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Citation

Issue Date
2010-02-08

URL
http://hdl.handle.net/2433/98035

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Type
Journal Article

Textversion
publisher

Kyoto University
Loss of the BMP antagonist USAG-1 ameliorates disease in a mouse model of the progressive hereditary kidney disease Alport syndrome

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Introduction
The renal glomerular basement membrane (GBM) is a key component of the filtering unit in the kidney. Mutations involving any of the collagen IV genes (COL4A3, COL4A4, and COL4A5) affect GBM assembly and cause Alport syndrome, a progressive hereditary kidney disease with no definitive therapy. Previously, we have demonstrated that the bone morphogenetic protein (BMP) antagonist uterine sensitization–associated gene-1 (USAG-1) negatively regulates the renoprotective action of BMP-7 in a mouse model of tubular injury during acute renal failure. Here, we investigated the role of USAG-1 in renal function in Col4a3−/− mice, which model Alport syndrome. Ablation of Usag1 in Col4a3−/− mice led to substantial attenuation of disease progression, normalization of GBM ultrastructure, preservation of renal function, and extension of life span. Immunohistochemical analysis revealed that USAG-1 and BMP-7 colocalized in the macula densa in the distal tubules, lying in direct contact with glomerular mesangial cells. Furthermore, in cultured mesangial cells, BMP-7 attenuated and USAG-1 enhanced the expression of MMP-12, a protease that may contribute to GBM degradation. These data suggest that the pathogenetic role of USAG-1 in Col4a3−/− mice might involve crosstalk between kidney tubules and the glomerulus and that inhibition of USAG-1 may be a promising therapeutic approach for the treatment of Alport syndrome.

Conflict of interest: The authors have declared that no conflict of interest exists.

Citation for this article: J Clin Invest doi:10.1172/JCI39569.
Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice showed less glomerular and tubular injury. (A) Representative histological findings in Usag1<sup>+/−</sup>Col4a3<sup>−/−</sup> mice (WT/KO) and Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (KO/KO) at 6 weeks and 10 weeks of age. Scale bars: 100 μm. (B) Quantitative assessment of the number of glomeruli, percentages of sclerotic and hemorrhagic glomeruli, and tubulointerstitial fibrosis score in Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (WT/KO) and Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (KO/KO) at 6 weeks and 10 weeks of age. Bars indicate the mean ± SD. **P < 0.01; ***P < 0.05. (D) Electron microphotographs in Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (WT/KO) and Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (KO/KO) at 4 weeks and 10 weeks of age. Arrows indicate the splitting of GBM. Scale bars: 5 μm. (E) Immunostaining for α1(IV) and α3(IV) collagen in the glomeruli of WT littermates (WT/WT), Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (WT/KO), and Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (KO/KO) at 6 weeks of age. Podocin was used as a podocyte marker. Note the positive staining for α1(IV) collagen along with the GBM of Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (WT/KO) and Usag1<sup>−/−</sup>Col4a3<sup>−/−</sup> mice (KO/KO), while the staining is restricted to mesangial areas in the glomeruli of WT littermates.
expressed in distal tubules and colocalizes with BMP-7 in distal convoluted tubules and connecting tubules (26). Furthermore, Usag1−/− mice are resistant to tubular injury such as acute renal failure and interstitial fibrosis, and USAG-1 is the central negative regulator of BMP function in the adult kidney (27). Because in adults the expression of USAG-1 is confined to the kidneys, targeting the activity of this protein might yield safer and more kidney-specific therapies than the administration of BMP-7 (23). For this, it will be important to first elucidate the role of USAG-1 in the pathology of progressive glomerular injury.

Here we show that genetic ablation of USAG-1 significantly attenuated the disease progression and preserved renal function in Col4a3−/− mice, a model for human Alport syndrome. The observations in this study suggest that USAG-1 might contribute to the pathogenesis of renal deterioration by a mechanism we believe to be novel that involves crosstalk between the macula densa of the distal tubules and the mesangium of the belonging glomerulus. In addition, we demonstrate that in the kidney of Col4a3−/− mice, TGF-β signaling includes phosphorylation of Smad1/5/8, transcription factors classically considered to be the downstream effectors of BMP signaling.

