Oral Administration of an Active Form of Vitamin D_3 (Calcitriol) Decreases Atherosclerosis in Mice by Inducing Regulatory T Cells and Immature Dendritic Cells With Tolerogenic Functions

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Objective—To determine whether the administration of an active form of vitamin D_3 (calcitriol) could prevent atherosclerosis through anti-inflammatory actions.

Methods and Results—Recent clinical studies have shown that lack of vitamin D_3 is a risk factor for cardiovascular events. Oral calcitriol administration decreased atherosclerotic lesions, macrophage accumulation, and $CD4^+$ T-cell infiltration at the aortic sinus, when compared with the corresponding observations in control mice. We observed a significant increase in $Foxp3^+$ regulatory T cells and a decrease in $CD80^+CD86^+$ dendritic cells (DCs) in the mesenteric lymph nodes, spleen, and atherosclerotic lesions in oral calcitriol–treated mice in association with increased interleukin 10 and decreased interleukin 12 mRNA expression. $CD11c^+$ DCs from the calcitriol group showed reduced proliferative activity of T lymphocytes, suggesting the suppression of DC maturation. Neutralization of CD25 in vivo revealed that calcitriol inhibited atherosclerosis mainly in a regulatory T cell–dependent manner but also partly because of a decrease in DC maturation.

Conclusion—Oral calcitriol treatment could prevent the development of atherosclerosis by changing the function or differentiation of DCs and regulatory T cells. These findings suggest that intestinal and systemic immune modulation by calcitriol may be a potentially valuable therapeutic approach against atherosclerosis. **(*Arterioscler Thromb Vasc Biol*. 2010;30:2495-2503.)**

Key Words: atherosclerosis ■ regulatory T cells ■ dendritic cells ■ immune system ■ calcitriol

The active form of vitamin D_3, $1,25(OH)_2$-dihydroxyvitamin D_3, is a secosteroid hormone that not only plays a central role in bone and calcium metabolism but also modulates the immune response. Recent epidemiological studies have shown a relationship between low plasma levels of vitamin D_3 and a predisposition to cardiovascular events.[1–3] This finding is supported by a meta-analysis showing that oral vitamin D_3 treatment contributes to the improvement of mortality from all causes, in part by decreasing cardiovascular deaths.[4] Transgenic rats constitutively expressing vitamin D-24-hydroxylase, a model of vitamin D_3 deficiency, showed aggravated atherosclerosis under a high-fat and high-cholesterol diet, when compared with control rats.[5] However, there are no reports about the direct effects of an orally administered active form of vitamin D_3 on atherosclerosis.

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It is widely recognized that atherosclerosis is a complex inflammatory disease of the arterial wall,[6,7] in which the T-lymphocyte–mediated pathogenic immune response plays a critical role. Clinical strategies developed to modulate the immune response have been insufficient for preventing atherosclerosis. Cumulative data based on experimental animal models suggest that $CD4^+$ T cells are present within plaques from the initial stages of the disease in mice, and adaptive transfer of these cells is potentially proatherogenic.[8] Accumulating evidence has revealed novel functions of several subsets of regulatory T cells (Tregs), which maintain immunologic tolerance to self-antigens and inhibit atherosclerosis development by suppressing the inflammatory response of effector T cells.[9–12] These studies have provided new insights into the immunopathogenesis of atherosclerosis and imply that promotion of regulatory immune responses may have therapeutic potential for suppression of atherosclerotic diseases.

In addition to Tregs, dendritic cells (DCs) are also reportedly involved in maintaining immune tolerance to self-

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antigens. DCs are the most potent antigen-presenting cells. They efficiently stimulate the differentiation of effector T cells from naïve T-cell precursors. DCs are also thought to perform the important function of presenting antigens to T cells, which leads to peripheral tolerance by inducing Tregs or inhibiting effector T cells.[13] DCs can be tolerogenic and immunogenic.[14] In particular, immature DCs, which downregulate major histocompatibility complex class II molecules and costimulatory molecules (eg, CD40, CD80, and CD86) have had tolerogenic properties associated with decreased interleukin (IL) 12 and enhanced IL-10 production. Recently, the contribution of DCs to atherogenesis has been extensively examined.[15–17] Furthermore, DCs and Tregs may be helpful in inducing tolerance against self-antigens within plaques. Therefore, an agent able to modulate the function of DCs and Tregs may be beneficial in the treatment of atherosclerotic disease.

Recently, several articles have reported that 1,25(OH)$_2$-dihydroxyvitamin D$_3$ induced reciprocal differentiation and/or expansion of Tregs and induced tolerogenic DCs characterized by downregulation of costimulatory molecules.[18] Calcitriol and its analogues have inhibited autoimmune disease, allergy, and the rejection of transplanted organs in animal models via induction of tolerogenic DCs and Tregs.[19–21] However, the interaction between DCs and Tregs remains to be fully elucidated. Given this background, we examined whether orally administered calcitriol would induce Tregs and tolerogenic DCs in apolipoprotein E–knockout (*ApoE*$^{-/-}$) mice and how these immune cells might contribute to the inhibition of atherosclerosis. We focused not only on systemic immune responses but also on regulation of the intestinal immune system as therapeutic targets for suppressing the formation of atherosclerotic lesions. Our findings provide the first evidence that oral calcitriol administration induces Tregs and immature DCs via the intestinal immune system and that these 2 immune cells are induced both systemically and locally in atherosclerotic lesions, resulting in mutually suppressing pathogenic immune processes that play a pivotal role in the progression of atherosclerosis.

Methods

Detailed Methods are provided in the supplemental data (available online at http://atvb.ahajournals.org).

Experimental Design

We fed 6-week-old female *ApoE*$^{-/-}$ mice 20 or 200 ng of calcitriol dissolved in carboxymethylcellulose or vehicle alone by gastric intubation with a plastic tube twice a week for 12 weeks. Mice under the same protocol as previously described were injected with either 100 μg of neutralizing CD25 monoclonal antibody (clone PC61) to deplete CD4$^+$CD25$^+$ Tregs or 100 μg of isotype-matched control rat IgG once every 4 weeks at the age of 6, 10, and 14 weeks. Mice were euthanized at the age of 18 weeks, and atherosclerotic lesions were examined as previously described.[12] All animal experiments were conducted according to the Guidelines for Animal Experiments at Kobe University School of Medicine, Kobe, Japan.

