厚生科学研究費補助金難治性疾患等克服研究事業
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関節リウマチにおける血漿中マイクロRNAの臨床的解析

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研究要旨:
血漿中にはマイクロRNAが存在し、悪性腫瘍のマーカーとなり得ることが2008年に報告され、研究協力者の村田らは血漿・関節液中マイクロRNAが関節リウマチのマーカーとなり得ることを5種類のマイクロRNAを解析し世界に先駆けて示した。本研究では血漿中マイクロRNAがリウマチ因子や抗CCP抗体とは異なった新機軸のバイオマーカーとして臨床応用可能かを、100 人レベルの関節リウマチ患者および健常人の検体を用いて解析した。関節リウマチ特異的な血漿中マイクロRNAとしてmiR-24、miR-26a、miR-125a-5p およびそれらの複合値 ePRAM が 60%程の感度と 90%程の特異度を認めることを示した。また興味深いことに、血漿中マイクロRNAは抗CCP抗体が陰性の群でも同様の感度特異度を示し、抗CCP抗体陰性症例の早期診断に寄与する可能性が示唆された。

A. 研究目的

血漿中にはマイクロ RNA が存在し、悪性腫瘍のマーカーとなり得ることが 2008 年に報告された。研究協力者の村田らは血漿・関節液中マイクロ RNA が関節リウマチのマーカーとなり得ることを5種類のマイクロ RNA を解析し世界に先駆けて示した(Arthritis Res Ther. 2010 55(2)巻 R86 項)。

本研究では血漿中マイクロ RNA が関節リウマチ治療の臨床現場に応用可能かを明らかにするため、網羅的に解析し得られたマイクロ RNA の感度・特異度や、疾患活動性および抗 CCP 抗体などの臨床マーカーとの相関等を100人レベルの関節リウマチ患者および健常人由来の検体を用いて検討する。

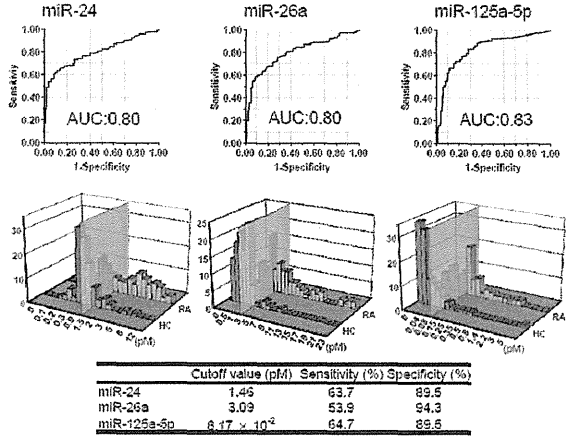
B. 研究方法

関節リウマチ患者と健常人の血漿中の 768 種類のマイクロ RNA を、リアルタイム PCR 法を用いた網羅的アレイにて3検体ずつ解析し比較した。P 値が 0.05 以下または発現差が 4 倍以上あるものを第一次候補とした。これらのマイクロ RNA に対して8検体ずつで発現比較を行い、P 値が 0.05 以下で有意差のあるものを第二次候補とした。さらに、関節リウマチ患者および健常人での第二次候補マイクロ RNA の発現をそれぞれ 100 名程度の検体で解析し、感度・特異度やリウマチ因子(RF)、抗CCP抗体、MMP3 等のマーカーおよび疾患活動性との相関を解析した。また変形性関節症患者や SLE 患者の血漿でのこれらのマイクロ RNA の発現を解析し、関節リウマチに対する特異性を確認した。

C. 研究結果

網羅的に解析されたマイクロ RNA 768 個のうち健常人・関節リウマチそれぞれ3検体の解析で候補となった一次候補血漿中マイクロ RNA は 26 種であった。これらのマイクロ RNA のうち関節リウマチ患者、健常人それぞれ8検体で差が認められた血漿中マイクロ RNA は miR-24, miR-26a, miR-28-5p, miR-28-3p, mir-30a-5p, miR-30c, miR-30e-3p, miR-125a-5p, miR-126-3p の 8 種類であった。これらの血漿中マイクロ RNA はこれまでヒト疾患との関連が報告されていないものがほとんどであった。これらのマイクロ RNA について、それぞれ 100 名

の健常人と関節リウマチ患者を区別するROC 解析にて、優れた検査の指標であるAUC0. 8以上となるマイクロRNAはmiR-24、miR-26a、miR-125a-5pの3種類認められ、それぞれ感度 63.7%で特異度 89.5%、感度53.9%で特異度 94.3%、感度 64.7%で特異度89.5%であった(図1)。



	Cutoff value (pM)	Sensitivity (%)	Specificity (%)
miR-24	1.46	63.7	89.5
miR-26a	3.09	53.9	94.3
miR-125a-5p	8.17×10^{-2}	64.7	89.5

図 1　血漿中 miR-24、miR-26a、miR-125a-5pの RA に対する感度特異度

また、血漿中マイクロ RNA の内、内部標準的な変化を示すものとしてmiR-30a-5pを同定した。これと miR-24、miR-125a-5p を組み合わせた複合値 (Estimated Probability of RA by plasma MiRNA (ePRAM))を作成することにより、78.4%の感度と92.3%の特異度が得られた(図2)。

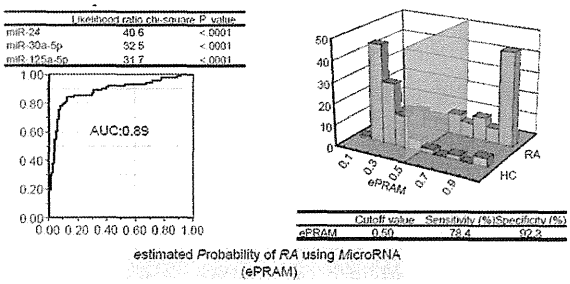


図2 複合値(ePRAM)による感度特異度

また 8 種類の候補血漿中マイクロ RNA と各関節リウマチ疾患活動性との相関を解析したところ、抗CCP抗体と相関を認めたものは miR-26a と miR-30e-3p、CRP とは miR-26a, miR-28-3p, miR-30c, miR-30e-3p, miR-126-3p, 全身状態の患者 VAS と miR-24, miR-26a,miR-30c, miR-126-3p, DAS28(ESR)と miR-24, miR-26a, miR-30c, miR-126-3p, DAS28(CPR) と miR-24, miR-26a, miR-30c に相関を認めた。

また、抗CCP抗体陰性症例(15 名)と陽性症例(87 名)とでそれぞれの診断率を見たところ、miR-24 で 47%と 64%、miR-26a で 40%と 55%、miR-125a-5p で 67%と 64%、ePRAMで 73%と 78%と有意な差を認めなかったことから、血漿中マイクロ RNA を用いて抗CCP抗体陰性症例診断の臨床応用が期待された。

D. 考察

血漿中マイクロRNAと関節液中マイクロRNAの発現パターンは異なり、関節液中のマイクロRNAは関節局所の状況を反映していると考えられた。血漿中マイクロ RNA はリウマチ因子や抗CCP抗体などの自己抗体とは産生機序の異なる新機軸のバイオマーカーで、血漿中 miR-24, miR-26a, miR-125a-5p, ePRAM はこれまでのバイオマーカーに劣らない感度および特異度を示すだけではなく、抗CCP抗体陰性患者においても同様の診断性を示し、抗CCP抗体陰性関節リウマチの早期診断に有用である可能性が示唆された。また、これまで主観的な評価であったVASを血漿中マイクロ RNA にて客観的に裏付けられる可能性が考えられた。本研究により、established RA において血漿中マイクロ RNA は抗CCP抗体と独立した性質をもつ有用なバイオマーカーであることが示された。今後は、血漿中マイクロ RNA を用いて早期 RA の診断や機能的予後予測が可能かを検討していく必要がある。

E. 結論

血漿中マイクロ RNA の関節リウマチに対する感度・特異度は十分に高く新たな診断

マーカーとして実臨床で使用が期待される。特に抗 CCP 抗体陰性症例の関節リウマチ診断に有用である可能性がある。今後、関節リウマチに対する新たな検査として血漿中マイクロRNAの臨床応用が期待される。

F. 研究発表

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G. 知的財産研の出願・登録状況

関節液・血漿中 microRNA に関する特許申請中

III. 研究成果の刊行に関する一覧・別刷

研究成果の刊行に関する一覧表
【H22. 4. 1～H24. 3. 31】

雑誌

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Lectin-like Oxidized Low-Density Lipoprotein Receptor 1 Signal Is a Potent Biomarker and Therapeutic Target for Human Rheumatoid Arthritis

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Objective. **To determine whether lectin-like oxidized low-density lipoprotein (ox-LDL) receptor 1 (LOX-1) and the soluble form of LOX-1 (sLOX-1) are novel target molecules for the diagnosis and treatment of rheumatoid arthritis (RA).**

