Collagenases and cracks in the plaque

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The core of an atheromatous plaque contains lipids, macrophages, and cellular debris, typically covered by a fibrous cap that separates the thrombogenic core from the blood. Rupture of the fibrous cap causes most fatal myocardial infarctions. Interstitial collagen confers tensile strength on the cap, as it does in skin and tendons. In 1994, Peter Libby and colleagues demonstrated overexpression of collagenolytic enzymes in atheromatous plaques and implicated MMPs in the destabilization of these lesions.

The formation of plaques within the arterial intima characterizes atherosclerosis. Plaques typically consist of a lipid core covered by a fibrous cap rich in extracellular matrix, produced largely by arterial smooth muscle cells (Figure 1A). Most fatal myocardial infarctions result from a fracture in the plaque’s fibrous cap (1). The fibrous cap derives tensile strength from interstitial collagen, as do skin and sinew. Twenty years ago, my colleagues and I proposed the hypothesis that excessive collagen catalyzed the first step in collagen catabolism (Figure 1B). To sidestep laboratory artifacts, my colleagues and I used rabbits as in vivo “incubators.” Foam cells in atherosclerotic plaques of hypercholesterolemic rabbits contained abundant MMP-1, while alveolar macrophages in the same animals showed negligible MMP-1 expression (9). This ensemble of experiments presented a coherent but circumstantial set of observations that supported a role for MMP interstitial collagenase action in determining the collagen content of atherosclerotic plaques.

Closing the loop of causality
To determine directly whether MMPs regulated the collagen content of atherosclerotic plaques, we used genetic and pharmacologic approaches to induce gain or loss of collagenase function in atherosclerotic mice. Mice with a “knockin” mutation that rendered interstitial collagen resistant to MMP collagenases showed accentuated collagen accumulation (10). Conversely, mice lacking MMP-13, a principal interstitial collagenase in mice, or receiving a selective inhibitor of MMP-13 showed similar collagen accumulation in plaques (11). Ex vivo biomechanical analysis showed that collagen accumulation actually increased the tensile strength of an atherosclerotic aorta (12). All of these pieces pointed to a key role of collagen breakdown in controlling the content of this critical component of the plaque’s fibrous cap — all that stands between many patients and the acute thrombotic complications of atherosclerosis.

Lipid lowering calms collagenolysis
Another avenue of research tested the hypothesis that therapeutic interventions that reduced atherosclerotic events in humans would limit collagenase expression and increase collagen content of experimental atherosclerotic plaques. Rabbit experiments showed that dietary lipid lowering reduced MMP-1 expression and increased plaque collagen content (13). Other experiments tested whether statin treatment could achieve similar alterations in collagen economy. These experiments used Watanabe heritable hyperlipidemic (WHHL) rabbits, a strain with reduced LDL receptor function. Although WHHL rabbits showed only modestly decreased serum cholesterol when treated with statins, these agents decreased lesional collagenase activity and increased collagen content (14). Lipid lowering through diet or statins decreased plaque thrombogenicity by reducing tissue factor expression and limited other manifestations of inflammatory activation (15, 16). This body of observations provided insight into the cellular and molecular mechanisms by which lipid-lowering therapy reduced clinical atherothrombotic events. Observations in human atherosclerotic plaques using histopathology and various imaging modalities similarly showed an increase in the estimated fibrous character of plaques from humans treated with statins (17, 18). Despite the limitations of these observations in humans, they support the pathobiologic principles demonstrated by our animal experiments.

Unanswered questions
Although satisfying, this body of research leaves many important questions unanswered. First, plaques contain many non-metallloproteinases, and proteolytic enzymes have functions beyond matrix breakdown. Cysteinyl proteinases, for example, also alter arterial biology during atherogenesis (19). MMPs process non-matrix...
substrates — among them, cytokines and chemokines — sometimes activating them and other times inactivating them (20). Unraveling the roles for different classes of these enzymes in various aspects of arterial remodeling will require further experiments.

My group’s observations in 1994 fueled the trend of using “vulnerable plaques” or “thin-capped fibroatheroma” — terms that have gained daily clinical currency — as well as the concept that inflammation begets proteolysis that renders plaques “vulnerable.” Yet, these simple schemata don’t suffice to explain the clinical biology of plaque disruption. Most proteinase-rich plaques probably evade rupture. The number of such plaques by far exceeds clinical events, challenging the “vulnerable plaque” concept. Even when inflamed and collagenase-packed plaques do rupture, the vast majority of these disruption events pass unnoticed. Instead, cycles of subclinical disruption and healing may promote the progression of plaques from lipid-rich atheromatous lesions to those with more fibrous and calcified character that may cause flow-limiting stenosis but have less tendency to rupture.

So-called “vulnerable plaques” can persist for decades, yet an acute event can develop in an instant. What determines when a particular plaque will rupture and provoke a clinical event? Plaque disruption requires not only a suitable anatomic substrate, but also a triggering event. Candidate triggers include catecholamines, vasospasm, and thrombin, contribute to enzymatic activation of these enzymes that is required for their proteolytic activity. Macrophages in human plaques overexpress the three known MMP interstitial collagenases, MMP-1, MMP-8, and MMP-13. The endogenous inhibitors of this family of enzymes, the tissue inhibitors of MMPs (TIMPs), do not change markedly between unaffected and atherosclerotic arteries. The MMP interstitial collagenases catalyze the initial proteolytic cleavage of intact triple helical fibrillar collagen.

Rupture of the fibrous cap does not account for all fatal coronary artery thrombosis in humans. Superficial erosion of the intima without frank plaque rupture accounts for more than one-fifth of fatal coronary thromboses (25). Given the effects of statins and lipid lowering on the structure of plaques described above, in the current era, rupture of the fibrous cap as a mechanism of coronary thrombosis might wane as superficial erosion increases. The proportion of acute coronary syndromes due to ST-segment elevation myocardial infarction (STEMI) has dropped, while the contribution of non-ST segment elevation myocardial infarction (NSTEMI) has risen (26). Could statins have altered the biology of acute coronary syndromes such that plaque rupture has become less important as a cause?

In scientific stories, as in good novels, as one chapter closes, the narrative often raises unresolved conflicts to explore in coming pages. In medicine, we never reach the final
chapter — the denouement seems eternally beyond reach. We must relentlessly strive to solve the next layer of complexity uncovered in our Sisyphean quest to understand nature and to advance our art.

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