**Results**

*Loss of USAG-1 slows progression of glomerular injury in Alport mice.*

Col4a3−/− mice, a mouse model of human Alport syndrome, develop progressive glomerulonephritis associated with tubulointerstitial fibrosis leading to renal failure. Kidneys from Col4a3−/− mice showed irregular thickening and splitting of the GBM at 4 weeks of age by electron microscopy. At 5 weeks of age, proteinuria is initiated, and at 6 weeks of age, minor glomerular lesion is occasionally observed by light microscopy. At 10 weeks of age, severe glomerular lesions associated with tubulointerstitial fibrosis are observed, and renal function deteriorates.

To test the role of USAG-1 in the progression of end-stage renal disease originating from glomerular injury, mice deficient in both Col4a3 gene and Usag1 gene were generated (Usag1−/−Col4a3−/− mice). A histological examination of the kidneys from Usag1−/−Col4a3−/− mice revealed segmental sclerosis and intraglomerular hemorrhage at 6 weeks of age, while these changes were almost completely absent in Usag1−/−Col4a3−/− mice (Figure 1, A and B). At 10 weeks of age, Usag1−/−Col4a3−/− mice demonstrated glomerulosclerosis associated with inflammatory cell infiltration, interstitial fibrosis, tubular atrophy, and cast formation, while these changes significantly decreased in Usag1−/−Col4a3−/− mice (Figure 1, A and C).

An ultrastructural analysis of GBM using transmission electron microscopy at 4 weeks of age showed that Usag1−/−Col4a3−/− mice had extensive splitting of the GBM, while Usag1+/−Col4a3−/− mice showed almost normal GBM structure (Figure 1D). Usag1−/−Col4a3−/− mice at 10 weeks of age also exhibited a significant preservation of GBM structure in comparison with age-matched Usag1+/−Col4a3−/− mice (Figure 1D).

The immunostaining of α1(IV) or α3(IV) collagen was performed to compare the glomerular localization of α1(IV) collagen in both genotypes (Figure 1E). The expression of α1(IV) collagen was detected in the GBM of both Usag1−/−Col4a3−/− and Usag1+/−Col4a3−/− mice, while the expression was confined to mesangial area in the WT mice. The expression of α3(IV) collagen was absent in the GBM of both Usag1−/−Col4a3−/− and Usag1+/−Col4a3−/− mice, while the expression was detected along the GBM in the WT mice. Therefore, regardless of the presence or absence of USAG-1, no alteration was observed in the glomerular localization of α(IV) collagen.

Usag1−/−Col4a3−/− mice showed less albuminuria, preserved renal function, and longer life span. An analysis of urinary albumin excretion at 6 weeks of age is shown in Figure 2A, demonstrating significantly less albuminuria in Usag1−/−Col4a3−/− mice than in Usag1+/−Col4a3−/− mice. The systolic blood pressure of Usag1−/−Col4a3−/− mice at 5 weeks of age was slightly lower than that of Usag1+/−Col4a3−/− mice (Supplemental Figure 2; supplemental material available online with this article; doi:10.1172/JCI39569DS1). Renal function of Usag1−/−Col4a3−/− mice at 10 weeks of age, as assessed by serum creatinine and blood urea nitrogen, was also significantly preserved in comparison with that of Usag1−/−Col4a3−/− mice (Figure 2B), consistent with the results of renal histology and urinary albumin excretion. Furthermore, upon aging beyond 13 weeks, Usag1−/−Col4a3−/− mice showed less mortality than Usag1+/−Col4a3−/− mice (Supplemental Figure 1).

Inflammatory cytokine expression was significantly reduced in Usag1−/−Col4a3−/− mice. As previously reported, the mRNA of inflammatory cytokines such as TNF-α, IL-1β, monocyte chemoattractant protein-1 (MCP-1), and TGF-β was upregulated in the kidneys of Usag1−/−Col4a3−/− mice at 10 weeks of age (28, 29). In Usag1−/−Col4a3−/− mice, however, increases in inflammatory cytokines were signifi-
RESULTS

Figure 3
The expression of inflammatory cytokines significantly decreased in the kidneys of Usag1+/−Col4a3+/− mice. (A) Real-time RT-PCR analysis of inflammatory cytokine mRNA in the kidneys of WT littermates (WT/WT), Usag1+/−Col4a3+/− mice (WT/KO), and Usag1+/−Col4a3−/− mice (KO/KO) at 10 weeks of age. The expression levels were normalized to those of GAPDH and expressed relative to those of WT littermates (n = 10). Bars indicate the mean ± SD. *P < 0.001; **P < 0.01; ***P < 0.05. (B) Representative immunostaining for MCP-1 in the kidneys of WT littermates (WT/WT), Usag1+/−Col4a3+/− mice (WT/KO), and Usag1+/−Col4a3−/− mice (KO/KO) at 10 weeks of age. Scale bars: 100 μm.