Methods. **Expression of ox-LDL and LOX-1 proteins in human RA synovium was evaluated by immunohistochemistry. Human RA fibroblast-like synoviocytes (FLS) were assessed for ox-LDL–induced expression of LOX-1 and ox-LDL–induced production of matrix metalloproteinase 1 (MMP-1) and MMP-3. Levels of sLOX-1 in the plasma and synovial fluid of patients with RA, compared with patients with osteoarthritis (OA), were determined by a specific chemiluminescence enzyme-linked immunoassay. In animal experiments, ox-LDL was injected into the knee joints of mice, with or without an anti–LOX-1 neutralizing antibody or sLOX-1, and the severity of arthritis was analyzed by histology and immunohistochemistry.**

Results. **Oxidized LDL and LOX-1 proteins were detected in the RA synovial tissue. Levels of MMP-1 and MMP-3 were enhanced by stimulation of RA FLS with ox-LDL, and the production of both MMPs was inhibited by blockade of the ox-LDL–LOX-1 interaction with the anti–LOX-1 neutralizing antibody or sLOX-1. Levels of sLOX-1 in the plasma and synovial fluid of RA patients were significantly higher than those in OA patients and healthy controls and were positively correlated with inflammation markers and the extent of RA disease activity. In the knees of mice, blockade of the ox-LDL–LOX-1 interaction suppressed arthritic changes and reduced the expression of MMP-3 induced by ox-LDL.**

Conclusion. **These findings strongly indicate that sLOX-1 is a novel biomarker that may be useful for the diagnosis of RA and for the evaluation of disease activity in RA. Furthermore, the results suggest that LOX-1 may be a potent therapeutic target for RA.**

Rheumatoid arthritis (RA) is a systemic autoimmune disease characterized by inflammatory synovitis, ultimately leading to the destruction of articular cartilage and the subchondral bone. The use of biologic agents that target proinflammatory cytokines and lymphocytes has revolutionized the treatment of RA, producing significant improvements in clinical, radiographic, and functional outcomes (1). Although these biologic treatments have achieved a marked reduction in disease progression, the rate of remission induction has not been as high as promised (1), and the inhibitory effects of the treatments on joint destruction are far from satisfactory, especially in large joints such as the knee. Thus, early diagnosis and aggressive treatment have become the fundamental strategy to suppress inflammation before irreversible joint destruction develops (1,2).

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However, to make a diagnosis and to evaluate the severity of disease activity, physicians still depend on general biomarkers of inflammation, such as the C-reactive protein (CRP) level and erythrocyte sedimentation rate (ESR), together with physical findings and patient-reported clinical data. Recently, matrix metalloproteinase 3 (MMP-3) and other molecules have been shown to be potent biomarkers of joint destruction (3). However, the reliability of these markers as diagnostic and prognostic tools in RA remains insufficient.

The destruction of articular cartilage in RA is mediated mainly by a series of proteinases. Among these, the MMPs, especially MMP-1 and MMP-3, play pivotal roles in the degradation of cartilage matrices. MMPs are up-regulated by proinflammatory cytokines, such as tumor necrosis factor α (TNFα) and interleukin-1β (IL-1β), in RA joints, which has led to the assumption that anticytokine treatment could sufficiently block the destruction of cartilage. However, treatment with these agents, which are represented by anti-TNFα biologic therapy, has failed to result in complete inhibition of articular cartilage degradation. This has prompted researchers to develop new agents for the control of joint cartilage degradation, although such research has thus far been based on unknown pathogenic mechanisms related to inflammation.

Accumulating evidence indicates that patients with RA have higher morbidity and mortality related to cardiovascular diseases (CVDs) compared with patients with osteoarthritis (OA) (4,5). A recent study even demonstrated that patients with RA and patients with diabetes mellitus are equally at risk of developing a CVD (6). Similar to RA, atherosclerosis, an important causative factor in CVD, is closely related to systemic inflammation (7), thus suggesting that there is a common pathophysiologic mechanism in RA and atherosclerosis.

Low-density lipoprotein (LDL) is a well-known key risk factor for atherosclerosis. Oxidized LDL (ox-LDL), which is produced by oxidative modification of LDL at the site of oxidative stress and inflammation, plays a central role in the pathogenesis of atherosclerosis (8,9). Furthermore, ox-LDL induces a variety of autoimmune responses and contributes to other inflammatory conditions, such as RA (10). We previously reported that lectin-like ox-LDL receptor 1 (LOX-1) is the major receptor of ox-LDL (11). In the last decade, findings from several studies have supported the emerging notion that ox-LDL–LOX-1 signaling plays a pivotal role in various inflammatory and atherosclerotic diseases (12,13). LOX-1 is expressed in various cells, including endothelial cells, macrophages, and chondrocytes, and its expression is enhanced by proinflammatory cytokines (12–14).

In a previous study, we demonstrated that treatment with an anti–LOX-1 antibody suppressed articular cartilage degeneration in rat zymosan-induced arthritis (14), and that ox-LDL can penetrate the cartilage matrix via LOX-1 and via the enhancement of MMP-3 production in explant cultures of articular cartilage from patients with RA (15). Thus, the importance of LOX-1 in RA has been suggested. However, little is known regarding whether LOX-1 is expressed in human joint synovium, which is a major site of inflammation in RA, or whether anti–LOX-1 treatment can block the articular cartilage degradation caused by ox-LDL in vivo.

Previous studies have shown that activation of LOX-1 by its ligands leads to a positive feedback loop in which the ligand–receptor interaction up-regulates the receptor itself at the cell surface, in addition to inducing its expression via proinflammatory cytokines (16,17), which leads to cleavage and release of LOX-1 from the cell surface as soluble LOX-1 (sLOX-1) (18). Several recent studies demonstrated that sLOX-1 is a diagnostic and prognostic biomarker for acute coronary syndrome (19–21), probably because the abundance of LOX-1 and enhanced protease activity, leading to cleavage of LOX-1 from the cell surface, in these lesions are reflective of the extent of disease activity. Considering the similarity between atherosclerosis and RA, it appears reasonable to hypothesize that sLOX-1 is also a potent biomarker for RA. However, the production and function of sLOX-1 remain largely unknown.

Here, we demonstrated that LOX-1 is expressed in the lining layer of human joint synovium. We also showed that sLOX-1 is a useful biomarker for the diagnosis and evaluation of disease activity in human RA. Furthermore, we showed that sLOX-1, as well as an anti–LOX-1 antibody, can block the uptake of ox-LDL and the production of MMPs in human RA fibroblast-like synoviocytes (FLS) in vitro, leading to protection against the articular cartilage degradation caused by ox-LDL in vivo. Thus, these results clearly showed that the ox-LDL–LOX-1 interaction is involved in the pathogenesis of accelerated joint inflammation and cartilage destruction in RA, that sLOX-1 is a useful biomarker in RA, and that LOX-1 is a potent therapeutic target for RA.

PATIENTS AND METHODS

Reagents. The antibodies and reagents used were as follows: monoclonal antibodies against recombinant human IL-1β and TNFα, an anti-human LOX-1 monoclonal antibody, anti-human MMP-1 and MMP-3 polyclonal antibodies (R&D

Systems), and an anti–HOCl–ox-LDL polyclonal antibody (Calbiochem). The recombinant human LOX-1 extracellular domain and a neutralizing anti-mouse LOX-1 monoclonal antibody (TS58) were prepared as described previously (22,23).

Subjects. Ethics approval for this entire study was granted by our institution's Ethics Committee, and written consent was obtained from each patient. In analyses of patients who had received only nonbiologic treatments, patients with a diagnosis of RA (n = 47) according to the American College of Rheumatology revised criteria (24) and patients with OA (n = 32) were studied. Most patients with RA had received methotrexate, and none of the patients had received a biologic agent. Healthy control subjects (n = 30) were individuals who did not meet the classification criteria for RA or any other inflammatory disease (details available from the corresponding author upon request).

In analyses of patients who had received biologic treatments, patients with RA who had no previous exposure to a biologic agent (n = 11) were studied. All of these patients had active disease, defined as a Disease Activity Score in 28 joints (DAS28) of ≥3.2 (25). Blood samples were obtained before and 6 weeks after the beginning of the biologic treatment. In each patient, the biologic agent administered (TNFα soluble receptor [etanercept], antibodies [either infliximab or adalimumab], or IL-6 receptor antibody [tocilizumab]) was chosen at the discretion of the physician. Patients' responses to the treatment were recorded, and the DAS28 was calculated at every visit (details available from the corresponding author upon request).

Preparation of blood, synovial fluid, and synovial tissue samples. Peripheral blood and synovial fluid samples were obtained from the patients with RA and patients with OA. Blood samples were collected in tubes containing ethylenediaminetetraacetic acid dipotassium salt, to separate the plasma. The samples were centrifuged at 400*g* for 7 minutes and stored at −20°C until analyzed. Plasma was isolated from the blood at 1 hour after the blood withdrawal, to avoid the possibility of a change in sLOX-1 by the time of isolation. Synovial tissue samples were obtained from patients with RA undergoing knee joint surgery.