Cell Isolation Using In Vitro Cell Functional Experiments and Flow Cytometry Analyses

Purified CD4$^+$ T cells and CD11c$^+$ DCs were isolated from mesenteric lymph nodes (MLNs) and spleens. A cell proliferation assay was performed by assessing [^{3}H]thymidine incorporation. Fluorescence-activated cell sorter (FACS) analysis was performed. Total RNA was extracted from these cells for real-time RT-PCR.

Table. Body Weight, Blood Pressure, and Plasma Analyses*

Characteristics	Control Group	D$_3$ Group 20 ng	D$_3$ Group 200 ng
Body weight, g	21.2±1.1	20.8±1.0	21.5±1.0
Blood pressure, mm Hg			
Systolic	109.3±1.4	106.8±6.8	103.1±1.4
Diastolic	65.4±11.0	57.1±9.7	57.3±12.7
1,25(OH)$_2$-dihydroxyvitamin D$_3$, pg/mL	85.1±40.5	78.8±56.4	180.6±75.5†
25(OH)-hydroxyvitamin D$_3$, ng/mL	29.7±5.4	30.2±9.7	25.6±3.2
Intact PTH, pg/mL	49.5±8.1	51.9±9.1	50.0±8.8
Calcium, mg/dL	7.2±0.5	7.4±0.9	7.7±1.2
Phosphorus, mg/dL	7.7±1.0	7.3±2.7	7.7±2.3
Cholesterol, mg/dL			
Total	422.7±45.4	400.4±61.5	534.1±53.5†
Low-density lipoprotein	74.6±16.9	67.2±13.5	80.2±15.2
High-density lipoprotein	10.0±3.7	10.2±3.3	11.7±3.6
Triglyceride, mg/dL	38.2±11.6	47.5±24.7	39.3±22.6
Renin mRNA levels	1.00±0.48	NA	0.88±0.36

NA indicates not applicable; PTH, parathyroid hormone.
*Data are given as mean±SEM (6 to 9 mice per group).
†$P<0.05$ vs control mice.

Statistical Analysis

Data were expressed as mean±SEM. To detect significant differences between 2 groups or among 3 groups, an unpaired Student *t* test, a Mann–Whitney *U* test, or a 1-way ANOVA with a post hoc test was used when appropriate. $P<0.05$ was considered statistically significant.

Results

Effects of Oral Calcitriol Treatment on General Conditions and Plasma Examination Values

Calcitriol at various doses inhibits autoimmune disease (0.03 μg/kg PO per day), allergy (0.5 μg/kg SC per day), and rejection of transplanted organs (5 μg/kg PO 3 times per week) in animal models.[19–21] Compared with previous reports, the dose used in our study (10 μg/kg [200 ng] PO 2 times per week) was somewhat higher. However, severe adverse effects, such as loss in body weight and hypercalcemia, were not observed in the present study. Notably, 200 ng of calcitriol (2 times per week) significantly increased its plasma level without affecting plasma levels of 25(OH)-hydroxyvitamin D$_3$, intact parathyroid hormone, calcium, or phosphorus. Although plasma 25(OH)-hydroxyvitamin D$_3$ levels were inversely associated with renin activity in hypertensive patients,[2] and calcitriol administration led to suppression of renin in an animal model,[22] in the present study, calcitriol administration affected neither blood pressure nor renin mRNA expression in the kidney (Table). The effect of vitamin D$_3$ supplementation on blood pressure may be limited only to subjects under hypertensive conditions or vitamin D$_3$ insufficiency. Contrary to our expectations, the administra-

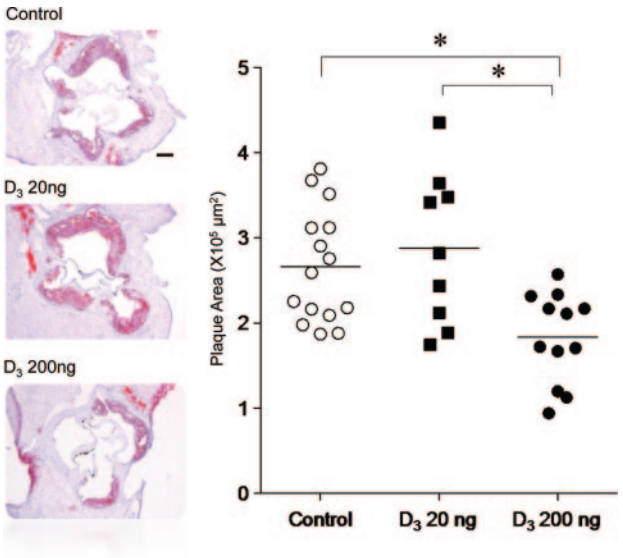

Figure 1. Oral calcitriol treatment inhibits atherosclerotic plaque formation. Images are representative photomicrographs of oil red O staining and measurement analysis of atherosclerotic lesion size in the aortic sinus of female *ApoE*$^{-/-}$ mice treated with vehicle (control), 20 ng of calcitriol (D_3 20 ng), or 200 ng of calcitriol (D_3 200 ng) for 12 weeks. The black bar on the left represents 200 μm; and horizontal bars on the right, means. *$P<0.05$ vs controls.

tion of 200 ng of calcitriol significantly increased plasma total cholesterol level (Table).

Oral Calcitriol Treatment Inhibits Atherosclerotic Plaque Formation in *ApoE*$^{-/-}$ Mice

To determine the effect of calcitriol administration on the development of atherosclerosis, 6-week-old female *ApoE*$^{-/-}$ mice receiving a standard diet were orally treated with 20 or 200 ng of calcitriol dissolved in carboxymethylcellulose or with vehicle alone twice a week for 12 weeks. At the age of 18 weeks, the mice were euthanized; and cryosections of the aortic root from the 3 groups were stained with oil red O and analyzed. Surprisingly, 200 ng of calcitriol induced a marked 39.1% reduction in atherosclerotic lesion formation (plaque area, $1.84\pm0.53\times10^5$ μm^2), when compared with the values in controls ($2.88\pm0.90\times10^5$ μm^2 [calcitriol, 20 ng] and $2.66\pm0.67\times10^5$ μm^2 [vehicle]; $P<0.05$; Figure 1).