Figures 3 and 4

The phosphorylation of Smad1/5/8 in the kidneys of Usag1+/−Col4a3+/− mice was significantly increased in comparison with WT mice as well as Usag1+/−Col4a3−/− mice (Figure 3A). This resulted in enhanced expression of MCP-1, TNF-α, and IL-1β (Figure 3B). However, the phosphorylation of Smad1/5/8 was unexpectedly increased in the kidneys of Usag1+/−Col4a3−/− mice in comparison with WT mice as well as Usag1−/−Col4a3−/− mice.

The expression of inflammatory cytokines significantly decreased in the kidneys of Usag1+/−Col4a3+/− mice. (A) Real-time RT-PCR analysis of inflammatory cytokine mRNA in the kidneys of WT littermates (WT/WT), Usag1+/−Col4a3+/− mice (WT/KO), and Usag1+/−Col4a3−/− mice (KO/KO) at 10 weeks of age. The expression levels were normalized to those of GAPDH and expressed relative to those of WT littermates (n = 10). Bars indicate the mean ± SD. *P < 0.001; **P < 0.01; ***P < 0.05. (B) Representative immunostaining for MCP-1 in the kidneys of WT littermates (WT/WT), Usag1+/−Col4a3+/− mice (WT/KO), and Usag1+/−Col4a3−/− mice (KO/KO) at 10 weeks of age. Scale bars: 100 μm.

Figure 3

The expression of inflammatory cytokines significantly decreased in the kidneys of Usag1+/−Col4a3+/− mice. (A) Real-time RT-PCR analysis of inflammatory cytokine mRNA in the kidneys of WT littermates (WT/WT), Usag1+/−Col4a3+/− mice (WT/KO), and Usag1+/−Col4a3−/− mice (KO/KO) at 10 weeks of age. The expression levels were normalized to those of GAPDH and expressed relative to those of WT littermates (n = 10). Bars indicate the mean ± SD. *P < 0.001; **P < 0.01; ***P < 0.05. (B) Representative immunostaining for MCP-1 in the kidneys of WT littermates (WT/WT), Usag1+/−Col4a3+/− mice (WT/KO), and Usag1+/−Col4a3−/− mice (KO/KO) at 10 weeks of age. Scale bars: 100 μm.
USAG-1 was not expressed in the Alport glomeruli. USAG-1 is expressed predominantly in the distal tubules, more specifically, in the thick ascending limb, distal convoluted tubules, and connecting tubules in adult kidneys, and not expressed in glomeruli (26). In situ hybridization was used to determine the expression of USAG-1 in Usag1+/Col4a3−/− mice and demonstrated that USAG-1 expression was not detectable in the glomeruli of Usag1+/Col4a3−/− mice either (Figure 6A) and was confined to tubules.

USAG-1 colocalizes with BMP-7 in the macula densa. Deficiency of USAG-1 significantly attenuated glomerular pathology in the Col4a3−/− mouse model of Alport syndrome in spite of the absence of USAG-1 expression in glomeruli. Further experiments focused on the part of the distal tubule that came in contact with its own glomerulus, the macula densa (Figure 6B). To investigate potential mechanisms that are responsible for the beneficial effect of USAG-1 deficiency in Alport syndrome, the effect of BMP-7 and USAG-1 in cultured mesangial cells was examined. The expression of MMP-12 in cultured mesangial cells was upregulated by the administration of IL-1β and TGF-β, but not by the administration of MCP-1 (Figure 6D), in spite of the fact that MCP-1 is reported to stimulate MMP-12 expression in podocytes (29). The administration of BMP-7 suppressed TGF-β–induced MMP-12 upregulation in mesangial cells, and simultaneous administration of USAG-1 antagonized the suppressive effect of BMP-7 (Figure 6E). These results indicate that USAG-1 might enhance MMP-12 expression in the glomeruli by suppressing the inhibitory effect of BMP-7 and exacerbate glomerular disease progression in Alport syndrome.
expression and activity of MMPs, which play key roles in disease progression of Alport syndrome. Furthermore, USAG-1 and BMP-7 colocalized in the macula densa, a part of the distal tubules in contact with its own glomerulus, and BMP-7 reduced MMP-12 expression in mesangial cells, which was antagonized by USAG-1.