Chemiluminescence enzyme-linked immunoassay (CLEIA). Circulating sLOX-1 levels in the plasma and synovial fluid were measured as previously described (26). Briefly, sLOX-1 levels were measured by a sandwich CLEIA using 2 different human LOX-1–specific monoclonal antibodies, one of which was labeled with a chemiluminescent agent, and recombinant human LOX-1 extracelluar domain as an assay standard. JMP software version 7.01 (SAS Institute) was used to calculate receiver-operating characteristic (ROC) curve values and cutoff points for positivity.

Preparation of LDL and ox-LDL. Human LDL (density 1.019–1.063) was isolated from fresh plasma by ultracentrifugation, as described previously (11). LDL was oxidized at a protein concentration of 3 mg/ml by exposure to 7.5 m*M* $CuSO_4$, and in every preparation, lipopolysaccharide contamination was ruled out. DiI-labeled ox-LDL was prepared according to the manufacturer's instructions (Molecular Probes).

Preparation of conditioned medium. Chinese hamster ovary K1 (CHO-K1) cells stably expressing bovine LOX-1 (BLOX-1–CHO) were cultured in F-12 medium (Sigma-Aldrich) containing 10% fetal bovine serum supplemented with 10 mg/ml of blasticidin S (Funakoshi), as described previously (11). After 48 hours in culture, the cells were washed with phosphate buffered saline (PBS) and subsequently cultured with serum-free F-12 medium for 24 hours. After incubation, the supernatants were pooled for use as conditioned medium (referred to as sLOX-1 original conditioned medium). Alternatively, the supernatants were concentrated using an Amicon Ultra-4 centrifugal filter device (Millipore), and this was used as sLOX-1 concentrated conditioned medium, containing abundant sLOX-1 as a fractionated concentrate (10–50 kd).

DiI-labeled ox-LDL uptake assay. FLS from the knee joint synovium of patients with RA were incubated with serum-free medium for 24 hours. DiI-labeled ox-LDL (20 μg/ml) or medium alone was added to each well, followed by incubation for 24 hours. To exclude nonspecific binding, unlabeled ox-LDL (100 μg/ml) was added to some wells simultaneously with the DiI-labeled ox-LDL. In other wells, an original conditioned medium of BLOX-1–CHO cells containing sLOX-1 was added in combination with DiI-labeled ox-LDL. After a 24-hour incubation period, the RA FLS were washed and fixed in 4% paraformaldehyde/PBS for 10 minutes at room temperature, and after washing, the FLS were counterstained using a SYBR Green I DNA staining system (Molecular Probes). Uptake of the DiI-labeled ox-LDL in these cells was visualized using confocal microscopy (Olympus).

Assessment of experimental knee joint inflammation in vivo. C57BL/6 mice (all 10-week-old males) were used to assess knee joint inflammation. The skin of the mice was incised longitudinally on the center of the right knee joint, and the capsule and patellar tendon were exposed. The mice in the experimental group were subjected to intraarticular injections (10 μl once daily for 7 days) of ox-LDL (2 mg/ml), native LDL (2 mg/ml), or PBS into the right knee joint. One hour before the ox-LDL injection, a group of mice received an intraarticular injection (20 μl once daily for 7 days) of anti–LOX-1 antibody (10 μg/ml), human recombinant LOX-1 protein (1.0 mg/ml), or control IgG (10 μg/ml). After the ox-LDL injection, the incised skin was sutured, and the mice were returned to their cages. All mice were killed 24 hours after the last injection, and the knee joints were harvested. All animal studies were conducted in accordance with principles and procedures approved by the Kyoto University Committee of Animal Resources.

Histologic analysis. Knee joint specimens from the mice were processed as paraffin-embedded sections, with a thickness of 7 μm, and stained with hematoxylin and eosin and Safranin O–fast green. For immunohistochemical analyses, deparaffinized sections were blocked with 0.3% hydrogen peroxide in methanol for 20 minutes. An anti–LOX-1 antibody, an anti–ox-LDL antibody, an anti–MMP-3 antibody, or control IgG was applied to the specimens, followed by incubation for 60 minutes at room temperature. The reaction products were visualized using a Vectastain ABC Kit and a DAB Peroxidase Substrate Kit (Vector) according to the manufacturer's instructions. The severity of joint inflammation was scored on a scale of 0–4, based on the degree of cellular infiltration into the joint tissue and the extent of pannus formation (27). In addition, proteoglycan depletion was scored on an arbitrary scale of 0–4 (28). Joint inflammation and proteoglycan depletion in each section were scored in a

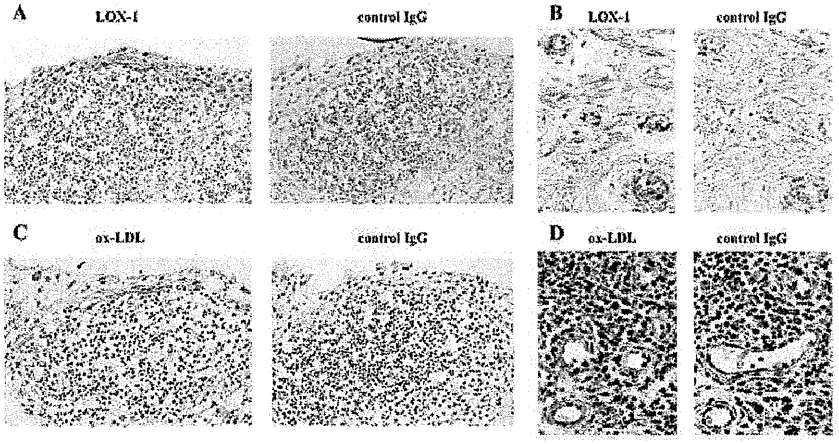

Figure 1. Expression of lectin-like oxidized low-density lipoprotein (ox-LDL) receptor 1 (LOX-1) and ox-LDL in inflamed synovium from a patient with rheumatoid arthritis. Immunohistochemical staining of a representative RA synovial tissue sample for LOX-1 (**A** and **B**) and ox-LDL (**C** and **D**) demonstrates the expression of LOX-1 and ox-LDL in the lining layer (**A** and **C**) and around blood vessels (**B** and **D**). Nonimmune IgG was used as a negative control. Original magnification × 40 in **A** and **C**; × 200 in **B** and **D**.

blinded manner by 2 independent observers (HS and TK), to obtain the mean scores for each measure.

Statistical analysis. Data are presented as the mean ± SEM. Statistical comparisons between 2 groups were per-

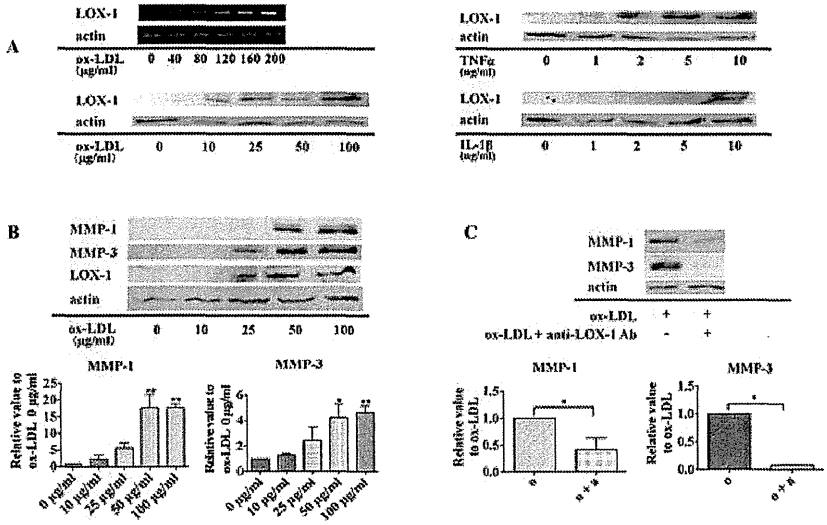

Figure 2. Induction of matrix metalloproteinase 1 (MMP-1) and MMP-3 production by lectin-like oxidized low-density lipoprotein (ox-LDL) receptor 1 (LOX-1) in fibroblast-like synoviocytes (FLS) from patients with rheumatoid arthritis (RA). **A** and **B**, RA FLS were stimulated with the indicated concentrations of ox-LDL, tumor necrosis factor α (TNFα), or interleukin-1β (IL-1β) for 24 hours. Total RNA was assessed by reverse transcription–polymerase chain reaction (**A** [top left]), and supernatants were assessed by immunoblotting (**A** [bottom left, top and bottom right] and **B** [top]), to determine the expression of LOX-1 (**A**) and MMPs 1 and 3 (**B**); β-actin was used as a positive control. The cumulative data derived from immunoblotting were assessed semiquantitatively in densitometric analyses, with results expressed as the mean ± SEM levels of MMPs 1 and 3 after stimulation with the various concentrations of ox-LDL, relative to the values without stimulation (0 μg/ml ox-LDL) (**B** [bottom]). * = $P < 0.05$; ** = $P < 0.01$, versus cultures without stimulation. **C**, RA FLS were incubated with anti–LOX-1 antibody (Ab) (10 μg/ml) (a) for 1 hour before exposure to ox-LDL (100 μg/ml) (o) for 24 hours. Cells were then lysed and subjected to immunoblotting to detect protein levels of MMPs 1 and 3 (top). The cumulative data derived from immunoblotting were assessed semiquantitatively in densitometric analyses, with results expressed as the mean ± SEM levels of MMPs 1 and 3 in cultures with ox-LDL plus antibody relative to cultures with ox-LDL alone (bottom). * = $P < 0.05$. The data in **B** and **C** are representative of at least 4 independent experiments.

