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The ability of cells to detect and respond to nucleotide signals in the local microenvironment is essential for vascular homeostasis. The enzyme ectonucleotide tri(di)phosphohydrolase-1 (ENTPD1, also known as CD39) on the surface of leukocytes and endothelial cells metabolizes locally released, intravascular ATP and ADP, thereby eliminating these prothrombotic and proinflammatory stimuli. Here, we evaluated the contribution of CD39 to atherogenesis in the apolipoprotein E–deficient (ApoE-deficient) mouse model of atherosclerosis. Compared with control ApoE-deficient animals, plaque burden was markedly increased along with circulating markers of platelet activation in \( Cd39^{+/−} \) ApoE\(^{−/−}\) mice fed a high-fat diet. Plaque analysis revealed stark regionalization of endothelial CD39 expression and function in ApoE\(^{−/−}\) mice, with CD39 prominently expressed in atheroprotective, stable flow regions and diminished in atheroprone areas subject to disturbed flow. In mice, disturbed flow as the result of partial carotid artery ligation rapidly suppressed endothelial CD39 expression. Moreover, unidirectional laminar shear stress induced atheroprotective CD39 expression in human endothelial cells. CD39 induction was dependent upon the vascular transcription factor Krüppel-like factor 2 (KLF2) binding near the transcriptional start site of *CD39*. Together, these data establish CD39 as a regionalized regulator of atherogenesis that is driven by shear stress.

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Flow-dependent expression of ectonucleotide tri(di)phosphohydrolase-1 and suppression of atherosclerosis

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The ability of cells to detect and respond to nucleotide signals in the local microenvironment is essential for vascular homeostasis. The enzyme ectonucleotide tri(di)phosphohydrolase-1 (ENTPD1, also known as CD39) on the surface of leukocytes and endothelial cells metabolizes locally released, intravascular ATP and ADP, thereby eliminating these prothrombotic and proinflammatory stimuli. Here, we evaluated the contribution of CD39 to atherogenesis in the apolipoprotein E–deficient (ApoE-deficient) mouse model of atherosclerosis. Compared with control ApoE-deficient animals, plaque burden was markedly increased along with circulating markers of platelet activation in Cd39+/−Apoe–/– mice fed a high-fat diet. Plaque analysis revealed stark regionalization of endothelial CD39 expression and function in Apoe–/– mice, with CD39 prominently expressed in atheroprotective, stable flow regions and diminished in atheroprone areas subject to disturbed flow. In mice, disturbed flow as the result of partial carotid artery ligation rapidly suppressed endothelial CD39 expression. Moreover, unidirectional laminar shear stress induced atheroprotective CD39 expression in human endothelial cells. CD39 induction was dependent upon the vascular transcription factor Krüppel-like factor 2 (KLF2) binding near the transcriptional start site of CD39. Together, these data establish CD39 as a regionalized regulator of atherogenesis that is driven by shear stress.

Introduction

Atherosclerotic disease remains the leading cause of death in the world (1). Development of atherosclerotic plaque is driven by dynamic interactions among the lipid milieu, fluid shear forces, cells of the vascular wall, and cells recruited from the circulation. Endothelial cells, monocytes, T cells, and platelets have all been implicated in atherogenesis (2–4). Recent studies have described the role of platelet activation in the early stages of atherogenesis via transient endothelial and mononuclear interactions and in situ release of mitogens and chemoattractants (5, 6). Activated platelets provide cholesterol that is scavenged by macrophages to form foam cells (7, 8). Studies in the last 4 decades have established the role of shear stress–induced platelet activation as well as susceptibility to atherosclerosis. Atherosclerosis predominates at branch points and areas of disturbed flow in human arteries, while regions encountering stable flow are more resistant to plaque formation (9–15). Further, a partial carotid ligation surgery induced robust atherosclerosis within 2 weeks, demonstrating that disturbed flow directly causes atherosclerosis under hyperlipidemic conditions (16). Central to this concept is the insight that flow-regulated genes, microRNAs, and epigenomic changes initiate programs that trigger activated or quiescent endothelial phenotypes and, in turn, susceptibility to or protection from atherosclerosis (4, 17–21).