Effects of Calcitriol on Tregs in the Small Intestine, MLNs, and Spleen

To investigate the effects of 200 ng of calcitriol treatment on Tregs in *ApoE*$^{-/-}$ mice, we performed immunohistochemical studies in the small intestine and flow cytometry analyses in MLNs and spleens. FACS analyses revealed that all of the Treg subsets, such as $CD4^+CD25^+$, $CD4^+CD25^+Foxp3^+$, and $CD4^+Foxp3^+$, were significantly increased in the calcitriol group in MLNs and spleen (compared with the control group: $P<0.05$; Figure 2A–2D). A further detailed investigation just after starting calcitriol treatment revealed that the number of Tregs first increased in MLNs (but not thymus), suggesting that the active form of vitamin D_3 mainly induces Tregs peripherally (supplemental Figure I). We also demonstrated a significant increase in intestinal $Foxp3^+$ Tregs by immunohistochemistry in the calcitriol group ($P<0.05$, Figure 2E). Next, to confirm the induction of Tregs, we applied quantitative RT-PCR to assess mRNA levels of Treg-associated markers in $CD4^+$ T cells from MLNs after positively separating them with anti–$CD4^+$ microbeads (Figure 2F). We found a significant increase in mRNA levels of Treg-associated markers (ie, CD25, Foxp3, and cytotoxic lymphocyte antigen 4 [CTLA4]) in the calcitriol group ($P<0.05$). In addition, mRNA expression of IL-10 and transforming growth factor (TGF)-β tended to increase in $CD4^+$ T cells from the MLNs of calcitriol-treated mice ($P=0.0816$ and $P=0.510$, respectively), suggesting the possibility of Treg induction. To determine whether a calcitriol-induced increase in Tregs contributes to the suppression of T-cell function, we performed in vitro proliferation assays of $CD4^+$ T cells from MLNs and spleen of the calcitriol or control group. As shown in Figure 2G, $CD4^+$ T-cell proliferation was suppressed in the calcitriol group, suggesting an increased number of Tregs by calcitriol might contribute to the suppressive potential of T lymphocytes.

Effects of Calcitriol on DCs in the Small Intestine, MLNs, and Spleen

CD80 and CD86 are recognized as important costimulatory molecules related to the maturation of DCs. We performed FACS analyses using MLN cells (Figure 3A) and splenocytes and found a significant decrease in $CD80^+CD86^+$ mature DCs within the $CD11c^+$ DC population from calcitriol-treated mice ($P<0.05$, Figure 3B). To confirm the effects of calcitriol on inhibition of DC maturation, we assessed mRNA levels of DC-associated markers in $CD11c^+$ DCs from spleens after positive selection with anti–$CD11c^+$ microbeads (Figure 3C). RT-PCR analyses revealed that CD80 and CD86 mRNA levels tended to decrease in the calcitriol group ($P=0.098$ and $P=0.1023$, respectively). Furthermore, we found a significant decrease in IL-12p40 mRNA levels and an increase in those of IL-10 in the calcitriol group ($P<0.05$). Notably, we also found a significant increase in CC-chemokine ligand (CCL)17 and CCL22 mRNA levels, which were recognized as Treg-attracting chemokines, in the calcitriol group ($P<0.05$). Consistent with previous reports,[23,24] these results indicate that calcitriol induced immature DCs, which interact with Tregs to suppress activation of immune reactions via their tolerogenic properties. To determine whether a calcitriol-induced increase in the number of tolerogenic DCs contributes to the suppression of T lymphocytes, we performed in vitro proliferation assays of $CD4^+$ T cells from Balb/c mouse spleens stimulated by $CD11c^+$ DCs from the spleens of mice from the calcitriol or control group (Figure 3D). $CD4^+$ T-cell proliferation was suppressed to a greater extent when cocultured with DCs from the calcitriol group than when cultured with DCs from the control group. These results indicated that DCs from calcitriol-treated mice resulted in reduced proliferation activity of T lymphocytes. Taken together, tolerogenic DCs induced by oral calcitriol administration suppressed T-cell immune responses and worked as antiatherogenic factors mainly by changing their cytokine and chemokine productions. We further evaluated the number of $CD11c^+CD86^+$ mature DCs in the small