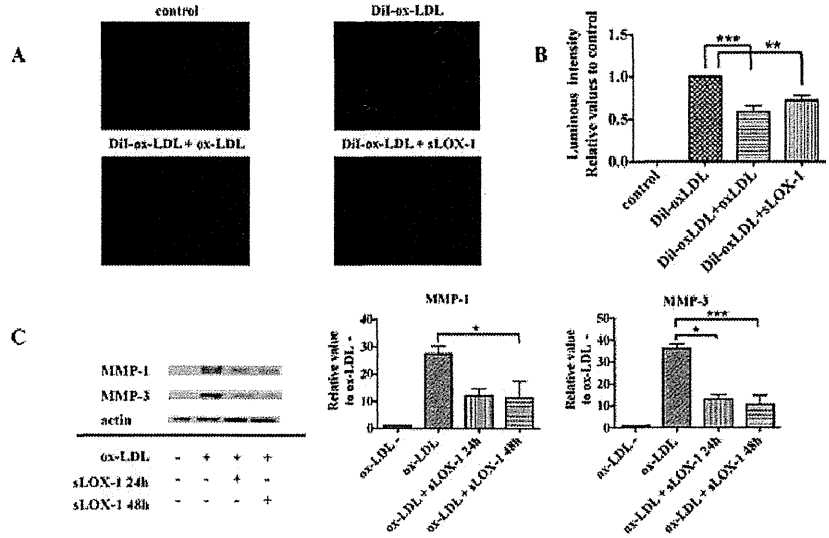

Figure 3. Uptake of DiI-labeled oxidized low-density lipoprotein (ox-LDL) into rheumatoid arthritis (RA) fibroblast-like synoviocytes (FLS), and decrease in the ox-LDL–induced production of matrix metalloproteinase 1 (MMP-1) and MMP-3 in RA FLS by soluble lectin-like ox-LDL receptor 1 (sLOX-1). **A,** RA FLS were treated with medium alone (control), 20 μg/ml of DiI-labeled ox-LDL (top right), DiI-labeled ox-LDL in the presence of an excess amount of unlabeled ox-LDL (100 μg/ml) (bottom left), or DiI-labeled ox-LDL in combination with an original conditioned medium containing sLOX-1 (100 μg/ml) (bottom right). Representative results are shown. Original magnification × 200. **B,** The relative fluorescence intensities of DiI labeling of ox-LDL uptake were measured in RA FLS treated with DiI-labeled ox-LDL alone, excess unlabeled ox-LDL, or excess sLOX-1, with results expressed as the mean ± SEM of 4 samples per group, relative to that in medium alone (control). ** = $P < 0.01$; *** = $P < 0.001$. **C,** Protein levels of MMP-1 and MMP-3 were determined in the supernatants after RA FLS were treated with an sLOX-1 concentrated conditioned medium that contained abundant sLOX-1 (100 μg/ml), in the absence or presence of ox-LDL, for 24 or 48 hours. Results were assessed by immunoblotting (left) and expressed as the mean ± SEM protein levels in 4 samples per group, relative to that in cultures without ox-LDL (ox-LDL−) (middle and right). * = $P < 0.05$; *** = $P < 0.001$.

formed using a Student's 2-tailed *t*-test. Differences among 3 groups were analyzed using the Bonferroni method. Relationships between sLOX-1 and other variables were evaluated using Pearson's correlation analyses. Differences were considered significant when *P* values were less than 0.05.

RESULTS

Abundant accumulation of ox-LDL and enhanced expression of LOX-1 protein in the synovial tissue of RA patients. We first assessed the expression of ox-LDL and LOX-1 proteins in human synovial tissue, the major site of RA inflammation. LOX-1 (Figures 1A and B) and ox-LDL (Figures 1C and D) proteins were clearly identified in the RA synovium, particularly in the lining layer (Figures 1A and C) and around blood vessels (Figures 1B and D), similar to the previously reported localization of MMP-1 and MMP-3 (29).

In addition, treatments with ox-LDL, TNFα, and IL-1β dose-dependently up-regulated the expression of LOX-1 messenger RNA and protein production from FLS in cultures of RA synovium (Figure 2A). Furthermore, incubation of RA FLS with ox-LDL (0–100 μg/ml) for 24 hours increased the production of MMP-1 and MMP-3 proteins in a dose-dependent manner (Figure 2B). Pretreatment of the FLS with the anti–LOX-1 antibody (10 μg/ml) significantly reduced the ox-LDL–stimulated production of MMP-1 and MMP-3 (Figure 2C). Pretreatment with native (nonoxidized) LDL or the anti–LOX-1 antibody alone had no effect on the basal production level of MMP-1 or MMP-3 (results not shown).

Inhibition of ox-LDL–induced production of MMPs 1 and 3 by sLOX-1 concentrated medium. To determine whether sLOX-1 inhibits the ox-LDL–LOX-1 interaction, we first examined the ability of sLOX-1 to inhibit the uptake of DiI-labeled ox-LDL in RA FLS. Incubation of the FLS with DiI-labeled ox-LDL (20 μg/ml) for 24 hours led to the detection of DiI inside the cells (Figure 3A). This uptake was found to be specific, as it was displaced by an excess amount of unlabeled ox-LDL (100 μg/ml). Subsequently, a conditioned medium containing sLOX-1 was added, in combination with the DiI-labeled ox-LDL, and incubated with the FLS for 24 hours. The uptake of ox-LDL was signifi-

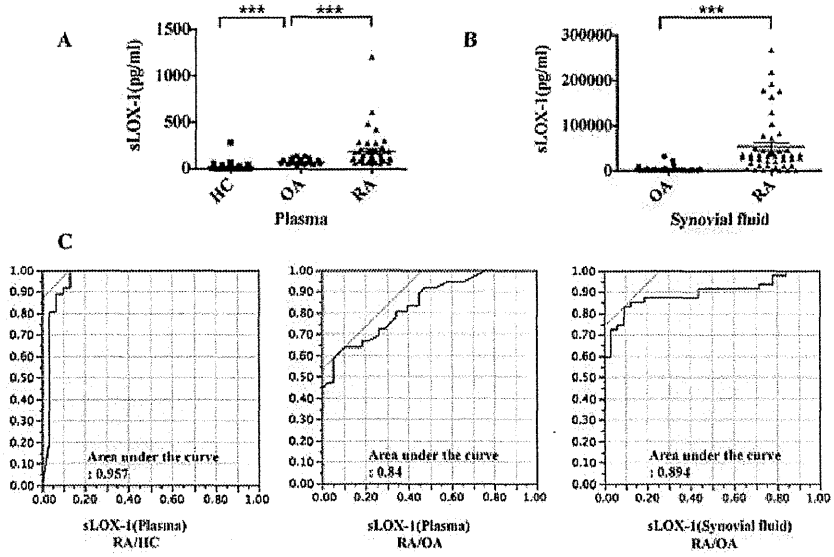

Figure 4. Comparisons of plasma and synovial fluid levels of soluble lectin-like oxidized low-density lipoprotein receptor 1 (sLOX-1) among patients with rheumatoid arthritis (RA), patients with osteoarthritis (OA), and healthy control subjects (HC). **A** and **B**, A marked increase in sLOX-1 levels was found in the plasma (**A**) and synovial fluid (**B**) of RA patients, as compared with OA patients and healthy controls. Bars show the mean ± SEM of samples from individual RA patients, OA patients, and healthy controls. *** = $P < 0.001$. **C**, Receiver operating characteristic curve analyses of the sLOX-1 levels in the plasma or synovial fluid demonstrate that the area under the curve can differentiate patients with RA from patients with OA and healthy controls. These results show that the levels of sLOX-1 in the plasma (left and middle) and in the synovial fluid (right) are a highly sensitive and specific diagnostic marker for RA.

cantly decreased by the sLOX-1 original conditioned medium (Figure 3A). Moreover, as shown in Figure 3B, the inhibitory effect of an excess amount of unlabeled ox-LDL or sLOX-1, compared to that of DiI-labeled ox-LDL alone, was significant.

To further investigate the role of sLOX-1 in mediating the effects of ox-LDL in RA FLS, we tested the effects of sLOX-1 on the expression of MMPs 1 and 3 in the presence of the sLOX-1 concentrated medium. Incubation of the FLS with the sLOX-1 concentrated medium for 24 or 48 hours caused a significant decrease in the ox-LDL–induced production of both MMP-1 and MMP-3 (Figure 3C).