The enzyme ectonucleotide tri(di)phosphohydrolase-1 (ENTPD1, also known as CD39) represents the main control system for blood fluidity and is a principal regulator of platelet and leukocyte activation in vivo. This enzyme, expressed on the surface of leukocytes and endothelial cells, is responsible for serial phosphohydrolysis of extracellular ATP to ADP and further to AMP, by virtue of its ecto-ATPase and ecto-ADPase activity (22–24). Since ADP is a potent platelet agonist via P2Y12 receptors, endothelial CD39-mediated dissipation of ADP serves as a critical negative regulator of platelet activation and recruitment (22–27). By metabolizing extracellular ATP and ADP, CD39 provides natural protection from nucleotides released from the injured vasculature or activated platelets. Here, we elucidate what we believe to be a previously unrecognized role for CD39 as an endogenous regulator of endothelial purine levels, serving as a modulator of key cellular drivers of atherosclerosis. Moreover, we demonstrate that CD39 expression is modulated by vascular fluid phase forces.

Results

CD39 deficiency enhances atherosclerotic lesion formation in ApoE-deficient mice. Expression of CD39 changes dynamically with a cell’s environment (28, 29). This phenomenon initially led us to examine the presence of CD39 in regions susceptible to atherosclerosis. Immunofluorescent staining of the apolipoprotein E–deficient (Apoe−/−)
mouse aortas revealed a stark regionalization of CD39 expression. Robust CD39 expression was present on endothelial cells overlying regions of the vascular wall protected from atherosclerosis, whereas CD39 was significantly diminished over areas prone to atherosclerosis (Figure 1, A and B). Cerium chloride staining of ATPase activity demonstrated a concordant loss of CD39 activity at these sites relative to healthy vasculature in the same mouse (Figure 1, C and D). Concordance was similar in the aorta from normolipidemic mice, indicating that CD39 expression is a general marker for atheroprotection. Hence, we employed a pharmacologic approach to selectively inhibit CD39 enzymatic activity in vivo. As ATP-sensitive receptors are stimulated by ATP, we used a pharmacologic approach to selectively inhibit CD39 enzymatic activity in vivo. We employed a pharmacologic approach to selectively inhibit CD39 enzymatic activity in vivo.

To assess whether loss of CD39 alters the course of atherosclerosis, Cd39+/– mice were crossed onto the hyperlipidemic Apoe–/– background to generate Cd39+/– Apoe–/–, Cd39+/ Apoe–/–, and Cd39–/– Apoe–/– mice. Cd39+/– Apoe–/– mice were haploinsufficient with respect to CD39 expression, as enzymatic activity decreased in a dose-dependent manner with allele copy number (Figure 2, A–C). After 16 weeks of an atherogenic diet, mice missing only 1 allele of CD39 (Cd39+/– Apoe–/–) developed atherosclerotic lesions that were 2-fold larger than those of their Cd39+/ Apoe–/– counterparts (Figure 2, D and E) (n = 11–12, P < 0.005). Total absence of CD39, however, did not alter total plaque burden relative to controls. In all experiments, heart rate, blood pressure, and cholesterol levels did not vary significantly between control and CD39-deficient mice (Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI79514DS1).

Effect of CD39 deficiency on platelet activation and reactivity. We next investigated whether platelet activation is altered in CD39-deficient mice. We examined the composition of atherosclerotic plaques in CD39-deficient mice. Platelet remnants identified by the constitutive surface marker CD41 glycoprotein IIb appeared to localize to the surface and leading edge of atherosclerotic plaques. Platelet quantification revealed Cd39+/– Apoe–/– mice showed a tendency for platelet deposition in their atherosclerotic plaques as compared with controls, although this did not meet statistical significance (Supplemental Figure 1). We next examined circulating platelet-derived factors and observed a concordant increase in circulating soluble P-selectin (SP-Sel) and RANTES, at 39% and 60% higher concentrations, respectively, in the plasma of Cd39+/– Apoe–/– mice compared with Cd39+/ Apoe–/– controls (Figure 2, F and G).

