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Brief Report  Vascular biology

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Introduction

Atherothrombotic vascular disease is the leading cause of death in the industrialized world. While the majority of atherosclerotic lesions are clinically silent, acute cardiovascular events can be triggered by lesions with plaque necrosis, thin collagenous “caps” covering necrotic cores, and increased inflammation (1). We and others have highlighted the role of 2 processes: defective efferocytosis and impaired resolution in atherosclerosis. In this context, we hypothesized that MerTK cleavage promotes defective efferocytosis and impaired resolution in atherosclerosis.

Results and Discussion

We analyzed cross sections of carotid artery endarterectomy specimens from 14 patients for soluble Mer (sol-Mer), a marker of MerTK cleavage (11, 12), and plaque necrosis and found that lesional sol-Mer was positively correlated with necrosis (Figure 1A and Supplemental Figure 1A; supplemental material available online with this article; doi:10.1172/JCI90520DS1). Sol-Mer was not detected in nonatherosclerotic human arteries. We next compared carotid plaques from additional subjects who either had suffered a transient ischemic attack or stroke (symptomatic) or were asymptomatic. Plaques of symptomatic patients had higher levels of sol-Mer compared with those of asymptomatic patients (Figure 1B), and plasma sol-Mer was also increased in symptomatic patients (Supplemental Figure 1B).

MerTK cleavage causes defective MerTK-mediated efferocytosis (8, 11, 12). A previous study showed that recombinant sol-Mer can inhibit efferocytosis in vitro, presumably through competition for molecules that bridge apoptotic cells (ACs) to MerTK, like GAS6 (11). However, we found that recombinant sol-Mer inhibited efferocytosis only at doses that were more than 1,000-fold those in plasma (Supplemental Figure 1C). Thus, unless sol-Mer concentrations in lesions reach extremely high levels, sol-Mer is most likely a marker rather than a cause of defective MerTK efferocytosis. In this context, we found that cell-surface MerTK in macrophage-rich areas in plaques from symptomatic patients was less than that in asymptomatic patients (Figure 1C) despite sim-
To study advanced atherosclerosis, WT or MertkCR bone marrow was transplanted into Ldlr–/– mice, and atherosclerotic lesions and plasma were analyzed after 16 weeks of WD feeding. These 2 groups had similar body weight, blood glucose, plasma lipids, and circulating leukocytes (Supplemental Figures 3 and 4). We confirmed that aortic sol-Mer was reduced and that MerTK was higher in the CR cohort (Figure 2, A and B). Most importantly, MertkCR lesions had substantially less plaque necrosis but no change in total lesion area or lesional cell composition (Figure 2C and Supplemental Figure 5), indicating a true decrease in percentage necrosis. Further, MertkCR lesions had a markedly lower ratio of free to macrophage-associated TUNEL+ (apoptotic) cells (Figure 2D), which reflects improved efferocytosis.

MertkCR lesions also had thicker fibrous cap thickness and increased collagen gene expression (Figure 3, A and B), which are associated with plaque stability and inflammation resolution (1, 15). These lesions also had more Tregs (Figure 3C), which can promote resolution (16, 17), are decreased in human and mouse advanced atheroma (18), and have been causatively linked to plaque progression in mice (19).

Defective inflammation resolution can be caused by an imbalance between specialized proresolving mediators (SPMs) and proinflammatory lipid mediators in both human and mouse lesions (20, 21). Using liquid chromatography–tandem mass spectrometry to assay a wide range of SPMs and proinflammatory lipid mediators in aortic extracts, we found that the global content of SPMs, including resolvin D2, D5, and E3, was significantly increased in MertkCR extracts (Supplemental Table 1 and Figure 3D).

The inflammation resolution program has a number of positive-feedback processes. First, SPMs can increase production of proteins that dampen inflammation and promote repair (22, 23).

To test the hypothesis that MerTK cleavage promotes plaque necrosis, we used a mouse model in which endogenous Mertk was replaced with a genetically engineered mutant gene encoding cleavage-resistant MerTK (MertkCR) (8). Cleavage-resistant MerTK is functional under basal conditions but, unlike WT MerTK, maintains full activity under cleavage-promoting conditions, e.g., in the presence of inflammatory stimuli (8). We show here that the atherogenic lipoprotein oxidized LDL (oxLDL) increased sol-Mer and decreased cell-surface MerTK in control (WT) macrophages but not in macrophages pretreated with the ADAM17 inhibitor TAPI-0 (Supplemental Figure 2A) or in macrophages isolated from MertkCR mice (Supplemental Figure 2, B and C). Importantly, oxLDL suppressed efferocytosis in WT but not MertkCR macrophages (Supplemental Figure 2D).
efferocytosis and inflammation resolution and disrupts several components of positive-feedback signaling. These findings likely explain the marked improvement in plaque morphology in the atherosclerotic lesions of MertkCR → Ldlr–/– mice.