Role of plasma and synovial fluid sLOX-1 as a potent diagnostic marker for RA. To examine whether sLOX-1 is useful for the diagnosis of RA, we analyzed sLOX-1 levels in plasma and synovial fluid from 47 patients with RA (mean age 59 years, age range 17–87 years), 32 patients with OA (mean age 72.1 years, age range 44–80 years), and 30 healthy control subjects (plasma only; mean age 46.5 years, age range 32–60 years). As shown in Figure 4A, sLOX-1 levels in the plasma of RA patients (mean ± SEM 189.3 ± 36 pg/ml) were significantly higher ($P < 0.001$) compared with those in the plasma of OA patients (74.2 ± 3.9 pg/ml) and healthy controls (21.4 ± 9.9 pg/ml). Similarly, in the synovial fluid, the levels of sLOX-1 were significantly higher in the RA group (mean ± SEM 53,548 ± 8,186 pg/ml) than in the OA group (3,893 ± 1,162 pg/ml; $P < 0.001$) (Figure 4B). No correlation between age and sLOX-1 concentration was found (results not shown).

To assess the diagnostic value of the plasma sLOX-1 level, an ROC curve analysis of sLOX-1 was performed (Figure 4C). ROC curve analyses of sLOX-1 plasma levels revealed a high sensitivity and specificity for differentiating patients with RA from healthy controls (area under the curve [AUC] 0.96, at an optimal cutoff point of 57 pg/ml). In ROC curve analyses of sLOX-1 plasma levels comparing RA patients with OA patients, the AUC was 0.84 (at an optimal cutoff point of 99 pg/ml). Similar AUC values were obtained in comparisons of the sLOX-1 levels in the synovial fluid. ROC curve analyses showed that the sLOX-1 levels in the synovial fluid had a higher sensitivity and specificity for differentiating patients with RA from patients with OA (AUC 0.89, at an optimal cutoff point of 11,145.7 pg/ml).

Plasma and synovial fluid sLOX-1 levels as a marker of RA disease activity. To investigate whether the plasma and synovial fluid sLOX-1 levels could reflect

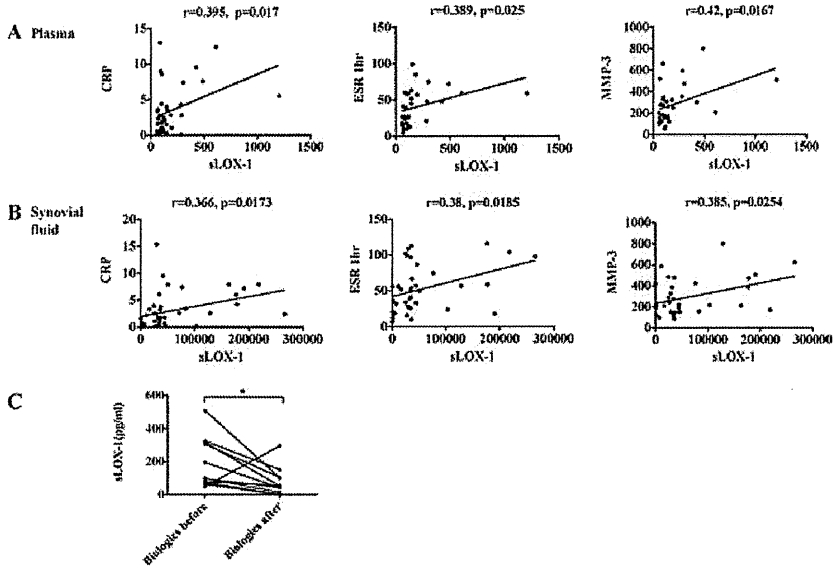

Figure 5. Correlation between the levels of soluble lectin-like oxidized low-density lipoprotein receptor 1 (sLOX-1) and rheumatoid arthritis (RA) biomarkers, such as the C-reactive protein (CRP) level, erythrocyte sedimentation rate (ESR), and matrix metalloproteinase 3 (MMP-3) level, in plasma and synovial fluid samples from patients with RA. **A** and **B,** Circulating sLOX-1 levels in the plasma (**A**) and synovial fluid (**B**) were positively correlated with the CRP level, ESR, and MMP-3 level. **C,** The plasma sLOX-1 levels were examined before and after treatment of RA patients with biologic agents. Plasma sLOX-1 levels were significantly decreased after biologic treatment in all but 1 patient. Representative results from individual patients are shown. * = $P < 0.05$.

the extent of RA disease activity, we examined the correlation between sLOX-1 levels and other clinical laboratory variables. The levels of sLOX-1 in the plasma (Figure 5A) and in the synovial fluid (Figure 5B) correlated with the serum levels of CRP, the ESR, and the levels of MMP-3, but not with the serum levels of LDL cholesterol or other lipoprotein-related markers (results not shown).

To investigate whether sLOX-1 levels in the plasma were decreased by effective biologic treatment, we examined the sLOX-1 levels before and after anticytokine treatment among 11 RA patients who had not previously been treated with a biologic agent. Almost all of the anticytokine therapies decreased the sLOX-1 concentration, irrespective of the agent administered (Figure 5C), and these effects correlated with decreases in the DAS28 (mean ± SEM change from 5.98 ± 0.21 before treatment to 3.19 ± 0.38 after treatment), the serum CRP level (from 3.33 ± 0.50 mg/dl before treatment to 0.33 ± 0.13 mg/dl after treatment), the ESR (from 52.4 ± 4.7 mm/hour before treatment to 15.7 ± 3.8 mm/hour after treatment), and the MMP-3 level (from 429.2 ± 67.4 ng/ml before treatment to 132.1 ± 39.0 ng/ml after treatment) (results not shown).

Improvement in articular cartilage degradation and arthritic changes in ox-LDL–treated mice after blockade of LOX-1. To assess the role of ox-LDL and LOX-1 in the pathogenesis of arthritis in vivo, we injected ox-LDL, native LDL, or PBS into the right knee joints of mice once per day for 7 days and evaluated the development of joint inflammation. The contralateral knees received a sham operation, with a skin incision but no injection. Injection of the materials did not cause any systemic effects, such as weight loss, or apparent morbidities (results not shown).

Differences in knee joint diameters between the injected knee and the contralateral sham-operated knee were substantially increased by the injection of ox-LDL into the right knee joint, whereas differences between the injected knee and the contralateral knee were less substantial when the right knee joint was injected with native LDL (results not shown). Results of immunohistochemistry showed prominent LOX-1 expression in the cartilage and synovium in the ox-LDL–treated group, whereas the native LDL–treated group displayed hardly any positive staining for LOX-1 (results not shown).

To examine whether anti–LOX-1 treatment had any therapeutic efficacy, we administered an anti–

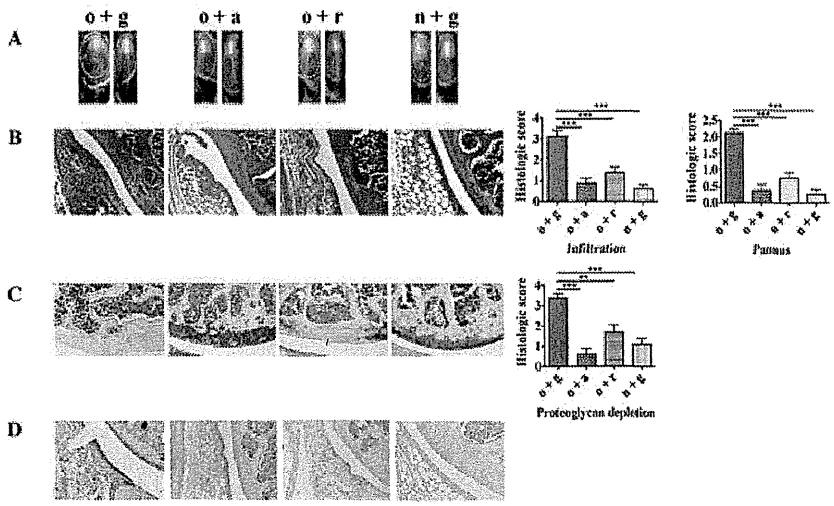

Figure 6. Effects of recombinant soluble lectin-like oxidized low-density lipoprotein (ox-LDL) receptor 1 (sLOX-1) extracellular domain and of an anti–LOX-1 neutralizing antibody on ox-LDL–induced arthritic changes in the knee joints of mice in vivo. **A,** To induce inflammatory arthritis, the right knee joints of mice received an intraarticular injection of ox-LDL (o), or native LDL (n) as a control (left panels in each pair); the contralateral knees received a sham operation (right panels in each pair). One hour prior to injection, the right knee joints were treated with anti–LOX-1 (o + a) or recombinant LOX-1 protein (o + r); IgG was used as a treatment control (o + g or n + g). Representative macroscopic images of paired knee joints from different mice are shown. **B,** Histologic features of joint inflammation (left) and histologic scores for inflammatory cell infiltration and pannus formation (right) were assessed in hematoxylin and eosin–stained, paraffin-embedded knee joint sections in each treatment group (corresponding to the groups shown in **A**). **C,** Histologic features of the cartilage (left) and histologic scores for proteoglycan depletion (right) were assessed in Safranin O–fast green–stained, paraffin-embedded knee joint sections in each treatment group (corresponding to the groups shown in **A**). Results in **B** and **C** are the mean ± SEM of 5 mice per group. ** = $P < 0.01$; *** = $P < 0.001$. **D,** Expression of matrix metalloproteinase 3 (MMP-3) protein was determined using immunohistochemical analyses of the knee joint sections from each treatment group (corresponding to the groups shown in **A**). Original magnification × 200 in **B–D.**

LOX-1 neutralizing antibody, recombinant LOX-1 protein (equivalent to sLOX-1), or control IgG via intra-articular injection 1 hour before ox-LDL administration. Pretreatment with the anti–LOX-1 antibody or recombinant LOX-1 suppressed joint swelling, whereas control IgG did not (Figure 6A). Hematoxylin and eosin staining also revealed that treatment with ox-LDL caused massive synovial hyperplasia, with significantly increased inflammatory cell infiltration and pannus formation, compared with that in the native LDL–treated controls (Figure 6B). In contrast, pretreatment with the anti–LOX-1 antibody or with the recombinant LOX-1 significantly inhibited the synovial hyperplasia induced by ox-LDL treatment, reducing it to the levels observed in the native LDL–treated controls.

