol in RPMI1640 medium containing 0.2% bovine serum albumin for 24 hours at 37°C. Cells were then incubated with RPMI1640 medium containing 0.2% bovine serum albumin supplemented or not with 50 μg/mL of high-density lipoprotein (HDL). After a further 48-hour incubation, medium and cell lysates were collected and radioactivity was determined by liquid scintillation counting. Cholesterol efflux was expressed as the percentage of radioactivity released into the medium relative to total radioactivity.

Quantification of mRNA expression

The mRNA was prepared from cells using the RNeasy-mini kit (QIAGEN, Hilden, Germany) and quantitative real-time PCR was run with a LightCycler480 (Roche) using FastStart SYBR Green Master (Roche) and the primers shown in the Supplementary Table.

Western blotting

Western blot analysis was carried out as described previously. Band images were obtained by LAS-4000 (FujiFilm) and quantified by MultiGauge ver. 3.1. Fold changes in protein expressions as compared with β-actin were determined in triplicate. Cells were lysed with lysis buffer: 10mM Tris-HCl pH 7.4, 150mM NaCl, 2mM EDTA, 1% Triton-X, 10mM NaF, 10mM Na3P2O7, 1mM o-Vanadate, 1x Complete Protease Inhibitor Cocktail (Roche). Supernatants from cell lysates were boiled in Laemmli sample buffer containing 100 mmol/l dithiothreitol. Then, 10μg of protein were separated by SDS-PAGE and electrophoretically transferred to membranes, which were then incubated with a specific antibody. The
antigen-antibody interactions were visualized using horseradish peroxidase-conjugated secondary antibody and SuperSignal West Pico Chemiluminescent Substrate (Thermo Scientific). Protein expressions as compared with β-actin were determined in triplicate.

Flowcytometry analysis of peritoneal macrophages

Flowcytometric analysis was performed as previously described. The Fc receptor on peritoneal macrophages was blocked by incubation with anti-CD16/32 Ab for 10 min, and macrophages were incubated with fluorochrome conjugated primary antibodies (F4/80/CD11c/CD206) for 30 min at 4°C. For RELMβ detection, cells were permeabilized with methanol, and anti-RELMβ Ab incubation was followed by secondary anti-rabbit IgG Ab-PE/Cy7. Cells were subjected to FACS Vantage SE (BD Biosciences). The data analysis was performed using FlowJo (Tree Star, OR, USA).

Quantification of cytokine secretions

Inflammatory cytokines secreted into the media were quantified using Bioplex (Bio-Rad, CA, USA) according to the manufacturer's instructions.

Statistical analysis

Statistical analyses were performed using Jmp 8.0.1 (SAS institute, NC, USA) and R version 2.13.1 (The R Foundation for Statistical Computing). Results are expressed as means ± SE, SD, or median and quartiles, and statistical significance was assessed using unpaired Student’s t tests and ANOVA followed by the Tukey HSD test, unless otherwise indicated.
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