To examine platelet reactivity in CD39-deficient and hyperlipidemic mice, we used whole blood aggregometry. Consistent with previous studies, Cd39+/– mice were desensitized to ADP-mediated platelet activation (Figure 3, A and B, and refs. 26, 30, 31). Hemizygous deficiency of CD39 did not confer desensitization to ADP stimulation. Interestingly, these mice had enhanced responses to ADP agonism. This increased sensitivity was particularly pronounced at low concentrations of ADP stimulation. At higher concentrations of ADP, total aggregation of platelets in whole blood of Cd39+/+ and Cd39–/– mice was similar, implying that the maximal aggregation threshold of the 2 genotypes is not different. Instead, there is a saturable difference in sensitivity to ADP stimulation with enhanced platelet aggregation in CD39 haploinsufficiency at a low dose of ADP stimulation. In hyperlipidemia, the activation sensitivity of platelets from Cd39+/– Apoe–/– mice persisted, though maximal aggregation was achieved at an even lower dose of ADP than that in normolipidemic counterparts (Figure 3C). Hyperlipidemia has been previously shown to enhance platelet reactivity (32). These ex vivo data support the hypothesis that CD39 haploinsufficiency may promote atherosclerosis by exaggerating platelet activation.

Enhanced lipid uptake in CD39-deficient macrophages. Macrophages exert a central role in atherogenesis development by their migration, lipid uptake, foam cell formation, and proliferation (33). Previous studies have shown dysregulated migration in CD39-deficient macrophages (31, 34). Assessment of plaque lesions in Cd39+/– Apoe–/– and Cd39–/– Apoe–/– mice did not show appreciably altered macrophage numbers when compared with controls.

Although CD39 haploinsufficiency confers a proatherogenic phenotype, the atherosclerotic burden seen in Cd39+/– Apoe–/– mice might not be explained by macrophage number. Modulation of foam cell formation has profound effects on the formation of aortic plaque without altering plaque macrophage content (35). We investigated lipid uptake in macrophages deficient in CD39. Peritoneal macrophages from CD39 hemizygous mice took up significantly greater acetylated LDL (AcLDL) and oxidized LDL (OxLDL) than those from Apoe–/– controls (Figure 4A). Concordantly, CD39 overexpression in murine macrophages (31) suppressed expression of the scavenger receptors SraI and Cd36 (Figure 4B) and reduced both AcLDL and OxLDL uptake (Figure 4, C–F). To test the hypothesis that CD39-mediated dissipation of ATP reduces stimulation of ATP-sensitive receptors and thereby mitigates lipid scavenging, we employed a pharmacologic approach to selectively inhibit
expression in the vasculature. We observed stark regionalization of CD39 expression in aortas of hyperlipidemic Apoe−/− mice (Figure 1B). CD39 was preferentially lost from regions susceptible to plaque development in aortic branching points, and the lesser curvature was associated with disturbed flow, but CD39 expression was preserved in adjacent, healthy regions.

Earlier work has shown that reactive oxygen species disrupt CD39 function (39). We explored whether a similar mechanism involving the oxidative milieu of an atherosclerotic plaque could account for the focal loss of CD39. Surprisingly, comparison of aortas from both normolipidemic and hyperlipidemic mice demonstrated that CD39 expression was regionalized (Figure 1B and Figure 5, A and B), implying that the driver of CD39 regional heterogeneity was not hyperlipidemia per se or the nascent plaque. When purinergic receptors to determine their contribution to foam cell formation. Modified LDL uptake was not significantly affected by treatment with a nonselective P2X receptor inhibitor (TNP-ATP) (ref. 36 and Figure 4, G and H), while the pleiotropic purine receptor inhibitor suramin (37) had no effect on AcLDL uptake, but did suppress OxLDL uptake. The most striking effect was seen with oxidized ATP (OxATP) (a selective P2X, receptor antagonist) (38), which strongly suppressed the uptake of both AcLDL and OxLDL. These data show CD39 may act via local purine metabolism to alter macrophage foam cell formation in the atherogenic process.