USAG-1 exacerbates glomerular injuries as well as tubular interstitial fibrosis. Tubular damage and interstitial fibrosis are the final common pathways leading to end-stage renal disease (ESRD) (38, 39) irrespective of the nature of the initial renal injury, and the degree of tubular damage parallels the impairment of renal function (39). Severe tubulointerstitial fibrosis is observed following glomerular injury in Col4a3−/− mice, and this exacerbates renal function. Because Usag1−/− mice were resistant to tubulointerstitial fibrosis (27), this resistance might contribute at least in part to the preservation of renal function in Usag1−/−Col4a3−/− mice. In addition, Usag1−/− Col4a3−/− mice showed preserved GBM with less albuminuria in the early stage when tubular injury has yet to appear. Therefore, Usag1−/−Col4a3−/− mice were resistant to both glomerular and tubular injuries.

USAG-1 increases the expression of MMP in Col4a3−/− mice. The molecular mechanisms by which the altered GBM composition in Alport syndrome causes renal pathogenesis remain unclear. It is proposed that abnormal persistence of α1/α1/α2(IV) collagen network in the adult GBM is associated with increased susceptibility to proteolysis by proteases in Alport syndrome (3, 9) and pharmacological ablation of MMP activities, especially MMP-12, leads to a significant attenuation in Alport disease progression (29, 40). The expression and activities of MMPs were significantly upregulated in the kidneys of Usag1−/−Col4a3−/− mice, which is consistent with previous reports, and they were suppressed in the kidneys of Usag1−/−Col4a3−/− mice. The suppression of MMP activities probably contributed, at least in part, to slow glomerular pathogenesis in Usag1−/−Col4a3−/− mice. In addition, the administration of BMP-7 decreased the expression of MMP-12 in cultured mesangial cells, and USAG-1 antagonized the action of BMP-7. Therefore, USAG-1 might increase the expression of MMP in glomeruli and accelerate GBM destruction in Col4a3−/− mice.

Other possible roles of USAG-1 and BMP-7 in glomerular pathogenesis in Col4a3−/− mice. In addition to the inhibitory effect on MMP expression, BMP-7 possibly inhibits the progression of glomerular pathogenesis in Col4a3−/− mice at multiple steps. BMP-7 reduces the damage in podocytes (20, 41, 42) and mesangial cells (43–45) and attenuates the expression of inflammatory cytokines (46) and...
Apoptosis in several types of cells (12, 41). Antagonizing the beneficial effects of BMP-7 by USAG-1 might enhance these injuries and accelerate glomerular pathogenesis in Alport syndrome.

USAG-1 secreted from distal tubules reaches the glomerulus and accelerates glomerular injury. Although the mechanism by which USAG-1 secreted from distal tubules reaches the glomerulus and exacerbates glomerular pathogenesis is not entirely clear, a crosstalk may exist between the distal tubule and the glomerulus in the same nephron.

The distal tubule of a nephron makes contact with the vascular pole of its glomerulus from which the distal tubule originated. At this point, there is a plaque of very specialized and differentiated cells in the distal tubule known as the macula densa (Figure 6B). The macula densa detects changes in the distal tubular fluid composition and transmits signals to the adjacent extraglomerular mesangial cells and afferent arterioles (47–53). Extraglomerular mesangial cells are anatomically in continuity with the glomerular mesangial cells and transmit the signal from the macula densa to the glomerular mesangial cells.
The signals from the macula densa to the mesangial cells involve small diffusible substances (ATP or adenosine) released from the macula densa (47, 54). Multiphoton imaging demonstrates the water flow across the macula densa into the mesangial cell field at varying osmolarities in the luminal fluid (47). The histological characteristics of the macula densa also support the idea of substance transportation from the macula densa to mesangial cells: the nuclei of macula densa cells are apically located, while most of cell organelles tend to be located basally and laterally, thus indicating that the substances from the macula densa are possibly secreted basolaterally (Figure 7A). In addition, the basement membrane of the macula densa is fused with the basement membrane of the extraglomerular mesangial cells, indicating the lack of a barrier to interfere with the substance transportation from the macula densa to the glomerulus (Figure 7A). Furthermore, Hugo et al. demonstrated that extraglomerular mesangial cells function as reserve cells for glomerular mesangial cells (55). Extraglomerular mesangial cells stimulated by substances secreted from the macula densa migrate into glomerulus after glomerular injury and repopulate as mesangial cells.

