Mechanisms of Acute Coronary Syndromes and Their Implications for Therapy

Peter Libby, M.D.

Atherosclerotic lesions in humans typically form over the course of years to decades, one of the longest incubation periods among human diseases. Despite the chronicity of atherosclerosis, thrombotic complications — the most dreaded clinical consequences of this disease — occur suddenly, and often without warning. Our familiarity with the disease has generally led us to accept this apparent paradox without wonder. What mechanisms explain the abrupt transition from stable ischemic heart disease or asymptomatic atherosclerosis to acute coronary syndromes? This review examines our current understanding of the mechanisms underlying these syndromes. According to the traditional view, progressive stenosis narrows an atherosclerotic coronary artery to a lumen the size of a pinpoint, so small that a platelet thrombus could occlude the vessel completely. Thus, an occlusive thrombus complicating a high-grade stenosis would arrest flow and cause ST-segment elevation myocardial infarction. Acute coronary syndromes without ST-segment elevation would result from an incomplete or transient obstruction of flow in the culprit coronary artery at a site of critical stenosis.

These concepts have governed our traditional approaches to atherosclerosis therapy. Our diagnostic tools generally evaluate the ischemia that results from established, fixed stenosis (e.g., stress testing and perfusion scanning) or visualize the stenosis itself by means of arteriography. Our treatments have targeted the stenosis with the use of percutaneous intervention or bypass surgery.

Pathogenesis of Acute Coronary Syndromes

Findings from clinical and pathological studies have challenged these commonly held notions of the pathophysiological features of coronary atherosclerosis and its treatment.1-4 Surprisingly, serial angiographic studies have revealed that the site of the culprit lesion of an acute myocardial infarction is usually characterized by stenosis that does not limit flow on antecedent angiograms. Angiographic monitoring of responses to thrombolytic therapy has shown that after lysis of the offending thrombus, the underlying stenosis is often not the cause of the critical stenosis of the artery. In a prospective angiographic study involving patients undergoing percutaneous intervention for coronary artery disease, only half the subsequent events arose from lesions with sufficient stenosis to have warranted intervention at the time of revascularization.5 Computed tomographic (CT) angiography, which permits evaluation of the arterial wall (not just the lumen), has shown that the characteristics of plaque associated with acute coronary syndromes include low differentiation (i.e., noncalcification) and outward expansion of the artery wall, a process that tends to accommodate the growth of plaque while minimizing luminal encroachment.6-8 Intravascular ultrasonography has shown that in acute coronary syndromes, the culprits are often proximal to the sites of maximal stenosis — the
traditional targets of revascularization therapies.9 This dissociation between the degree of stenosis and the propensity to provoke an acute coronary syndrome helps to explain why myocardial infarction often occurs without being heralded by the demand-induced symptoms of angina that would result from a high-grade stenosis.

Technologies that permit cross-sectional imaging of the coronary arteries, such as intravascular ultrasonography or CT angiography, underscore the pathological observation that the outward expansion of atherosclerotic arteries accommodates the growth of plaque for much of its life history.2 Luminal stenosis occurs relatively late in the process of atherogenesis, when plaque growth outstrips the ability of the artery to compensate by expanding outward.10,11 These findings support the distinction between the degree of stenosis and the size of a plaque. Compensatory enlargement (outward expansion) of the artery during plaque growth can conceal a considerable burden of atheroma by preventing stenosis and thereby obscuring signs and symptoms of ischemia. Sizable plaques can reside in the walls of affected arteries without being detected on arteriograms and without issuing any warning to the patient or physician.

Clinical data acquired during the current era of medical management of atherosclerosis have affirmed that invasive procedures for the treatment of stenoses generally do not prevent future thrombotic events more effectively than noninvasive treatments. The Occluded Artery Trial concluded that restoring coronary flow in the subacute phase of an acute coronary syndrome did not improve outcomes.12 Similarly, the Clinical Outcomes Utilizing Revascularization and Aggressive Drug Evaluation (COURAGE) trial showed overall that medical therapy provided as much protection from future acute coronary syndromes as did mechanical revascularization.13 This assemblage of clinical data challenges the traditional view of the pathogenesis of acute coronary syndromes, which ascribes a leading role to stenotic lesions.