**Endothelial CD39 protein is functionally upregulated by atheroprotective stable flow in vivo and laminar shear stress in vitro.** As regional deficiency of CD39 may be contributing to the formation and regionalization of atherosclerotic plaque, we explored CD39’s expression in the vasculature. We observed stark regionalization of CD39 expression in aortas of hyperlipidemic Apoe−/− mice (Figure 1B). CD39 was preferentially lost from regions susceptible to plaque development in aortic branching points, and the lesser curvature was associated with disturbed flow, but CD39 expression was preserved in adjacent, healthy regions.

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significantly diminished activity in areas of turbulent blood flow. We extended these observations by exploring fluid shear stress as a regulator of CD39 expression in vitro using a cone-plate viscometer to treat endothelial cells with laminar shear stress. Antiatherogenic, unidirectional laminar shear (15 dynes/cm²) induced a significant increase in transcripts of CD39 in human aortic endothelial cells (HAECs) and HUVECs (Figure 6A), but not of other ectonucleotidases expressed at the endothelial cell surface (ref. 40 and Supplemental Figure 2). We observed a corresponding increase in aortic and umbilical vein endothelial CD39 protein expression when compared with no-flow static controls (Figure 6B). Our group and others have previously demonstrated that CD39 undergoes posttranslational modification that modifies its enzymatic activity (10). To determine whether the regionalized vascular CD39 expression was enzymatically active, we evaluated CD39’s ATPase activity in aortic sections using a cerium chloride assay. Electron micrographs of the aortic branch points showed strong ATPase activity (Figure 5C) in areas associated with high laminar shear (9) and significantly diminished activity in areas of turbulent blood flow. We extended these observations by exploring fluid shear stress as a regulator of CD39 expression in vitro using a cone-plate viscometer to treat endothelial cells with laminar shear stress. Antiatherogenic, unidirectional laminar shear (15 dynes/cm²) induced a significant increase in transcripts of CD39 in human aortic endothelial cells (HAECs) and HUVECs (Figure 6A), but not of other ectonucleotidases expressed at the endothelial cell surface (ref. 40 and Supplemental Figure 2). We observed a corresponding increase in aortic and umbilical vein endothelial CD39 protein expression when compared with no-flow static controls (Figure 6B). Our group and others have previously demonstrated that CD39 undergoes posttranslational modification that modifies its enzymatic activity (10).
Cd39 expression 48 hours after partial left carotid ligation as compared with that of contralateral controls (Figure 6F). These findings demonstrate that laminar shear stress induces endothelial CD39 transcript and protein as well as its enzymatic activity.

Regulation of CD39 by the transcription factor KLF2. Krüppel-like factor 2 (KLF2) is a transcription factor potently induced by laminar shear known to induce expression of atheroprotective genes, such as thrombomodulin and eNOS (19, 42), and suppress expression of prothrombotic and proinflammatory genes, such as plasminogen activator inhibitor-1 (19, 43) and tissue factor release. We investigated whether the induction of vascular CD39 could be modulated by KLF2 induction.

In silico analysis of the first 1 kb of the CD39 promoter revealed several canonical KLF-binding domains clustered within 100 bps upstream from the CD39 transcriptional start site (TSS).
To investigate whether KLF2 could regulate CD39 expression, we silenced KLF2 in WT bone marrow–derived macrophages and noted that even a modest, 29% reduction in Klf2 expression resulted in a significant, 44% decrease in Cd39 expression (Figure 7A). To determine whether this regulatory effect persists across different vascular cell types, we then silenced KLF2 in endothelial cells. Reduction of KLF2 expression by 75% led to a nonsignificant decrease in CD39 expression under static shear conditions (Figure 7, B and C). However, under conditions of laminar shear stress, we observed a 55% decrease in KLF2 expression under laminar shear conditions with shKLF2 transduction, leading to a significant, 36% suppression of endothelial CD39 gene expression when compared with transduction with a nontargeting sequence (Figure 7, B and C). We next sought to examine whether overexpression of KLF2 could induce CD39 expression. Transducing endothelial cells with a lentivirus to overexpress KLF2 resulted in a concordant increase in CD39 transcript (Figure 7D). This implies KLF2 plays a critical role in driving the basal and shear-induced upregulation of CD39 expression in macrophages and the endothelium.