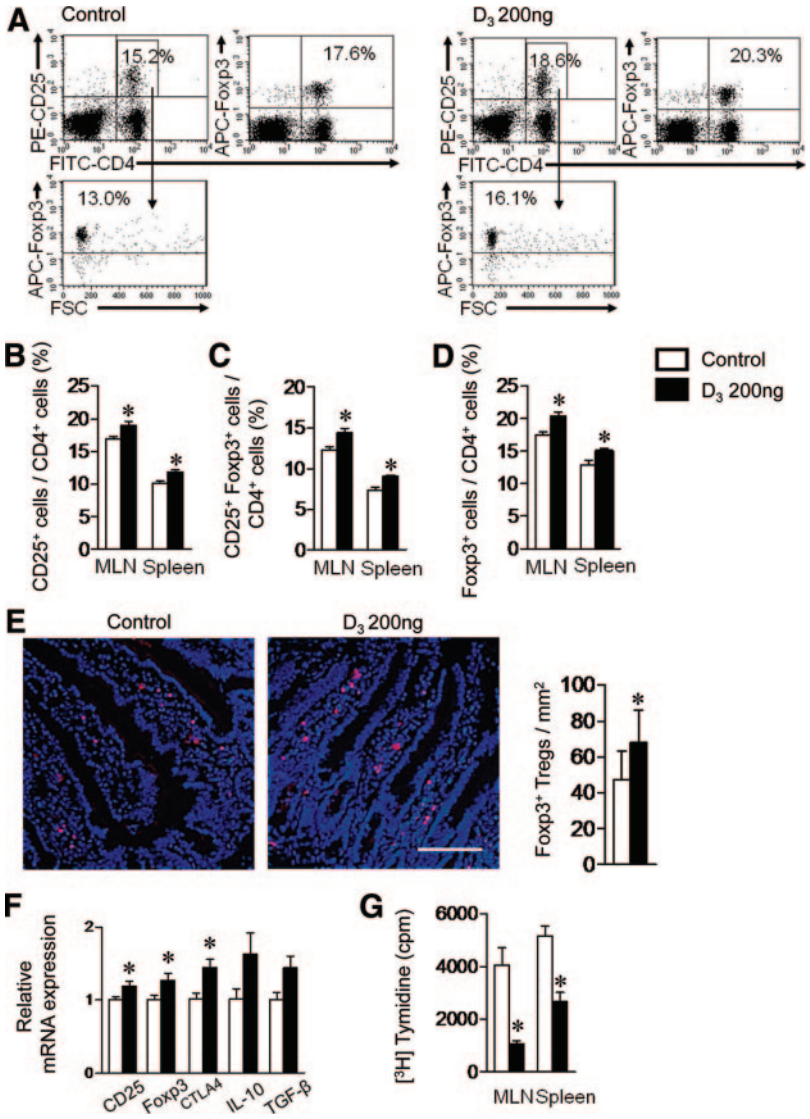

Figure 2. Effects of calcitriol on Tregs in the small intestine, MLNs, and spleen. A, Representative results of CD4, CD25, and Foxp3$^+$ expression in MLNs from the control or calcitriol group, assessed by flow cytometry. B through D, The graphs represent the percentage of CD25$^+$ cells within the CD4$^+$ population (B), CD25$^+$Foxp3$^+$ cells within the CD4$^+$ population (C), and Foxp3$^+$ within the CD4$^+$ population (D) in MLNs and spleen. For all FACS analyses, data represent mean±SEM of at least 9 mice in each group. The horizontal bars represent means. *$P<0.05$ vs control. E, Representative photomicrographs and measurement analyses of Foxp3$^+$ Treg immunostaining in the small intestine from control and calcitriol-treated mice. The white bar represents 100 μm. Data represent mean±SEM of 8 mice in each group. *$P<0.05$ vs control mice. F, Total RNA extracted from CD4$^+$ T cells from MLNs of control or calcitriol-treated mice. Expressions of CD25, Foxp3, CTLA4, IL-10, and TGF-β were quantified by quantitative RT-PCR and normalized to GAPDH. Fold changes relative to the control group are shown; n=5 to 9 per group. *$P<0.05$ vs control. G, CD4$^+$ T cells were positively selected with anti–CD4$^+$ antibody microbeads. Proliferation of CD4$^+$ T cells from MLNs and spleen of control or calcitriol-treated mice was assessed by [^{3}H]thymidine incorporation, stimulated with anti–CD3 and anti–CD28 antibodies; n=3 per group. *$P<0.05$ vs control mice. APC indicates allophycocyanin; FITC, fluorescein isothiocyanate; PE, phycoerythrin.

intestine by immunohistochemistry and revealed that there were no significant differences in the number of CD11c$^+$ DCs and CD11c$^+$CD86$^+$ mature DCs between the 2 groups (Figure 3E). However, the percentage of CD86$^+$ cells in CD11c$^+$ DCs was lower in the calcitriol group.

Effects of Calcitriol on Tregs, DCs, and Inflammatory Cells in Atherosclerotic Plaques

To evaluate the effects of calcitriol on Tregs and DCs in atherosclerotic plaques, we conducted immunohistochemical studies and RT-PCR in atherosclerotic lesions. The immunohistochemical analyses of Foxp3$^+$ Tregs in atherosclerotic lesions showed a significantly increased number of Foxp3$^+$ Tregs in the calcitriol group ($P<0.05$, Figure 4A and 4B). We further examined the expression of Treg-associated markers, such as CD25, Foxp3, and CTLA4, in atherosclerotic lesions and demonstrated that mRNA levels of all Treg-associated markers significantly increased in the calcitriol group when compared with the control group ($P<0.05$, Figure 4C). Recent studies have suggested that antigen presentation may occur within atherosclerotic plaques and in lymphoid organs and that Tregs migrate to atherosclerotic lesions to suppress local immune responses.[25] Our finding supports this notion and implies that Tregs could be a promising target in treating atherosclerotic plaques. Next, we investigated the effect of calcitriol on DCs in atherosclerotic lesions and found that the numbers of CD11c$^+$ DCs and CD11c$^+$CD86$^+$ mature DCs and the percentage of CD86$^+$ cells among CD11c$^+$ DCs were significantly decreased in the calcitriol group ($P<0.05$, Figure 4D and 4E). These results indicated that calcitriol decreased the number of DCs recruited into the plaque and that they were maintained in an immature state in atherosclerotic lesions. To reveal the effects of oral calcitriol treatment on inflammatory cells, such as macrophage and CD4$^+$ cells, we conducted immunohistochemical studies of the atherosclerotic lesions (Figure 4F and 4G). Interestingly, the 200-ng calcitriol group showed a 29.0% reduction in the accumulation of macrophages ($P<0.01$) and also a 26.4% decrease in CD4$^+$ T-cell infiltration ($P=0.02$), compared with the values recorded for the control group.

Next, to reveal the mechanisms of reduced atherosclerotic plaque development and inflammatory cell recruitment, we