Understanding processes involved in the formation of the unique types of atherosclerotic plaques that cause acute cardiovascular events is a critical goal in cardiovascular research. Progression to plaque necrosis is a key process because of the highly inflammatory and plaque-destabilizing nature of the necrotic core (26). Data from human and mouse studies suggest that plaque necrosis results from 2 complementary processes, postapoptotic necrosis secondary to defective efferocytosis as examined here (2, 3) and a primary cell necrosis process called necroptosis (27, 28). While the current study is focused on an efferocytosis defect in phagocytes themselves, a recent study showed that some apoptotic cells in human and mouse lesions inappropriately retain CD47, which blocks their engulfment by normal phagocytes (29). Interestingly, oxLDL, which was shown here to promote MerTK cleavage and defective efferocytosis, can induce necroptosis in macrophages, and these cells are also poorly

Two such proteins, TGF-β1 and IL-10, were significantly increased in MertkCR plasma (Supplemental Figure 6A). Second, SPMs can upregulate their own receptors (24), and we found that the expression of the SPM receptor ALX/FPR2 was markedly induced in the lesions of MertkCR mice (Supplemental Figure 6B). Third, engagement of MerTK by apoptotic cells and other ligands in cultured macrophages and in sterile inflammation in vivo enhances the synthesis of 5-LOX-derived SPMs at the expense of inflammatory leukotrienes (8, 25). We therefore analyzed the ratio of 5-LOX–derived SPMs to leukotrienes and found that this ratio was markedly increased in MerTKCR extracts (Figure 3E). Moreover, this ratio was negatively correlated with necrotic core area (Figure 3F). Fourth, using bone marrow–derived macrophages, we found that resolvin D1 (RvD1) blocks LPS-induced MerTK cleavage (Supplemental Figure 7, A and B). Importantly, when WD-fed Ldlr–/– mice were treated with RvD1, which suppresses plaque necrosis and improves lesional efferocytosis (20), lesional MerTK expression was increased (Supplemental Figure 7C). Thus, MerTK cleavage during plaque progression suppresses the integrated processes of efferocytosis and inflammation resolution and disrupts several components of positive-feedback signaling. These findings likely explain the marked improvement in plaque morphology in the atherosclerotic lesions of MertkCR → Ldlr–/– mice.

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internalized by normal phagocytes (28). Defects in multiple steps of efferocytosis, together with activation of necroptotic pathways in advanced plaques, would create a “perfect storm” for the development of plaque necrosis.

Our data support the concept that MerTK plays an integral part in a program of feedback signaling that amplifies resolution. This concept aligns with previous studies showing that (a) engagement of MerTK by apoptotic cells or other activators can activate both antiinflammatory and proresolving pathways (6–8, 30–32); and (b) proresolving mediators can promote MerTK expression and efferocytosis (7, 33, 34). Thus, when MerTK is rendered inactive by proteolytic cleavage, not only is there a defect in efferocytosis, but positive-feedback signaling in resolution is impaired, leading to loss of resolving mediators and further defects in efferocytosis. In the setting of advanced atherosclerosis, this profound deficit promotes key features of clinically dangerous plaques, including necrosis, imbalance of proresolving versus proinflammatory lipid mediators, fibrous cap thinning, and deficiency of Tregs. The finding that cleavage of a single molecule in the setting of a chronic inflammatory condition could have such robust pathophysiologic effects not only suggests its potential as a therapeutic target but also raises the question of the possible role of MerTK cleavage in other chronic inflammatory conditions previously linked to MerTK and sol-Mer, e.g., systemic lupus erythematosus and Sjögren’s syndrome (35–38).

Methods
A complete description of methods is provided in the Supplemental Methods.

Statistics. Data are displayed as mean ± SEM. Because all data in this study fit a normal distribution, a 2-tailed Student’s t test was used to determine statistical significance. P values less than 0.05 were considered significant. For the data in Figure 1A, correlation coefficient (R) and P value were calculated using Pearson product-moment correlation analysis. A 2-tailed Student’s t test was used for A–E.
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