In addition, we analyzed the extent of proteoglycan depletion in the mouse joints, using Safranin O staining. The results showed significantly higher depletion in the ox-LDL–treated joints compared with those treated with native LDL (Figure 6C). In contrast, pretreatment with the anti–LOX-1 antibody or the recombinant LOX-1 significantly prevented proteoglycan loss in the articular cartilage.

To clarify the involvement of proteinases in the loss of proteoglycans, the expression of MMP-3 was examined in the mouse joints using immunohistochemical analysis (Figure 6D). High levels of MMP-3 protein were observed in the synovium and articular cartilage after administration of ox-LDL plus control IgG. In contrast, MMP-3 protein expression was markedly reduced in the joints pretreated with the anti–LOX-1 antibody or recombinant LOX-1.

DISCUSSION

The importance of early diagnosis and intervention to prevent the progression of joint damage is well recognized in RA, considering the high propensity of the disease toward joint destruction, even during periods of clinical remission (30). Laboratory tests are critical for the identification of RA at an early stage, as exemplified by the fact that the newly developed RA classification criteria include both diagnostic markers and inflammation markers, in addition to physical findings (31). Recently, we and others have reported that the circulating level of sLOX-1 is a potential diagnostic and prog-

nostic biomarker for acute coronary syndrome (19–21) and is associated with levels of inflammation markers (32).

Consistent with these findings from previous studies, we showed here that sLOX-1 levels in the plasma and synovial fluid of RA patients were markedly elevated as compared with those in non-RA controls. Furthermore, the ROC curve analyses indicated that the diagnostic sensitivity and specificity of sLOX-1 levels for RA were much higher than those obtained when using anti–cyclic citrullinated peptide antibody levels for the diagnosis of RA (33). These results clearly indicate that sLOX-1 is a powerful biomarker to differentiate patients with RA from patients with OA and healthy controls.

Among the currently available clinical tests for the evaluation of RA disease activity, the DAS28 (which includes the CRP level or ESR) is the most widely used in clinical practice. Although the CRP level and ESR are frequently used in the monitoring of patients, these measures are nonspecific for RA and were only weakly correlated with the other parameters of disease activity (34). The present study showed that sLOX-1 levels were positively correlated not only with laboratory markers, such as the CRP level, ESR, and MMP-3 level, but also with the extent of disease activity. A variety of cell types contribute to the increase in sLOX-1 levels in the plasma and synovial fluid, including endothelial cells, articular chondrocytes, and, more importantly, synovial fibroblasts, as well as cells involved in the activation of the immune system in response to various cytokines and ox-LDL. These findings suggest that the production of sLOX-1 is reflective of a whole set of inflammation mechanisms that may contribute to the pathogenesis of RA, and therefore, that sLOX-1 may be a sufficiently reliable biomarker for RA disease activity (Figure 4).

Although previous studies have demonstrated the potential roles of sLOX-1 in atherosclerotic diseases (19–21), the functional role of sLOX-1 in the pathogenesis of RA is not fully understood. We previously reported that ox-LDL was taken up by rat chondrocytes and reduced the viability of the cells via LOX-1 (35). Similarly, in the present study, we demonstrated that ox-LDL was taken up by human RA FLS, thus reducing the viability of the cells (results not shown), and also showed that the addition of sLOX-1 concentrated medium into the cultures significantly decreased the effects of ox-LDL on the production of MMPs 1 and 3 in FLS in vitro (Figure 3C). Consistent with this observation, we demonstrated that the knee joint arthritis induced by ox-LDL injection was decreased in mice treated with recombinant LOX-1 extracellular domain (sLOX-1) in vivo (Figure 6).

Taken together, these results indicate that sLOX-1 may compete with LOX-1 for the uptake of ox-LDL at the cell surface and neutralize inflammation to reduce joint destruction. Therefore, our current results collectively suggest that sufficient pharmacologic amounts of sLOX-1 can competitively prevent ox-LDL from binding to cell surface LOX-1 and reduce the detrimental effects of ox-LDL–LOX-1 signaling. These mechanisms may present an attractive avenue for the development of a desired novel treatment for RA using sLOX-1.

FLS and macrophages are 2 of the predominant cell types involved in RA synovitis. Both types of cells produce high levels of proinflammatory cytokines and mediate inflammatory cell responses in RA. Studies have shown that LOX-1 is expressed by vascular endothelial cells and macrophages in atherosclerotic lesions (36,37), but in the present study, LOX-1 was highly expressed not only in these cells, but also in FLS in the RA synovium (Figure 1). Importantly, the LOX-1 gene is an immediate early gene that processes the NF-κB response (11,13) and is dynamically modulated by proinflammatory mediators. Since LOX-1 is easily upregulated by cytokines, LOX-1 could have an important role in amplification of the local inflammatory response during systemic inflammation, as in RA. Therefore, blockade of the LOX-1 signal would be beneficial for the prevention of inflammation and cartilage destruction in RA.

The use of biologic agents yielded a paradigm shift in the treatment of RA. At present, the biologic treatments that are currently available target proinflammatory cytokines and lymphocytes; however, direct prevention of joint destruction is required, as the degree of physical disability in RA patients depends on the extent of joint destruction (38). In the present study, we showed, for the first time, that ox-LDL induces synovial inflammation and cartilage destruction in RA, and that this mechanism may be mediated by the production of MMP-3 and, possibly, MMP-1 in humans. Although MMP-3 (and MMP-1) may not be the only molecules produced from FLS via LOX-1 signaling, and they may not be uniquely responsible for the degradation of the cartilage, such a mechanism of ox-LDL–LOX-1 signaling, via the direct and potent induction of MMP-1 and MMP-3 from FLS, may render the anti–LOX-1 treatment unique in terms of its regulative abilities in both synovial inflammation and cartilage matrix degradation.

The lipid profiles and lipoprotein patterns observed in patients with RA are reportedly altered and may contribute to the high incidence of atherosclerotic CVD (39,40). This suggests that there is a common

pathophysiologic background between RA and atherosclerosis. Similar to what occurs in atherosclerosis, the lipids and lipoproteins present in the synovial fluid from inflamed joints in RA patients are oxidized (41), and the serum levels of ox-LDL are associated with the levels of disease activity in RA (42). We have previously shown that blockade of LOX-1 in animal models suppresses intimal hyperplasia after balloon injury and inhibits myocardial ischemia (43,44). Results from previous studies and those of the present study demonstrate that blockade of LOX-1 suppresses synovitis and cartilage destruction in the inflamed joints, as shown in zymosan-induced arthritis and ox-LDL–induced arthritis. In this study, sLOX-1 levels in the plasma and synovial fluid of RA patients were markedly elevated and were positively correlated with the extent of RA disease activity, similar to the findings reported previously in atherosclerotic diseases. Taken together, these results suggest that anti–LOX-1 therapy is highly potent in terms of preventing not only the destruction of the joints, but also the cardiovascular events that may occur in patients with RA.

One of the major limitations of this study was the lack of clinical trial data pertaining to LOX-1 blockade in human RA. Before such trials are initiated, mouse RA models should be used to validate the efficacy and side effects of a neutralizing anti–LOX-1 antibody and sLOX-1. Moreover, in this study, we administered a neutralizing anti–LOX-1 antibody and sLOX-1 directly into the knee joints. Further investigations are needed to estimate the effects of systemic administration on multiple joint swelling and joint cartilage destruction.

Although proinflammatory cytokines, such as TNFα, have profiles that are similar to those of ox-LDL in inflammation and cartilage degradation, we and others have reported that even proinflammatory cytokines have physiologic functions in homeostasis and tissue healing (45,46). Compared with the action of such cytokines, ox-LDL–LOX-1 signaling seems to play a major role in only a harmful way, thus lessening any concern regarding the undesirable side effects of anti–ox-LDL–LOX-1 treatments when compared with the side effects of anticytokine agents. Therefore, an anti–ox-LDL treatment that would achieve blockade of LOX-1 could be highly promising, as this signal is crucial for the fundamental inflammation that occurs during the pathophysiologic processes and degradation of joint cartilage in RA.