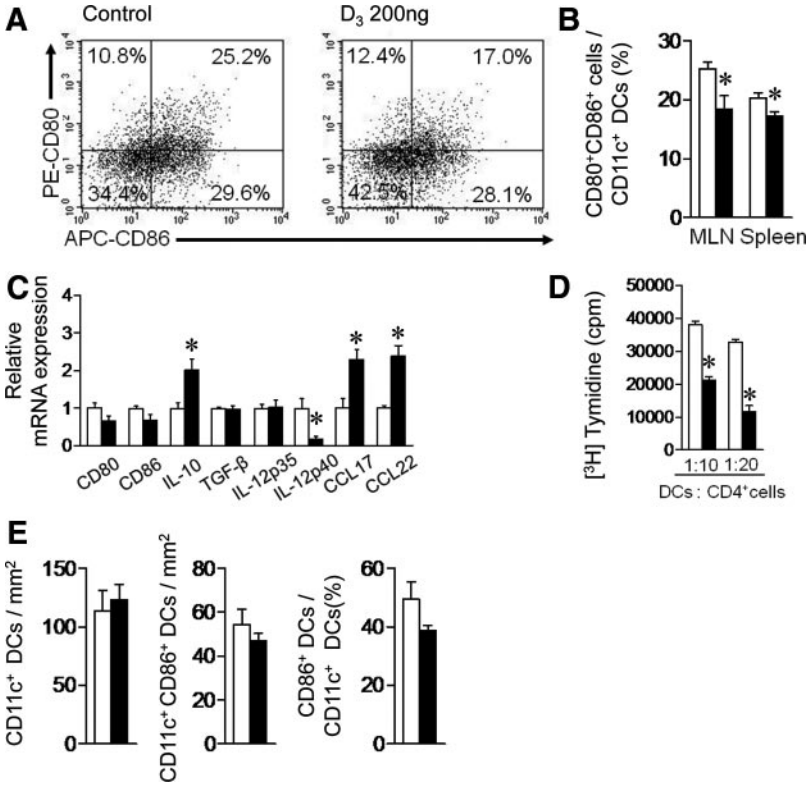

Figure 3. Effects of calcitriol on DCs in the small intestine, MLNs, and spleen. A, Representative results of CD80 and CD86 expression in $CD11c^+$ DCs of MLNs from the control or calcitriol group, assessed by flow cytometry. B, Measurement analyses of $CD80^+CD86^+$ cells in the $CD11c^+$ population in MLNs and spleens. For all FACS analyses, data represent mean±SEM of at least 6 mice in each group. The horizontal bar represent means. *$P<0.05$ vs control. C, Total RNA was extracted from $CD11c^+$ DCs from spleens of control or calcitriol-treated mice. Expressions of CD80, CD86, IL-10, TGF-β, IL-12p35, IL-12p40, CCL17, and CCL22 were quantified by quantitative RT-PCR and normalized to GAPDH. Fold changes relative to the control group are shown; n=5 to 7 per group. *$P<0.05$ vs control. D, Proliferation of $CD4^+$ T cells from spleens of Balb/c mice with $CD11c^+$ DCs from spleens of control or calcitriol-treated mice, as assessed by [^{3}H]thymidine incorporation; n=3 per group. *$P<0.05$ vs control mice. E, Measurement analyses of $CD11c^+$ DCs, $CD11c^+CD86^+$ DCs, and percentage of $CD86^+$ within the $CD11c^+$ DC population in the small intestine from control and calcitriol-treated mice. Data represent mean±SEM of 4 mice in each group. APC indicates allophycocyanin; PE, phycoerythrin.

examined mRNA expression of the proinflammatory molecules in atherosclerotic plaques by quantitative RT-PCR (Figure 4H). We found that adhesion molecule and proinflammatory chemokine and cytokine, such as vascular cell adhesion molecule-1, monocyte chemoattractant protein-1, and interferon-γ, were markedly reduced ($P<0.05$) and that anti-inflammatory cytokines, such as TGF-β and IL-10, were significantly increased ($P<0.05$) in the calcitriol group when compared with the control group. The expression of DC-derived chemokine CCL22 mRNA was significantly increased ($P<0.05$); and the expression of its receptor, CC-chemokine receptor (CCR) 4, tended to increase in atherosclerotic lesions of the calcitriol group ($P=0.0983$).

Taken together, these results indicated that calcitriol might inhibit the migration of effector T cells and macrophages into the plaques by increasing the proportion of immature DCs and Tregs systemically and locally in atherosclerotic plaques.

Inhibition of Tregs by Injection of Neutralizing Anti–CD25 Antibodies

To clarify the interaction between Tregs and DCs in preventing atherosclerosis after calcitriol treatment, we conducted an in vivo CD25 neutralization study with the injection of anti–CD25 antibody. According to a previous report,[9] the effect of a single intraperitoneal injection of 100 μg of CD25-depleting PC61 antibody was maintained for 4 weeks. In our experiment, we injected CD25-depleting PC61 antibody or isotype-matched control antibody into mice once every 4 weeks at the ages of 6, 10, and 14 weeks. Both the calcitriol and control groups receiving anti–CD25 antibody showed significantly increased atherosclerotic lesion formation when compared with the calcitriol group receiving isotype-matched control antibody ($P<0.05$, Figure 5A). These results suggested that Tregs had pivotal and major roles in inhibiting atherosclerosis after calcitriol treatment. Notably, when mice were injected with neutralizing antibody, there remained significant differences in atherosclerotic lesion formation between calcitriol-treated and control mice, indicating that calcitriol partially inhibited atherosclerotic lesion formation independent of Tregs ($P<0.05$). We also measured the percentage of Tregs by FACS in the MLNs and spleens after the injection of anti–CD25 antibody (Figure 5B–5E). In contrast with a previous report,[9] we observed a 60% to 80% depletion in $CD4^+CD25^+$ Tregs and $CD4^+CD25^+Foxp3^+$ Tregs in MLNs and spleens at 1 week after a single intraperitoneal injection of 100 μg of CD25-depleting PC61 antibody. However, all changes had reversed by 2 weeks after injection (supplemental Figure II).

We further analyzed DC maturation after partial depletion of $CD4^+CD25^+$ Tregs and observed that the rates of maturation were increased by anti–CD25 antibody administration and that the calcitriol group receiving anti–CD25 antibody still showed a decrease in the number of $CD80^+CD86^+$ mature DCs when compared with the control group receiving anti–CD25 antibody injection (Figure 5F). These data suggest that DC maturation was highly associated with the induction of Tregs, although calcitriol may partially decrease DC maturation independent of Tregs. It is likely that calcitriol mainly inhibits the progression of atherosclerosis via a Treg-dependent pathway but also a partly DC-mediated and Treg-independent manner.