KLF2 regulates CD39 expression by direct binding to the CD39 promoter. With the observation that KLF2 regulates CD39 expression, we next examined whether KLF2’s transcriptional control occurs via direct binding to the CD39 promoter. We focused on the candidate sites between the TSS and 100 bp upstream of the TSS. ChIP using an anti-KLF2 or nonspecific IgG antibody was performed on HUVECs exposed to 48 hours of laminar or static shear stress. Using quantitative RT-PCR analysis, we determined that KLF2 is bound to the CD39 promoter in static conditions when compared with IgG control antibody and this binding was significantly enhanced with arterial levels of shear stress (Figure 7E). These results suggest that induction of CD39 expression under arterial laminar shear stress conditions is transcriptionally regulated by direct binding of the transcription factor KLF2 to the CD39 promoter.

Discussion

This study presents what we believe is the first direct evidence linking CD39 expression to atherosclerotic plaque formation via increased platelet reactivity and foam cell formation. This finding is complemented by the identification of a regionalized pattern of endothelial CD39 expression, driven by fluid phase shear stress, within the aorta. Furthermore, we show that induction of CD39 is regulated by the highly conserved transcription factor KLF2, suggesting an endogenous system of atheroprotection.

Our findings help elucidate a potential mechanism based upon purinergic signaling leading to plaque formation. Humans with coronary atherosclerosis have been shown to have abnormal ADPase and ATPase activity (44). Under normal conditions, CD39 is a primary regulator of vascular homeostasis due to its avid catabolism of ATP and ADP (22, 23, 26, 30). Oxidative stress is a factor in the milieu of a plaque that can also affect CD39 by suppressing enzymatic activity independently of CD39 expression (39). Free radicals and TNF-α both play a role in the development of atherosclerotic plaque and are both known to suppress the activity of endothelial CD39. The loss of CD39 expression over plaque (Figure 1, A–D) may synergize with the local oxidative environment to further suppress regional CD39 function. The end result would be an atherosclerotic plaque virtually devoid of ectoapyrase activity on its surface (Figure 5C). Consequently, when CD39 expression is reduced by only 50%, atherosclerotic plaque burden is more than doubled (Figure 2, D and E).

These focal losses of CD39 as seen over atherosclerotic plaque could be of great consequence with respect to atherosclerosis. Previous studies have shown the critical role of CD39 in autoregula-
tion of leukocyte trafficking into regions of inflammation (31, 45). Simultaneously, deficiency of CD39 predisposes macrophages to markedly increase uptake of OxLDL and AcLDL due to overstimulation by purines, which could lead to augmented foam cell formation. Concordantly, CD39 overexpression decreased macrophage expression of the scavenger receptors CD36 and SRA-1, the latter of which is thought to be a critical mediator of lipid influx into macrophages and progression of atherosclerosis (33). Circulating activated platelets are known to accelerate plaque formation in ApoE−/− mice (5). Though the combination of platelets desensitized from excess extracellular nucleotide stimulation and enhanced foam cell formation does not increase atherosclerosis in Cd39−/− ApoE−/− mice, the summation of exaggerated platelet reactivity and foam cell formation in mice hemizygous for CD39 (Cd39+/− ApoE−/−) is associated with a profound increase in atherosclerotic plaque burden.