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AUTHOR CONTRIBUTIONS

All authors were involved in drafting the article or revising it critically for important intellectual content, and all authors approved the final version to be published. Dr. Ito had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Study conception and design. Ito, Kume, Yasuda, Nakamura.

Acquisition of data. Ishikawa, Akiyoshi, Yoshitomi, Mitsuoka, Tanida, Murata, Shibuya, Kasahara, Kakino, Fujita.

Analysis and interpretation of data. Ishikawa, Ito, Kume, Yoshitomi, Sawamura.

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Stromal Cell-Derived Factor 1 Regulates the Actin Organization of Chondrocytes and Chondrocyte Hypertrophy

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Abstract

Stromal cell-derived factor 1 (SDF-1/CXCL12/PBSF) plays important roles in the biological and physiological functions of haematopoietic and mesenchymal stem cells. This chemokine regulates the formation of multiple organ systems during embryogenesis. However, its roles in skeletal development remain unclear. Here we investigated the roles of SDF-1 in chondrocyte differentiation. We demonstrated that SDF-1 protein was expressed at pre-hypertrophic and hypertrophic chondrocytes in the newly formed endochondral callus of rib fracture as well as in the growth plate of normal mouse tibia by immunohistochemical analysis. Using SDF-1$^{-/-}$ mouse embryo, we histologically showed that the total length of the whole humeri of SDF-1$^{-/-}$ mice was significantly shorter than that of wild-type mice, which was contributed mainly by shorter hypertrophic and calcified zones in SDF-1$^{-/-}$ mice. Actin cytoskeleton of hypertrophic chondrocytes in SDF-1$^{-/-}$ mouse humeri showed less F-actin and rounder shape than that of wild-type mice. Primary chondrocytes from SDF-1$^{-/-}$ mice showed the enhanced formation of philopodia and loss of F-actin. The administration of SDF-1 to primary chondrocytes of wild-type mice and SDF-1$^{-/-}$ mice promoted the formation of actin stress fibers. Organ culture of embryonic metatarsals from SDF-1$^{-/-}$ mice showed the growth delay, which was recovered by an exogenous administration of SDF-1. mRNA expression of type X collagen in metatarsals and in primary chondrocytes of SDF-1$^{-/-}$ mouse embryo was down-regulated while the administration of SDF-1 to metatarsals recovered. These data suggests that SDF-1 regulates the actin organization and stimulates bone growth by mediating chondrocyte hypertrophy.

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Introduction

Endochondral ossification is an essential process for skeletal development [1]. During skeletogenesis, mesenchymal cells aggregate at the sites where skeletal elements will eventually be formed, and they differentiate into chondrocytic lineage and proliferate. The cartilage templates are composed of nonhypertrophic (resting and proliferating) and hypertrophic chondrocytes as well as vast amounts of extracellular matrix produced by chondrocytes [1]. Chondrocyte hypertrophy is a unique step in chondrocyte differentiation, in which the cells become bigger and rather transparent, and is a mandatory event allowing calcification, vascularization, osteoblast differentiation, and remodeling into bone to occur [2].

A number of secreted or intracellular polypeptides cooperatively regulate the transition of chondrocyte hypertrophy. PTH-related peptide, Indian hedgehog, fibroblast growth factors, SRY (sex determining region Y)-box 9 (Sox9) and Wnt proteins are reportedly essential factors for chondrocyte hypertrophy [3–8]. However, much less is known about the intracellular events, such as cytoskeletal reorganization that can allow the cell size and shape to change.

Stromal cell-derived factor-1 (SDF-1)/pre-B cell growth-stimulating factor belongs to CXC subfamily of chemokines as CXCL12 [9,10]. SDF-1 signals through a G-protein-coupled receptor, C-X-C chemokine receptor 4 (CXCR4) [10,11] and, CXCR7 [12,13], and critical roles of SDF-1/CXCR4 in hematopoietic stem cells (HSCs) have been extensively reported.

During the last decade, accumulating data have supported an emerging hypothesis that SDF-1/CXCR4 also plays pivotal roles in the biological and physiological functions of mesenchymal stem cells (MSCs) [14,15]. SDF-1 is up-regulated at sites of injuries and serves as a potent chemoattractant to recruit circulating or residing CXCR4-expressing MSCs which are necessary for a tissue-specific organ repair or regeneration in liver [16], heart [17,18], brain [19], kidney [20], and skin [21]. We have recently demonstrated

that SDF-1 recruited MSCs to bone repairing sites in the acute phase of endochondral bone repair [22]. However, little is known on roles of SDF-1/CXCR4 signal on the bone growth and the endochondral bone formation.

In the process of chondrogenesis, chondrocytes change cell shape from a fibroblastoid to a round or polygonal morphology, which is called as hypertrophic conversion [23], a unique and crucial step in chondrocyte differentiation. The molecular mechanisms responsible for this cell shape change are largely unknown, but the actin cytoskeleton presumably plays important roles in this context. The only intracellular signaling known to associate with the actin reorganization during chondrocyte differentiation is RhoA/ROCK [24–26]. The reports on RhoA/ROCK suggest that the changes in morphology have important roles in chondrocyte differentiation. On the other hand, SDF-1 induces cytoskeleton rearrangements in homing and migration of hematopoietic cells through Phosphoinositide 3-kinase/Akt and RhoA/ROCK signaling [27,28], which can lead to an assumption of the important roles of SDF-1 on the shape and size changes of chondrocytes. This assumption, however, remains to be largely investigated.

We herein demonstrated that SDF-1 is crucial for endochondral bone development. The embryonic humeri of SDF-$1^{-/-}$ mice were shorter than those of wild-type mice, especially prominent in the hypertrophic zone. The actin cytoskeleton of SDF-$1^{-/-}$ chondrocytes in the humeri and in monolayer culture was disturbed. With cultured metatarsal explants of SDF-$1^{-/-}$mice, the lack of SDF-1 impaired the development of metatarsals and chondrocyte hypertrophy, and the addition of SDF-1 reversed the impairments. Our results strongly suggest that SDF-1 regulates actin polymerization and stimulates bone growth by mediating chondrocyte hypertrophy.

Results

Distribution of SDF-1 in the Growth Plate and the Endochondral Callus

To evaluate potential roles of SDF-1 in endochondral bone formation, we analyzed the distribution of SDF-1 in the tibial growth plates from 4-week-old wild-type mice and newly formed endochondral callus of rib fracture model at day 10 by immunohistochemistry. SDF-1 was expressed at prehypertrophic and hypertrophic chondrocytes both in the growth plate (**Figure 1A**) and in the endochondral callus (**Figure 1B**), suggesting important roles of SDF-1 on the transition from prehypertrophic to hypertrophic chondrocytes in endochondral bone formation.

Delayed Growth and Reduced Size of the Hypertrophic Zone of SDF-$1^{-/-}$ Mouse Humeri

To investigate the effect of SDF-1 in endochondral bone formation, we next evaluated the phenotypic differences between SDF-$1^{-/-}$ and wild-type mice. The humeri were resected from embryos at E13.5, E14.5, E15.5, and E16.5 (n = 4 at each point), and processed in paraffin sections (**Figure 2A**). The lengths of the total humeri and the ratios of proliferating, hypertrophic, and calcified zones were measured (**Figure 2B**). The total length of the whole humerus of SDF-$1^{-/-}$ mice was shorter than that of wild-type mice in E14.5, E15.5, and E16.5 by 17.9%, 24.7%, and 6.8%, respectively, with statistical significances. To examine which zone contributed to the total length difference, we evaluated the proliferating, hypertrophic, and calcified zones of the humeri as the percentages against the total length. The ratio of hypertrophic zone was significantly smaller in SDF-$1^{-/-}$ mice than in wild-type mice at E14.5 and E15.5 by 21.2% and 31.0%, respectively. The ratio of calcified zone was also smaller in SDF-$1^{-/-}$ mice than in wild-type mice at E14.5 and E15.5 by 45.0% and 36.0%, respectively, with statistical significances. The most marked difference was found at E15.5, especially in the hypertrophic zone, while no significant differences were observed in any zones at E13.5. No significant difference was found in cell proliferation rates between SDF-$1^{-/-}$ and wild-type mice based on 5-Bromo-2′ deoxy-uridine (Brd-U) staining (**Figure S1**). These results demonstrated the absence of SDF-1 mainly affects the growth of the hypertrophic zone rather than the proliferating zone.