Discussion

Recent clinical studies and experimental investigations have indicated that vitamin D_3 insufficiency increases the inci-

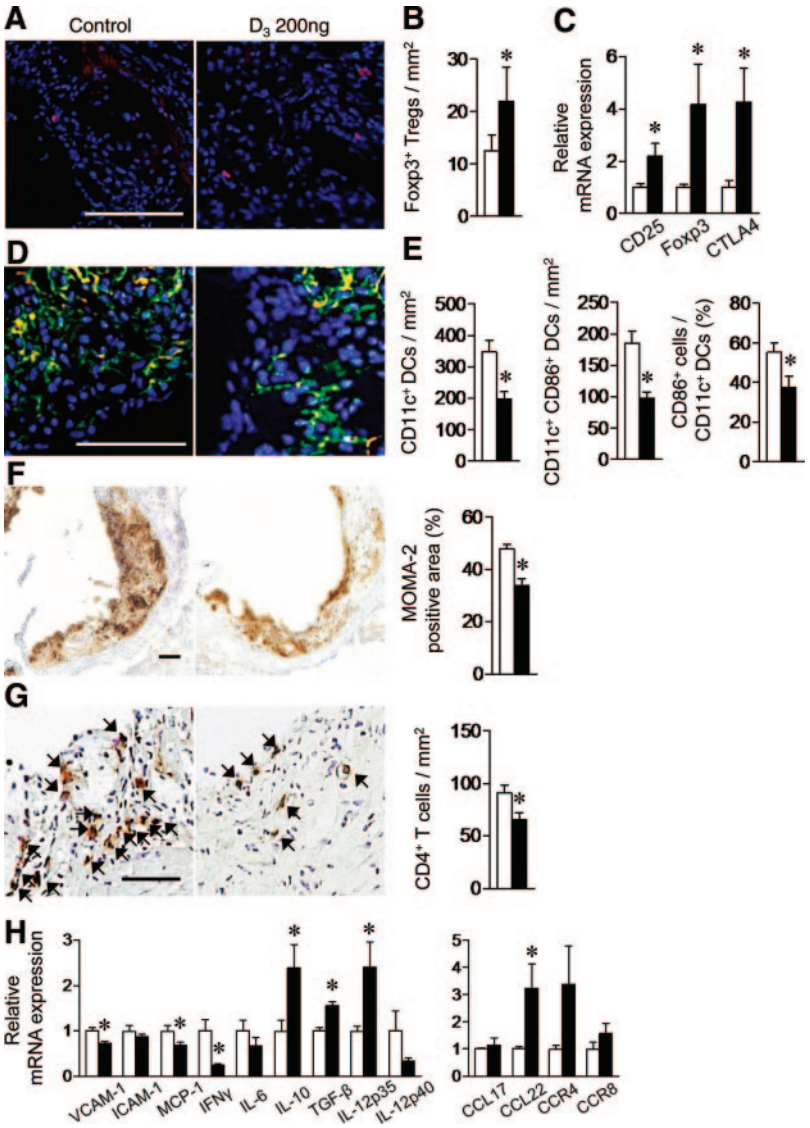

Figure 4. Effects of calcitriol on Tregs, DCs, and inflammatory cells in atherosclerotic plaques. A, Representative photomicrographs of Foxp3$^+$ Tregs in the atherosclerotic plaques of the aortic sinus from control and calcitriol-treated mice. The white bar represents 100 μm. B, Measurement analyses of Foxp3$^+$ Tregs in the plaques of the aortic sinus from control and calcitriol-treated mice. Data represent mean±SEM of 5 mice in each group. The horizontal bars represent means; and white bar, 100 μm. *P<0.05 vs control. C, Total RNA was extracted from the aortic roots of control or calcitriol-treated mice. The expressions of CD25, Foxp3, and CTLA4 were quantified by quantitative RT-PCR and normalized to GAPDH. Fold changes relative to the control group are shown; n=6 to 10 per group. *P<0.05 vs control. D, Representative photomicrographs of CD11c$^+$ (green), CD86$^+$ (red), and CD11c$^+$CD86$^+$ DCs (yellow) in the plaques of the aortic sinus from control and calcitriol-treated mice. E, Measurement analyses of CD11c$^+$ DCs and CD11c$^+$CD86$^+$ DCs and the percentage of CD86$^+$ in CD11c$^+$ DCs in the plaques of the aortic sinus from control and calcitriol-treated mice. Data represent mean±SEM of 5 mice in each group. *P<0.05 vs control mice. F and G, Representative photomicrographs of atherosclerotic lesions stained with antibodies specific for MOMA-2 for macrophages (F) and CD4$^+$ T cells (G) treated with control or calcitriol. Data represent mean±SEM of 12 mice in each group. The black bar represents 200 μm. Right panels indicate the measurement analyses of MOMA-2 and CD4$^+$ T cells of the left histological assays, respectively. The horizontal bars represent means. *P<0.05 vs control. H, Total RNA was extracted from the aortic roots of control or calcitriol-treated mice. Expression of typical adhesion molecules, cytokines, chemokines, and their receptors in atherosclerotic lesions was quantified by quantitative RT-PCR and normalized to GAPDH. Fold changes relative to the control group are shown; n=5 to 10 per group. *P<0.05 vs control. ICAM indicates intercellular adhesion molecule; IFN, interferon; MCP, monocyte chemoattractant protein; VCAM, vascular adhesion molecule.

dence of cardiovascular events.[1–3] Supplementation with an active form of vitamin D_3 (calcitriol) should have beneficial effects on cardiovascular disease (CVD) through anti-inflammatory and vasculoprotective actions.[4] However, there have been no clinical or animal studies showing the beneficial actions of vitamin D_3 in the treatment of CVD, including atherosclerosis. In the present study, we showed, for the first time to our knowledge, that oral calcitriol administration inhibited atherosclerosis in an animal model, suggesting a beneficial effect of vitamin D_3 on clinical CVD. At least 2 different cells (ie, Tregs and immature DCs) were involved in the antiatherogenic mechanisms of vitamin D_3 treatment. Although the antiatherogenic mechanism of Tregs' effect and the functional role of DCs in atherogenesis still remain to be determined, we have revealed, for the first time to our knowledge, that calcitriol-induced tolerogenic DCs and Tregs might have antiatherogenic properties.