**THROMBOTIC COMPLICATIONS OF ATHEROSCLEROSIS**

If the progression of luminal stenosis to a critical narrowing is not the cause of many acute coronary syndromes, what mechanism produces these dramatic and sudden manifestations of chronic atherosclerosis? The long-standing focus on stenosis has diverted attention from autopsy studies conducted by generations of pathologists that have ascribed most fatal coronary events to a physical disruption of coronary arterial plaques (Fig. 1). Frank rupture of the plaque’s fibrous cap causes the majority of these deaths; superficial erosion of a coronary artery is responsible for the balance of fatal events. Autopsy studies have shown that erosion through the intima of a calcified nodule and intraplaque hemorrhage each trigger only a small percentage of acute coronary syndromes.2,14

Much of the work addressing the mechanisms of coronary thrombosis has focused on plaque rupture, the most common cause of fatal acute coronary syndromes. A fibrous cap typically overlies the lipid-rich center — also known as the necrotic core — of an atheromatous plaque (Fig. 1). This fibrous cap stands between the blood compartment, with its latent coagulation factors, and the lipid core, a portion of the plaque filled with thrombogenic material. Quantitative morphometric studies have identified the characteristics of plaques that have ruptured and caused a fatal myocardial infarction. Such plaques often, but not always, have thin fibrous caps (50 to 65μm thick).2,15 Ruptured plaques also tend to have large lipid cores and abundant inflammatory cells, as well as punctate or spotty calcification.7,10 In a recent autopsy study,17 a fibrous-cap thickness of less than 55 μm was identified as the best morphologic indicator of plaques that had caused fatal ruptures. More than 30% of these plaques were associated with a luminal stenosis of less than 75%, even when not studied at postmortem physiological pressure. Typically, the sites where plaques rupture and provoke fatal coronary events have few smooth-muscle cells.18

**INFLAMMATION, COLLAGEN METABOLISM, AND PLAQUE RUPTURE AND THROMBOSIS**

The fibrous cap of the plaque has been the focus of extensive research because of its importance in the majority of fatal acute myocardial infarctions. This structure, which protects the plaque from rupture, owes its tensile strength to interstitial forms of collagen synthesized primarily by arterial smooth-muscle cells. The association between thinning of the fibrous cap and fatal plaque rupture has led to the hypothesis that a defect in plaque collagen metabolism contributes to the
depletion of this extracellular matrix protein, which has a critical role in strengthening the fibrous cap. These considerations have engendered much interest in molecular mediators of collagen metabolism that may operate during atherogenesis. Since inflammatory cells accumulate at the site of ruptured plaques, and since biomarkers of inflammation predict acute coronary syndromes, studies (discussed below) have focused on the hypothesis that macrophages — and the mediators that they produce and that regulate their function — disrupt the collagen in the plaque in a manner that may jeopardize the integrity of the fibrous cap, thus precipitating an acute coronary syndrome.

A study of the control of collagen biosynthesis by human vascular smooth-muscle cells in culture revealed that exposure to an inflammatory mediator known as interferon gamma, a product of activated T cells, strongly inhibited the ability of smooth-muscle cells to make the new collagen required to repair and maintain the integrity of the fibrous cap. Even in smooth-muscle cells maximally stimulated with transforming growth factor β to produce interstitial collagen, interferon gamma reduced collagen synthesis to baseline
levels or lower. Another study showed an inverse correlation between T-cell accumulation in human atherosclerotic plaques and the messenger RNA that encodes the precursor of interstitial collagen, an observation that supports the relevance in vivo of the profound inhibition of new collagen synthesis by a T-cell–derived mediator.20