As shown in Figure 6C, both USAG-1 and BMP-7 are expressed in the macula densa, and USAG-1 secreted from the basolateral membrane of macula densa could inhibit the action of BMP-7 on the adjacent mesangial cells. In the experiments using cultured mesangial cells, BMP-7 significantly attenuated TGF-β-induced MMP-12 upregulation, and the inhibitory effect of BMP-7 was abolished by the addition of USAG-1. Moreover, BMP-7 reduced TGF-β-induced cytotoxicity in mesangial cells (data not shown). Therefore, USAG-1 might exacerbate glomerular pathogenesis in Alport syndrome through accelerating upregulation of GBM-degrading enzyme and cytotoxicity by inhibiting the renoprotective effects of BMP-7 (Figure 7B).

An alternative possibility that may explain the effect of USAG-1 on glomerular injury is an interaction between circulating USAG-1 and BMP-7 in plasma. BMP-7 is present in plasma at a concentration range of 100–300 pg/ml (12). Due to the lack of an effective ELISA system, the plasma level of USAG-1 remains to be determined. If an appropriate amount of USAG-1 is present in the circulation, it could therefore bind to BMP-7 and thus inhibit its activity. To test the effect of circulating USAG-1 in the progression of Col4a3−/− mice, we performed systemic gene transfer of USAG-1 expression vector to Usag1−/−Col4a3−/− mice and demonstrated that the difference in albuminuria between the gene transfer group and the control group was not statistically significant (Supplemental Figure 3).

**Novel therapeutic approach for Alport syndrome.** At present there is no definitive therapy to prevent or slow renal disease progression in Alport syndrome. Several studies using a mouse model of Alport syndrome have provided potential therapies, such as MMP inhibitor (29, 40), angiotensin-converting enzyme inhibitor (56), statins (57), transplantation of bone marrow–derived stem cells (58–60), and total body irradiation (61). The results of the present study support the notion that therapeutic trials to inhibit the function of USAG-1 may become a novel therapeutic approach for Alport syndrome either alone or in combination with other approaches. A therapeutic trial targeting USAG-1 is promising because it is expected to be effective in both glomerular and tubular injuries, is more kidney-specific, and has fewer extrarenal effects because the expression of USAG-1 is confined to the kidney.

**Methods**

*Mice.* The Usag1−/− mice used in this study have been described previously (27), and Col4a3−/− mice were purchased from Jackson Laboratory (JAX mice strain 129-Col4a3m1Dec/J) (62). Usag1−/−Col4a3−/− mice were generated by breeding Usag1−/− and Col4a3−/− mice. Col4a3−/− littermates (Usag1−/−Col4a3−/− mice) and WT littermates (Usag1−/−Col4a3+/+ mice) served as controls. All animal studies were approved by the Animal Research Committee, Graduate School of Medicine, Kyoto University, and performed in accordance with the guidelines of Kyoto University.

**Figure 7** Hypothetical model for involvement of USAG-1 secreted from distal tubules in the pathogenesis of glomerular damage in Alport syndrome. (A) The macula densa (red), a part of the distal tubules, lies beside the extraglomerular mesangial cells (green), and the nuclei of the macula densa cells are apically located, suggesting the possibility that substances (blue) might be secreted from the basolateral membrane of the macula densa. Note that the basement membrane of the macula densa cells is continuous with the basement membrane of the extraglomerular mesangial cells. (B) In Usag1−/−Col4a3−/− mice (WT/KO), the mesangial cells are activated (purple) and secrete MMPs (scissors), which degrade GBM. Following GBM destruction, podocytes residing on the GBM are damaged (brown) and albuminuria is observed. BMP-7 (blue) secreted from the macula densa is captured by USAG-1, which is also secreted from the macula densa. As a consequence, BMP-7 cannot bind to its receptors and exert its renoprotective action. In Usag1−/−Col4a3−/− mice (KO/KO), BMP-7 secreted from the macula densa can bind to its receptors on mesangial cells and podocytes, and protect fragile alport GBM from degradation.
Age-matched mice were used for all studies. The ages of mice used in each experiment are described below.