Accumulating evidence has revealed that several subsets of Tregs have beneficial effects on atherogenesis.[9–12] Both naturally occurring CD4$^+$CD25$^+$ Tregs and IL-10–producing Tregs (Tr1) have inhibited atherosclerosis in mouse models.[10,11] Recently, it was demonstrated that an orally administrated immunomodulatory agent, anti–CD3 antibody, inhibits atherosclerosis by inducing Tregs, especially latency-associated peptide Tregs.[12] Vitamin D_3 receptor (VDR) ligands induce the differentiation of Foxp3$^+$ Tregs[18] and Tr1 in the presence of dexamethasone,[26] and both types of Tregs contribute to T-cell immune response inhibition. In the present study, FACS analyses in MLNs and spleens documented that Foxp3$^+$ Tregs were significantly increased in the calcitriol group. However, it is unlikely that Tr1 and latency-associated peptide Tregs play central roles in Treg induction by calcitriol (supplemental Figure III). Foxp3$^+$ Tregs were significantly increased in systemic lymphoid organs and atherosclerotic lesions in the calcitriol group. Although the actual roles of intraplaque Tregs in atherogenesis have not yet been clarified, a previous study suggested that increasing numbers of Tregs might suppress pathogenic T-cell immune responses or macrophage activation in atherosclerotic lesions.[12]

Several articles have previously reported that VDR ligands inhibit the differentiation and maturation of DCs.[18–21] These

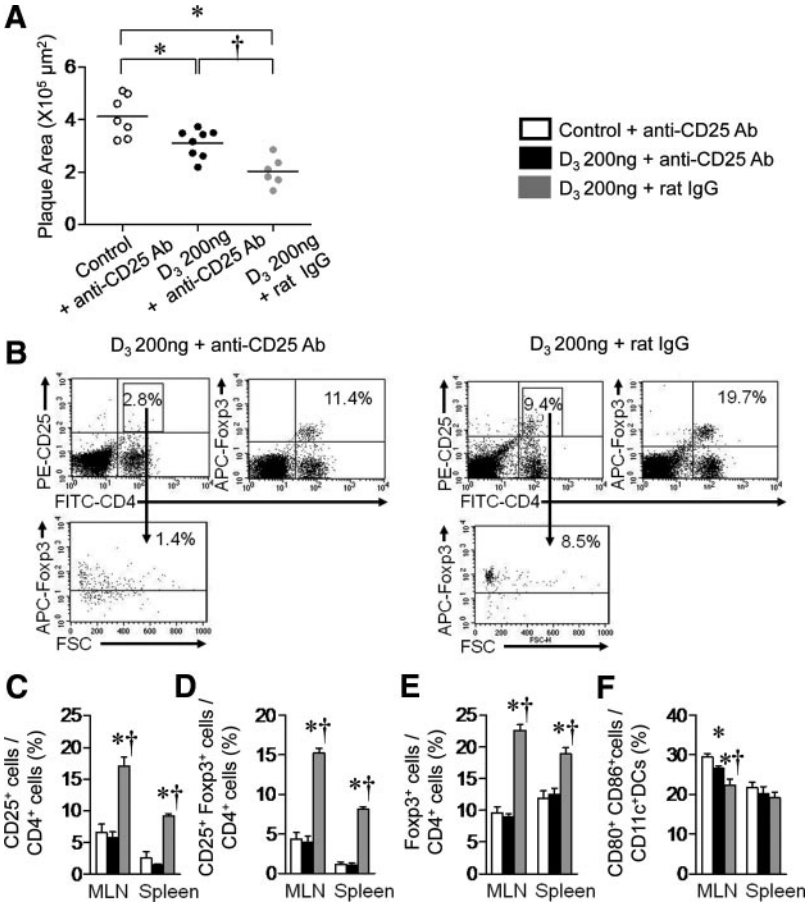

Figure 5. Inhibition of Tregs by injection of neutralizing anti–CD25 antibodies. A, Measurement analysis of atherosclerotic lesion size in the aortic sinus of female *ApoE*$^{-/-}$ mice treated with calcitriol and anti–CD25 antibodies (D_3 200 ng plus anti–CD25 antibody [Ab]), control with anti–CD25 antibodies (control plus anti–CD25 Ab), and calcitriol with isotype-matched control antibodies (D_3 200 ng plus rat IgG). The horizontal bar represents means. B, At 1 week after a single intraperitoneal injection of 100 μg of anti–CD25 or isotype-matched antibodies, lymphoid cells from spleens were prepared and stained with fluorescein isothiocyanate (FITC)–anti-CD4, phycoerythrin (PE)–anti-CD25, and allophycocyanin (APC)–anti-Foxp3. Representative results of CD4, CD25, and Foxp3$^+$ expression in MLNs from the control or calcitriol group with anti–CD25 antibodies, as assessed by flow cytometry. C through E, The graphs represent the percentage of CD25$^+$ cells within the CD4$^+$ population (C), CD25$^+$Foxp3$^+$ cells within the CD4$^+$ population (D), and Foxp3$^+$ within the CD4$^+$ population (E) in MLNs and spleen. Data represent mean±SEM of 5 mice in each group. F, The graph represents the percentage of CD80$^+$ and CD86$^+$ cells within the CD11c$^+$ population in MLNs and spleen. Data represent mean±SEM of 5 mice in each group. *$P<0.05$ vs control plus anti–CD25 Ab. †$P<0.05$ vs D_3 200 ng plus anti-CD25. FSC, forward scatter.

results included the observation that treatment of DCs with calcitriol leads to low surface expression of costimulatory molecules, such as CD80 and CD86; decreased IL-12 production; and enhanced secretion of IL-10 and CCL22, resulting in T-cell hyporesponsiveness. The presence of such costimulatory molecules on DCs is required for T-cell activation and for differentiation from naïve T lymphocytes into effector T cells. In the absence of costimulation, T cells interacting with DCs undergo anergy or apoptosis. IL-12p70, a heterodimeric cytokine consisting of p35 and p40, is released mainly by activated macrophages and DCs. IL-12p70 is a key mediator in inducing T-helper type 1 response and stimulates the production of interferon-γ from T-helper type 1. Inhibition of DC-derived IL-12p70 production is followed by a downregulated response of T-helper type 1. Furthermore, the anti-inflammatory cytokine IL-10 also inhibits T-cell immune response by acting on antigen-presenting cells, such as macrophages and DCs. Our FACS analysis revealed that CD80$^+$CD86$^+$ DCs are decreased in MLNs and spleens of calcitriol-treated mice, indicating augmentation of the immature DC phenotype. Expression of IL-12p40 mRNA in splenic DCs was decreased, and expression of IL-10 was increased. We clearly demonstrated that DCs from the calcitriol treatment group had less T-cell proliferation activity, which might indicate that DCs changed their phenotypes to tolerogenic. Recently, the functional importance of DCs in atherosclerosis has been highlighted in several animal and human studies.[15–17] Accumulating evidence suggests that DCs in atherosclerosis are involved in antigen presentation to T cells within plaques.[15] DCs present in normal arteries are immature and become activated during atherogenesis, and DCs in vessels have been involved in the initiation and progression of atherosclerosis.[16,17]