Absence of SDF-1 Impairs Cytoskeleton of Hypertrophic Chondrocytes

SDF-1 signaling leads to cytoskeleton rearrangements and integrin activation in hematopoietic cells [27]. Chondrocytes change their shape drastically from a fibroblastoid to a round shape during chondrogenesis. The reorganization of the actin cytoskeleton is also demonstrated to be important in hypertrophic transition of chondrocytes [24]. To determine whether SDF-1 affects the reorganization of the actin cytoskeleton and cellular morphology, we stained the frozen sections of the humeri from SDF-$1^{-/-}$ and wild-type mouse embryos (E15.5) with Rhodamine-Phalloidin. No clear difference between SDF-$1^{-/-}$ and wild-type hypertrophic chondrocytes was detected in the HE staining (data not shown) and in the differentiation interference image (**Figure 3A**). But interestingly, the Rhodamine-Phalloidin staining showed that the hypertrophic chondrocytes in SDF-$1^{-/-}$ mice was rounder than wild-type mice. Quantification of F-actin revealed that F-actin content of hypertrophic chondrocytes in SDF-$1^{-/-}$ mice was significantly lower than wild-type mice ($P<0.05$, **Figure 3B**). Next, to measure the ellipticity of chondrocytes, we calculated the ratio of a short axis to the long axis (1/ellipticity). The reciprocal of ellipticity was significantly higher in SDF-$1^{-/-}$ chondrocytes than in wild-type chondrocytes ($P<0.05$, **Figure 3C**), which support the roundness of SDF-$1^{-/-}$ hypertrophic chondrocytes. These tendencies were also observed in hypertrophic chondrocytes of SDF-$1^{-/-}$ metatarsals (data not shown).

SDF-1 Controls the Actin Organization of Primary Chondrocytes

Based on the results described above, we investigated whether SDF-1 regulates the actin cytoskeleton of the chondrocytes, F-actin of primary chondrocytes were stained with Rhodamine-Phalloidin. Untreated chondrocytes from wild-type mice had a defined cortical rim, minimal stress fibers, and a polyhedral shape (**Figure 4**). With treatment of SDF-1 (100 ng/ml), the chondrocytes changed their shape into contractile rounded shape in a time-dependent manner. Incubation of the chondrocytes for 10 m with SDF-1 showed the actin stress fiber formation.

Next, wild-type primary chondrocytes were treated with SDF-1, or SDF-1 and CXCR4 specific antagonist, TF14016 [29] (100 μM), or pertussis toxin (PTX, 100 ng/ml) for 60 m (**Figure 5A**). Treatment with SDF-1 to primary chondrocytes resulted in contractile rounded cells with thick cortical rim of actin filaments. The chondrocytes treated with SDF-1 and TF14016 showed the similar morphology to untreated chondrocytes. Cells treated with SDF-1 and PTX showed slight induction of actin stress fibers. In quantitation of the F-actin in the Rhodamine-Phalloidin-stained cells, the F-actin content treated with SDF-1 for 60 m was significantly higher than the actin density of the

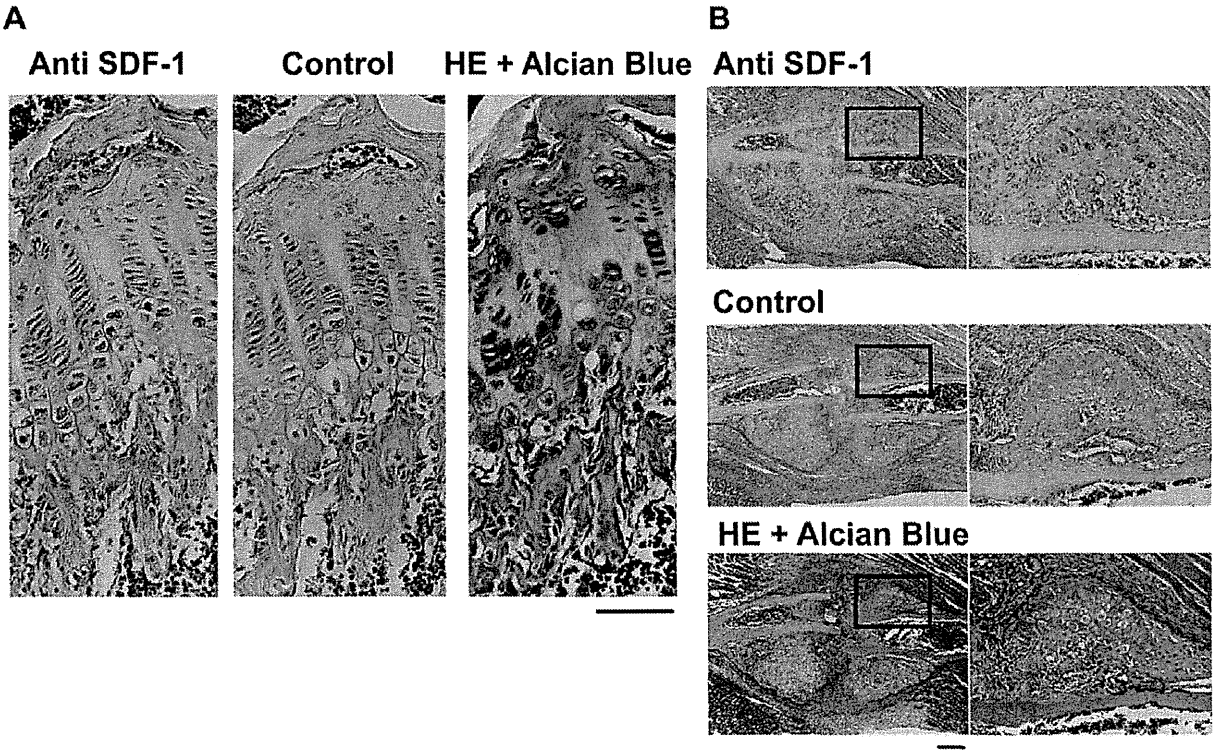

Figure 1. SDF-1 protein was expressed at the prehypertrophic and hypertrophic zones. The growth plate of 4-week-old mouse tibia (A) and endochondral callus of rib fracture (B) were stained with hematoxylin and eosin (HE), or immunohistochemically stained with antiSDF-1 antibody or IgG (control). Boxed areas in the panel are shown in a higher magnification (×200) in the right panels. The result is representative of three separate experiments; Scale bar, 200 μm.
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chondrocytes treated with either medium alone, SDF-1+PTX, or SDF-1+TF14016 (**Figure 5B**).

Then we investigated the actin filaments of primary chondrocytes from SDF-$1^{-/-}$ mice. Those chondrocytes clearly showed the enhanced formation of philopodia and the lost of F-actin through 7-day culture, compared with those of wild-type mice. The administration of recombinant SDF-1 to the chondrocytes of SDF-$1^{-/-}$ mice inhibited the philopodia formation and the loss of F-actin. The cortical rim and shape of SDF-$1^{-/-}$ chondrocytes with recombinant SDF-1 was similar to that of wild-type chondrocytes (**Figure 5C**). Quantification of F-actin revealed that actin density of SDF-$1^{-/-}$ chondrocytes was lower than that of wild-type chondrocytes and of SDF-$1^{-/-}$ chondrocytes incubated with recombinant SDF-1 ($P<0.01$, $P<0.05$, respectively) (**Figure 5D**). These results suggest that SDF-1/CXCR4 signaling strongly affects the reorganization of the actin cytoskeleton and the cellular morphology in primary chondrocytes.

Deficit of SDF-1/CXCR4 Signaling Delays the Growth of Metatarsals in Organ Culture

The phenotypic changes of SDF-$1^{-/-}$ mice exclusively occurred from E14.5 to E16.5. This period corresponds to the time of the vascular invasion, which indicates that molecular and/or cellular factors from circulation compensate for the lack of SDF-1. To verify the independent effects of endogenous SDF-1 in pre-vascularized bone, we used the primary metatarsal explant culture system. The metatarsal bones were harvested from wild-type mice at E15.5, cultured for 7 days, and the total length was measured at day 1, 3, 5 and 7 (**Figure 6**). We first confirmed that no vascular formation was observed in metatarsal bones at this stage by histology (data not shown).

As shown in **Figure 6A**, the metatarsal bones of wild-type mice kept up growing during the whole culture period and the ratio of the total length growth reached to 134% at day 7. The growth delayed at every time point in SDF-1+/− and SDF-$1^{-/-}$ mice, and the ratios of the total length growth remained 128% and 121% at day 7, respectively. At the end of this culture assay, the total length of SDF-$1^{-/-}$ metatarsal bones was 9.7% shorter than wild-type metatarsals with statistical significance, indicating the functional effect of endogenous SDF-1 in the normal bone growth. Then, to investigate whether SDF-1 can restore the perturbed growth of SDF-$1^{-/-}$ metatarsal bones, 100 ng/ml of SDF-1 was added to the primary metatarsal culture system. The treatment of SDF-1 significantly regained the ratio of the total length growth of SDF-$1^{-/-}$ metatarsals from 124% to 137% at day 7, which was the similar growth rate of wild-type metatarsals. Interestingly, during this assay, we observed calcified zones, verified by von Kossa staining, were found in 80.0%, 69.2%, and 16.7% of wild-type, SDF-1+/−, and SDF-$1^{-/-}$ metatarsals, respectively at day 7 (**Figures 6B, C**), indicating that the delayed differentiation of hypertrophic chondrocytes affects the calcification of those cells in SDF-$1^{-/-}$ mice, which was consistent with the phenotype of the SDF-$1^{-/-}$ humerus (**Figure 2**).

These results strongly support the notion that self-produced SDF-1 is crucial for endochondral bone development at the pre-vascularized stage.