The level of any macromolecule depends not only on its rate of synthesis but also on the rate at which it breaks down. Interstitial collagen is usually very stable and resists degradation by most proteolytic enzymes. Only a handful of human proteinases have interstitial collagenase activity capable of catalyzing the first wave of attack on fibrillar collagen. These enzymes belong to the matrix-metalloproteinase (MMP) family. The macrophage, a cell type that abounds in lesions that have caused fatal thrombi, overproduces all three human MMP interstitial collagenases — MMP-1, MMP-8, and MMP-13 — in plaques.21–25 Moreover, plaques with features similar to those that have caused thrombotic complications have displayed biochemical signatures of collagen cleavage in situ in macrophage-rich regions.24 Studies of the regulation of MMP production by human macrophages have shown that the T-cell–derived cytokine CD40 ligand (CD154) boosts the production of interstitial collagenase by human macrophages.26 Thus, cross-talk between adaptive immune cells (T cells) and the more numerous innate immune effector cells (macrophages) inhibits the synthesis and augments the degradation of interstitial collagen. These observations in human tissues and in isolated human cells provide a cellular and molecular mechanism linking inflammation to the thinning and weakening of the fibrous cap, which can precipitate plaque rupture, thrombosis, and acute coronary syndromes. Recent experiments show that the systemic inflammatory reaction to acute myocardial infarction can aggravate inflammation in the plaque, including increased protease activity.27 This finding helps explain why recurrent thrombotic events tend to cluster in the aftermath of an acute coronary syndrome and often involve lesions not deemed responsible for the initial presentation.5 It also clarifies why immediate revascularization, by limiting myocardial injury and consequent systemic inflammation, may reduce the risk of recurrent events, whereas revascularization after completion of an infarct does not generally confer such a benefit.

Another recently recognized regulator of plaque proteinase expression, local endothelial shear stress, also has clinical relevance to the formation of lesions prone to rupture. In pigs, regions with low endothelial shear stress colocalize with coronary atheromata with thin fibrous caps and exhibit enhanced expression of matrix-degrading proteinases, including interstitial collagenases.28 In humans, regions of low shear stress in coronary arteries are more likely to cause acute coronary events than regions of high shear stress.29–30

Despite their appeal, the initial data that supported the contribution of proteinases to the pathogenesis of acute coronary syndromes depended primarily on association, and evidence that altered collagen metabolism is a determinant of the collagen content of the fibrous cap remained speculative. Insights furnished by the study of experimental preparations that permit gain-of-function and loss-of-function manipulation now support a causal role for altered collagen metabolism in the collagen content of plaque (Table 1). In mice with a genetic susceptibility to diet-induced atherosclerosis, further mutation of a gene that encodes the precursor of interstitial collagen, rendering it resistant to MMP collagenases, yielded an accumulation of collagen in the plaque.33 In another experiment, genetic inactivation of collagenolytic enzymes or their activators increased the collagen content of plaque.34,35 Although such germline manipulations permit exquisite selectivity, the congenital absence of an enzyme or resistance of a substrate to an enzyme — such as the enzymes used in these experiments — could confound the interpretation of the results owing to the possibility of compensatory changes in other pathways. Moreover, the genetic approach does not allow for analysis of the influence of collagenolysis on aspects of plaque structure that relate to rupture in lesions that have already formed. A recent study has therefore used pharmacologic inhibition of interstitial collagenase to test this hypothesis. Indeed, oral administration of a selective inhibitor of a principal interstitial collagenase, MMP-13, in mice yielded an increase in the collagen content of the fibrous cap in established atherosclerotic plaques.36

The combined studies of plaque in humans and animals support the concepts formulated in the early 1990s.1 Decreased synthesis and increased breakdown of collagen, controlled by inflamma-
tory signals, reduce the content of this critical extracellular matrix macromolecule in plaques. The resultant friable fibrous cap may render plaques susceptible to rupture and thrombosis (Fig. 2). Yet, a weakened fibrous cap alone does not suffice to precipitate plaque rupture, and not all plaques that rupture have thin fibrous caps. Additional contributors to the triggering of plaque rupture may include coronary vasospasm and punctate calcifications. Recent computational analyses indicate that microcalcifications within the atherosclerotic intima can result in a striking increase in circumferential stress and could thus contribute to plaque rupture.