The results presented here and elsewhere (26, 30, 31) indicate that in the complete absence of CD39, platelet P2Y12 receptors are overwhelmed by ambient nucleotides and become desensitized to further stimulation. Mice in which platelets are desensitized (Cd39−/−) exhibit significantly blunted platelet reactivity to agonist challenge and a concordant blunting of atherogenesis. Our data show that partial expression of CD39 in mice (Cd39+/−) is
Hemodynamic forces play a fundamental role in atherosclerotic plaque localization. Blood vessels exposed to disturbed flow, such as arterial curvatures or bifurcations, are prone to develop atherosclerosis, whereas regions of laminar shear stress are more protected from atherosclerosis (13–15). The data presented here show that even before a plaque has formed, areas of regional CD39 abundance and CD39 deficiency exist in healthy WT mice. We show, for what we believe is the first time, that CD39 expression on the surface of endothelial cells in vivo and in vitro is regulated in a dynamic fashion by mechanical shear stresses, such as those imparted by blood flow. The upregulation of CD39 expression with laminar shear stress correlates with an increase in the nucleotide-dissipating ability of the endothelium. This local deficiency of CD39 in regions of disturbed flow may contribute to regional inflammation and coagulation at sites predisposed to atherogenesis. Mechanosensitive transcriptional networks regulate the endothelial response to hemodynamic forces. The gene expression programs of laminar shear stress impart a quiescent endothelium with antithrombotic, antiinflammatory, and atheroprotective properties. These programmatic pathways are largely regulated by a few transcription factors, KLF2, KLF4, and nuclear factor-like 2 (18, 46, 47). KLF2 is a zinc finger DNA-binding transcription factor critical for maintenance of vascular integrity and endothelial homeostasis and is central to these networks (17–19, 42, 48–50). Mechanistically, we show that induction of CD39 by laminar shear stress is KLF2 dependent, with direct binding of the transcription factor to the CD39 promoter in close proximity to the transcription start site. Partial silencing of KLF2 expression under laminar shear stress attenuated the expected increase in CD39 expression, but did not completely abrogate it. In addition, overexpression of KLF2 induced CD39 mRNA in endothelial cells. Taken together, these data suggest potent control by KLF2 or regulation of CD39 by additional factors under shear stress.
In conclusion, we have uncovered an important role for extracellular nucleotide dissipation by CD39 in the development of atherosclerosis. These experiments further identify a regulatory mechanism of endothelial and macrophage CD39 expression by KLF2. It will be important to determine whether manipulation of KLF2 represents a novel way to harness the therapeutic potential of CD39.

Methods

Tissue harvesting, preparation, oil red O staining, and immunostaining. For detailed information, see Supplemental Methods.

Cerium chloride staining of ATPase activity. ApoE-/- mice (26 weeks old) were euthanized prior to cerium chloride staining of the aorta to measure liberation of inorganic phosphate following ATP application as previously described (51). For detailed information, see Supplemental Methods.

Cell culture, cell and tissue protein isolation, immunoblotting, histology, RNA analysis, and measurement of plasma cytokines and lipids. For detailed information, see Supplemental Methods.

Measurement of CD39 function. Apyrase activity of the purified mouse membrane fraction was assayed with a Malachite Green Phosphate Assay Kit (BioAssay Systems). Radio-TLC was used to assess CD39 enzymatic function of live HUVECs as previously described (52). Equal numbers of cells were mixed with 1.0 mM [8-14C]ATP (ARC) in the presence of 286 μM AOPCP (Sigma-Aldrich), a CD73 inhibitor to arrest conversion of AMP to adenosine, and incubated at 37°C for 40 minutes. Reactions were stopped using 8 M formic acid, spotted onto silica gel TLC plates (Invitrogen), and nucleotides were separated by TLC. For detailed information, see Supplemental Methods.

Whole blood aggregometry, LDL uptake assay. For detailed information, see Supplemental Methods.

KLF2 gene-silencing and overexpression studies. shRNA oligonucleotides were generated against KLF2 (shKLF2) (50) and a nonspecific control (shScramble) (19) (Invitrogen). Lentivirus was produced and titrations performed by the University of Michigan Vector Core. Primary HUVECs and HAECs (PCS-100-011, ATCC) were transduced with shKLF2 or shScramble for 48 hours prior to treatment with laminar shear stress. Bone marrow-derived macrophages were transfected with siRNA (Invitrogen) against KLF2 (siKLF2) or a scramble sequence (siScramble) as previously described (53). Human KLF2 cDNA (Origene) was inserted into a lentivirus plasmid and pseudovirus with or without the cDNA insert generated using Lenti-vpak Packaging Kit (Origene) according to manufacturer protocol. Titration tables were compared, 1-way ANOVA was used with Tukey’s post hoc analysis to test for significant differences. P < 0.05 was considered significant.

Study approval. All animal experiments were conducted in accordance with NIH guidelines for the use of live animals and were approved by the Institutional Animal Care and Use Committee at the University of Michigan.

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