Regarding the interactions between Tregs and tolerogenic DCs, immature DCs lacking sufficient expression of costimulatory molecules have induced Tregs[13,14] and affected suppressive immunoresponses through the induction of anti-inflammatory cytokines, such as IL-10[27] and TGF-β.[28] In our study, we demonstrated that expression of IL-10 mRNA in DCs was significantly increased, whereas expression of TGF-β mRNA was not increased. In accordance with previously published findings that naïve T cells in the periphery can differentiate into Foxp3$^+$ Tregs in the presence of IL-10,[29] the increase of IL-10 in tolerogenic DCs might contribute to the induction of Tregs, including Tr1. Tregs play critical roles in the differentiation of immature DCs through the interaction of CTLA4 and CD80/CD86. Tregs constitutively express high levels of CTLA4 that bind to CD80 and CD86 with high affinity. CTLA4 activity is important for Treg-induced tolerance in several animal models.[30] The interaction of CTLA4 on Tregs with CD80/CD86 on CD11c$^+$ DCs conveyed a negative signal to DCs and reduced the expression of these costimulatory molecules on DCs in vitro.[31] In our study, CTLA4 mRNA expression in CD4$^+$ T cells was significantly increased in the calcitriol group. Taken together, we conclude that Tregs and tolero-

genic DCs might interact via CTLA4 and CD80/CD86 to induce each other, resulting in effective inhibitory immunoresponses in both cell types. We also found another important interaction between Tregs and tolerogenic DCs: expression of CCL17 and CCL22 mRNA in the splenic DCs was enhanced in the calcitriol group in this study. These chemokines are ligands for CCR4 and CCR8 expressed on Tregs.[32] DCs are the major source of CCL22 in vitro and in vivo,[33] and transcriptional changes and production of CCL22 in human myeloid DCs have been induced by calcitriol.[23,24] In the present study, calcitriol increased CCL22 expression in DCs, suggesting that DCs released Treg-attracting chemokines and attracted Tregs via CCR4. Tregs were also promoted in vivo by calcitriol administration. In addition, the percentage of immature DCs was increased in atherosclerotic lesions in the calcitriol group. Interestingly, the expression of CCL22 mRNA was significantly increased and its chemokine, CCR4, tended to increase in atherosclerotic lesions of the calcitriol group. It is likely that tolerogenic DCs release CCL22 to interact with CCR4-expressing Tregs in spleen and within atherosclerotic plaques; thus, DCs may function as antiatherogenic agents.

To clarify the roles of Tregs in the antiatherogenic effects of calcitriol and DC maturation, we examined the effect of CD25-neutralizing monoclonal antibody. Tregs characteristically express Foxp3 and, in most cases, CD25. Functional studies in which $CD4^+CD25^+$ Tregs were depleted with anti–CD25 antibodies in $ApoE^{-/-}$ mice resulted in an increase of atherosclerotic lesions.[9] In contrast to the previous study, in our model, Tregs were not completely deleted by anti–CD25 antibodies after 4 weeks; however, partial inhibition of Tregs by injection of anti–CD25 antibodies partially reversed the beneficial effects of calcitriol on atherogenesis and slightly increased DC maturation at 1 week after anti–CD25 antibody injection. These data suggest that Tregs induced by oral calcitriol administration may have an important role in inhibiting atherogenesis and that calcitriol directly decreased DC maturation and inhibited the progression of atherosclerosis, independent of Tregs; however, partly immature DCs were induced via a Treg-dependent pathway.

In the present study, oral administration of calcitriol definitely regulated and affected the function and proportion of DCs and Tregs in MLNs and reduced atherosclerotic lesion formation. It is likely that modulation of both intestinal and systemic immune systems is critical to calcitriol-induced antiatherogenic properties. In a previous article, it was reported that oral administration of anti–CD3 antibody induced latency-associated peptide T cells in MLNs and spleens.[12] We also confirmed that the maturation of DCs was inhibited and that the proportion of $CD11c^+$ $CD80^-CD86^-$ DCs in MLNs was increased at the same time, suggesting that an orally administered small amount of antibody reached the intestine (but not in the blood), possibly regulated intestinal immunity, and resulted in the mutual differentiation of tolerogenic DCs and Tregs in MLNs (N.S., unpublished data). In the present study, we demonstrated that oral calcitriol administration increased the number of Tregs in MLNs but not in the thymus (supplemental Figure I). Taken together, although we should be careful about the interpretation of our results, the intestinal immune system might be a novel therapeutic target for treatment of CVDs and atherosclerosis. This possibility must be further investigated.

In summary, we have demonstrated that oral administration of the active form of vitamin D_3 inhibits atherosclerosis development by inducing tolerogenic DCs and Tregs. We report herein, for the first time to our knowledge, that Tregs and tolerogenic DCs work as antiatherogenic agents and that both cells may play key roles in the beneficial effects of calcitriol on atherogenesis. It is likely that tolerogenic DCs recruit Tregs through chemokine CCL22 and its receptor, CCR4; both cells interact through the cell-to-cell contact of CTLA4 and CD80/CD86 at lymphoid organs and atherosclerotic lesions. These data indicate that calcitriol could be used clinically as a promising therapy for preventing atherosclerotic CVD. Clinical studies in humans are required to identify the efficacy of oral calcitriol in the prevention of atherosclerotic diseases and to evaluate the relationship between plasma levels of calcitriol and CVDs.

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Disclosures

None.

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