When the fibrous cap ruptures, allowing blood to come into contact with thrombogenic material in the plaque’s lipid core, thrombosis can ensue. When a plaque is disrupted, tissue factor, a potent procoagulant produced by macrophages in the plaque’s core, triggers thrombin generation and platelet activation and aggregation. The same proinflammatory signal that augments collagenase production — CD154 — also induces the expression of tissue factor in human mononuclear phagocytes. Thus, inflammatory cells and mediators not only regulate collagen synthesis and breakdown but also increase the thrombogenic potential of the atherosclerotic plaque. These dual actions explain the strong links between inflammation and the thrombotic complications of atherosclerosis.

### Superficial Erosion of Plaques

Superficial erosion of coronary atheromata causes approximately 20 to 25% of cases of fatal acute myocardial infarctions. Observations made with the use of optical coherence tomography support the relevance of findings in autopsy studies to clinical acute coronary syndromes. This anatomical substrate for coronary thrombosis occurs more frequently in women than in men and in persons with certain risk factors, such as hypertriglyceridemia. Many lesions that cause coronary thrombosis because of superficial erosion lack prominent inflammatory infiltrates; such plaques exhibit proteoglycan accumulation (Fig. 1). The mechanisms of superficial erosion have received much less attention than those involved in the rupture of the fibrous cap. The programmed cell death (i.e., apoptosis) of endothelial cells could contribute to their desquamation.

Oxidative stress can promote endothelial apoptosis. In particular, hypochlorous acid — the product of myeloperoxidase, an enzyme released by activated leukocytes associated with atheroma — can initiate apoptosis of endothelial cells. As these cells undergo apoptosis, they produce the procoagulant tissue factor. This oxidative species may thus initiate or propagate endothelial cell loss and local thrombosis in coronary arteries. Endothelial cells can also express proteinases that may sever their tethers to the underlying basement membrane. Modified low-density lipoprotein (LDL), for example, can induce the expression of the enzyme MMP-14 by human endothelial cells.

### Therapeutic Implications of New Mechanistic Insights

Although revascularization procedures that target occlusive coronary stenosis relieve anginal symptoms, they have not consistently reduced the risk of an acute coronary syndrome or death from coronary artery disease. In stark contrast, contemporary medical therapy — notably, statin treatment — has prevented both first and recurrent acute coronary syndromes in broad categories of patients. Curiously, even though these medical interventions reduce events, they have little effect on the degree of stenosis as assessed on angiography and result in only modest reductions in atheroma volume as assessed on intravascular ultrasonography.

Can the new insights...
into the mechanisms of acute coronary syndromes, described above, illuminate these clinical findings and explain how medical treatment reduces the thrombotic complications of atherosclerosis?

Event reduction that is out of proportion to the shrinkage of stenoses has led to the hypothesis that lipid lowering alters qualitative characteristics of atheromata — that such treatment causes modest quantitative improvement in lumen...
caliber but may qualitatively limit the propensity of plaques to rupture and their thrombogenicity. These changes in the biologic features of plaque are now considered to confer stabilization, a feature that distinguishes lipid-lowering interventions from those that address luminal stenosis without altering the molecular and cellular processes inculpated in the triggering of thrombotic complications. A comprehensive series of studies in rabbits and mice have tested this hypothesis. One series of investigations in rabbits with experimentally induced atherosclerosis was designed to lower lipid levels by means of diet alone, a “lifestyle” intervention. A combination of arterial injury and an atherogenic diet provoked the development of fibrofatty aortic plaques in rabbits. After a period of lesion generation, the rabbits were switched to a low-fat, low-cholesterol diet or were kept on a diet that maintained dyslipidemia. The lipid-lowering diet reduced the content of inflammatory cells, augmented interstitial collagen accumulation, and reduced tissue factor antigen and activity in concert with other effects that contrast with the features of human plaques prone to rupture and thrombosis (Table 2).

Other studies showed that statin treatment caused similar reductions in inflammatory-cell content and collagenase levels and augmented collagen accumulation in atheromata of Watanabe heritable hyperlipidemic rabbits. Because rabbits of this strain — characterized by mutated LDL receptors — have only modestly reduced LDL cholesterol levels when treated with statins, these studies indicate that statins have a stabilizing effect on plaques that extends beyond their lipid-lowering effect.