**Assessment of albuminuria.** The mice were placed in metabolic cages, and urine was collected over a 24-hour period. During the urine collection, mice were allowed free access to food and water. Urinary albumin concentration was measured using the Albuwell M assay kit (Exocell).

**Renal histopathology and electron microscopy.** The kidneys were fixed in Carnoy’s solution and embedded in paraffin. Sections (2-μm thick) were stained with PAS for routine histological examination, and the degree of morphological change was determined for ten 10-week-old mice and five 6-week-old mice per group by experienced pathologists who were blinded to the genotypes. The following parameters were evaluated: percentage of hemorhagic glomeruli and sclerotic glomeruli; and tubular atrophy/interstitial fibrosis score. Tubular atrophy/interstitial fibrosis was graded as follows: grade 0, 0%–24%; grade 1, 25%–49%; grade 2, 50%–74%; grade 3, ≥75%.

Frozen sections of the kidneys were immunostained as previously described (63). The primary antibodies were against podocin (64), α1 (H11), and α3 (H31) chains of type IV collagen (a gift from Y. Sado; ref. 65), MCP-1 (R&D Systems), MMP-12 (Santa Cruz Biotechnology Inc.), nNOS (Cayman Chemical and Abcam), and LacZ (Cappel Laboratory). For double staining with β-gal, immunostaining was performed before β-gal staining to avoid the possibility that the deposition of X-gal might interfere with the antibody binding to the antigen. For electron microscopy, portions of the cortex were fixed in 2% glutaraldehyde and post-fixed in 1% osmic acid. After embedding, ultrathin sections were stained with uranyl acetate and lead citrate.

**β-Gal staining and in situ hybridization.** β-Gal staining and in situ hybridization were performed as described previously (26, 66). The probe for in situ hybridization of USAG-1 mRNA contained the 1.0-kb open reading frame with GC content of 52.6%. Hybridization was detected using an anti-digoxigenin antibody conjugated with alkaline phosphatase and Nitro blue tetrazolium chloride/5-bromo-4-chloro-3-indolyl phosphate, 4-toluidine blue-N-staining to avoid the possibility that the deposition of X-gal might interfere with the antibody binding to the antigen. For electron microscopy, portions of the cortex were fixed in 2% glutaraldehyde and post-fixed in 1% osmic acid. After embedding, ultrathin sections were stained with uranyl acetate and lead citrate.

**Statistical analysis.** All data are presented as the mean ± SD. Statistical significance was assessed by Student’s t test for 2 group comparisons and by ANOVA, followed by Fisher’s protected least significant difference post-hoc test for multiple group comparisons. Significance was defined as a value of P < 0.05.

**Acknowledgments** We thank Y. Kaziroy, Y. Nabeshima, and T. Nakamura for valuable comments and discussion. We also thank Y. Sado for excellent subtype-specific antibodies against type IV collagen and J. Nakamura, N. Suzuki, and A. Hosotani for excellent technical assistance. This study was supported by grants-in-aid from the Ministry of Education, Culture, Science, Sports, and Technology of Japan (Wakate 177090551; Ho-Ga 19659219; Kidan C 20590954), a grant-in-aid for Research on Biological Markers for New Drug Development, Health and Labour Sciences research grants from the Ministry of Health, Labor, and Welfare of Japan (08062885), a grant from the Astellas Foundation for Research on Metabolic Disorders, a grant from the Novartis Foundation for the promotion of science, a grant from the Kato Memorial Trust for Nambyo Research, a grant from the Hayashi Memorial Foundation for Female Natural Scientists, a grant from the Takeda Science Foundation, and a grant from the Japan Foundation for Applied Enzymology.

Received for publication November 24, 2009, and accepted December 16, 2009.

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