Observations in humans support the concept, established in animals, that lipid lowering can increase the fibrous nature of plaques — a change that should confer resistance to rupture. Imaging studies suggest that plaques have a more fibrous character in patients receiving treatment with statins than in those not receiving such treatment. Statin therapy is also associated with reduced lipid content and indexes of macrophage activity and more fibrous atheromata as assessed on magnetic resonance imaging in both rabbits and humans. These studies in humans affirm the clinical relevance of the studies in animals described above and the classic observations of Armstrong and colleagues regarding the “regression” of atherosclerotic lesions in nonhuman primates after dietary restriction of lipids.

Despite the remarkable benefits of statin therapy, patients appropriately treated with this class of agents are still at risk for acute coronary syndromes — hence the need to make further inroads against this residual burden of disease. The advent of novel strategies for lowering LDL cholesterol levels below those achievable with statins alone (e.g., inhibition of serum proprotein convertase subtilisin/kexin 9 [PCSK9]) provides considerable promise in this regard. Therapies that target other aspects of the lipid profile have proved disappointing when put to the test, despite extensive preclinical and clinical biomarker data. Clinical trials of interventions that address levels of high-density lipoprotein (HDL) cholesterol have shown no benefit (e.g., the cholesteryl ester transfer protein [CETP] inhibitors tested thus far, and niacin). Similarly, recent large-scale trials of fibrates, agents that substantially lower triglyceride levels and modestly raise HDL cholesterol levels, in patients with type 2 diabetes mellitus have not shown a reduction in cardiovascular events.

Given the role of inflammation in the pathophysiologic aspects of plaque rupture, several studies are assessing the use of antiinflammatory therapies other than statins to reduce the risk of a recurrent acute coronary syndrome. A recent clinical trial of low-dose colchicine (0.5 mg per day) in patients with stable ischemic heart disease has shown a reduced incidence of acute coronary syndromes. This trial was relatively small (532 patients, with a total of 55 events), and the investigators did not use a double-blind design and did not report levels of inflammatory

| Table 2. Favorable Effects of Lipid Lowering in Experimentally Produced Atherosclerotic Plaques. |
|---------------------------------|-------------------------------------------------------------------------------------------------|
| Reduces inflammation (lowers levels of macrophages, cytokines, and chemokines and expression of leukocyte adhesion molecules) |
| Reduces expression of interstitial collagenase (MMP-1) |
| Increases levels of interstitial collagen |
| Lowers levels of oxidized low-density lipoproteins |
| Reduces production of reactive oxygen species |
| Increases expression of endothelial nitric oxide synthase |
| Reduces thrombotic potential (reduced tissue factor content and activity) |
| Increases fibrinolytic potential (reduced level of plasminogen activator inhibitor-1) |
biomarkers, which might have provided a glimpse into the possible mechanisms underlying the effects of colchicine. Nevertheless, these encouraging results should prompt a larger-scale, double-blind trial of this inexpensive agent, which has a long history of clinical use and a well-known and acceptable risk profile. Two large clinical trials are testing the use of darapladib, a small molecular inhibitor of a lipoprotein-associated phospholipase, to reduce clinical events. Although this intervention has the potential for antiinflammatory actions, in a phase 2 trial it did not reduce levels of C-reactive protein but did limit lipid core size, a characteristic that may render plaques susceptible to rupture. Other interventions under investigation include antibody neutralization of the proinflammatory cytokine interleukin-1 beta or the use of low-dose methotrexate on a weekly basis, treatments currently used successfully for other inflammatory conditions.

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SUMMARY

Our understanding of the pathogenesis of acute coronary syndromes has undergone a veritable revolution in the past 20 years. We now understand in molecular and cellular terms how most serious thrombotic complications of coronary atherosclerosis occur. In particular, inflammatory pathways have emerged as important drivers of plaque disruption and thrombosis. This insight into the pathophysiological features of acute coronary syndromes expands the scope of treatment of this disease beyond the traditional focus on reducing stenoses. The laboratory and clinical data summarized here should help us both to understand how contemporary therapies can reduce the risk of these events and to make further inroads against the residual burden of disease in the future.
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Mechanisms of Disease


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Update on the Pathophysiology of Acute Myocardial Infarction

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Brigham & Women's Hospital
Harvard Medical School

Pri-Med
2015

Characteristics of Atherosclerotic Plaques Associated with Various Presentations of Coronary Artery Disease

ACS
Stable demand angina
Plaque rupture caused ~ ¾ of fatal heart attacks

Structural Integrity of the Plaque’s Fibrous Cap
• Depends on interstitial collagen fibrils (types I & III) synthesized by smooth muscle cells

M.L. Higuchi
Interventions That Increase Collagen Content of Atherosclerotic Lesions in Studies in Animals

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Species</th>
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<td>Introduction of a mutation that renders resistance to collagenase</td>
<td>Mouse</td>
<td>Fukumoto et al. 39</td>
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<td>Induction of MMP-13 deficiency</td>
<td>Mouse</td>
<td>Deguchi et al. 34</td>
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<tr>
<td>Induction of MMP-14 deficiency</td>
<td>Mouse</td>
<td>Schneider et al. 35</td>
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<tr>
<td>Treatment with MMP-13 inhibitor</td>
<td>Mouse</td>
<td>Quillard et al. 36</td>
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Genetic gain or loss of function experiments in mice prove the importance of collagenases in regulating plaque collagen content.

Thrombosis on a ruptured plaque, the cause of most acute coronary syndromes, results from:
- weakening of the fibrous cap
- thrombogenicity of the lipid core

Inflammation drives high-risk plaque formation:
- Synthesis
- Breakdown
- Lipid core

CD40 and Tissue Factor in Atheroma

Challenges to the “vulnerable plaque” concept:
- Many so called thin-capped atheromata do not rupture
Few Thin-Cap Fibroatheromas cause events at a median follow-up of 3.4 Years (PROSPECT)


Challenges to the “vulnerable plaque” concept

♥ We tend to ignore certain unexplained features of acute coronary syndromes

What explains the focality of atheroma formation and thrombotic complications in space and in time?

Risk factors are “systemic.”
So, why do “vulnerable” plaques form focally?

Does endothelial shear stress regulate aspects of the high risk plaque?

Diabetic fat-fed pig

Collaboration with group of Prof. Peter Stone at Brigham & Women’s Hospital:
Charles Feldman
Yannis Chatzizisis
Kostas Koskinas

Arterioscler Thromb Vasc Biol.
2013; 33:1494-1504
Atheromata take years to form.
So, what causes a plaque to provoke an acute coronary syndromes at a particular moment?

Low ESS Increases mRNA Expression and Collagenolytic Activity of MMPs-1, -8, -13 and -14

Mechanisms that link low endothelial shear stress (ESS) and inflammation to high-risk plaque formation

Vasospasm of Atherosclerotic Coronary Arteries Precipitates Acute Ischemic Myocardial Damage in Myocardial Infarction–Prone Strain of the Watanabe Heritable Hyperlipidemic Rabbits

Provocation of coronary spasm in myocardial infarction–prone Watanabe heritable hyperlipidemic (WHHLMI) rabbits.


Chatzizisis, Blankenship, Libby

“Inflammation goes with the flow…”

Atheromata take years to form.
So, what causes a plaque to provoke an acute coronary syndromes at a particular moment?

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Vasospasm of Atherosclerotic Coronary Arteries Precipitates Acute Ischemic Myocardial Damage in Myocardial Infarction–Prone Strain of the Watanabe Heritable Hyperlipidemic Rabbits

Provocation of coronary spasm in myocardial infarction–prone Watanabe heritable hyperlipidemic (WHHLMI) rabbits.


How do we intervene to reduce risk of acute coronary syndromes?

The “New Biology” of Atherosclerosis

- Unstable coronary atheromata are often not the “tight” stenoses.
- Stabilization of lesions, by medical therapy, provides a new therapeutic target beyond revascularization.

How do we “stabilize” atherosclerotic plaques?

Plaque “Stabilization”: Plaques with a thick fibrous cap may have less tendency to rupture and cause thrombosis

“Unstable” plaque
- Thin fibrous cap
- Many inflammatory cells
- Lipid core

“Stable” plaque
- Thick fibrous cap
- Fewer inflammatory cells
- Lipid core


Lifestyle a key to CV prevention
Libby & Crea
European Heart Journal 2010
The effects of lowering LDL cholesterol with statin therapy in people at low risk of vascular disease: meta-analysis of individual data from 27 randomised trials

Cholesterol Treatment Trialists’ (CTT) Collaborators

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How does lipid-lowering improve patient outcome?

Regression of fixed stenoses?

Regression of Human Atherosclerosis?

Even profound reduction in low-density lipoprotein causes negligible reduction in atheroma volume


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Even profound reduction in low-density lipoprotein causes negligible reduction in atheroma volume

What accounts for the order of magnitude disparity between the degree of coronary artery stenosis or plaque volume and events?

The functional state of the atheroma, not merely its size or the degree of luminalencroachment, determines the propensity for development of acute coronary syndromes
How does lipid-lowering improve patient outcome?

Angiographic and intravascular ultrasound studies show only modest decreases in stenosis and plaque volume with lipid lowering.

Regression of fixed stenoses?  
Anti-inflammatory effect?

Dietary lipid lowering reduces collagenase expression and increases collagen accumulation in atheroma of cholesterol-fed rabbits

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Dietary lipid lowering reduces tissue factor procoagulant expression in rabbit atheroma

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Favorable Effects of Lipid Lowering in Experimentally Produced Atherosclerotic Plaques

Table 2. Favorable Effects of Lipid Lowering in Experimentally Produced Atherosclerotic Plaques.

- Reduces inflammation (lower levels of macrophages, cytokines, and chemokines and expression of leukocyte adhesion molecules)
- Reduces expression of interstitial collagenase (MMP-1)
- Increases levels of interstitial collagen
- Lowers levels of oxidized low-density lipoprotein
- Reduces production of reactive oxygen species
- Increases expression of endothelial nitric oxide synthase
- Reduces thrombotic potential (reduced tissue factor content and activity)
- Increases fibrinolytic potential (reduced level of plasminogen activator inhibitor-1)


Effect of high-intensity statin therapy on atherosclerosis in non-infarct-related coronary arteries (IBIS-4): a serial intravascular ultrasound study


European Heart Journal - Cardiovascular Imaging Advance Access published: January 30, 2014

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Long-term effects of maximally intensive statin therapy on changes in coronary atheroma composition: insights from SATURN

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How does lipid lowering prevent coronary events? New insights from human imaging trials

The Forgotten Majority: Residual Burden of Events in the Statin “Megatrials”

The Changing Face of the Acute Coronary Syndromes

More NSTEMI, fewer STEMI

Age- and Sex-Adjusted Incidence Rates of Acute Myocardial Infarction, 1999 to 2008

ACS Treatments Changing with Time

Previous Use of Medication on an Outpatient Basis

We tend to face battle prepared to fight the last war

♥ Our current therapies likely contribute to the decline in STEMI by “stabilizing” so-called “vulnerable plaques.”

♥ Is the “vulnerable plaque” a valid concept in 2014?

The Changing Face of the Acute Coronary Syndromes

♥ Many so called thin-capped atheromata do not rupture
Event Rates for Lesions That Were and Those That Were Not Thin-Cap Fibroatheromas, at a Median Follow-up of 3.4 Years (PROSPECT)

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Rate (%)</th>
<th>Event Type</th>
<th>Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaque rupture</td>
<td>4.9</td>
<td>Plaque erosion</td>
<td>1.1</td>
</tr>
<tr>
<td>Thin-cap fibroatheroma</td>
<td>13.2</td>
<td>OCT-calcified nodule (CN)</td>
<td>1.3</td>
</tr>
<tr>
<td>Minimal luminal area (MLA)</td>
<td>5.7</td>
<td>Others</td>
<td>1.6</td>
</tr>
<tr>
<td>Plaque burden (PB)</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Thin-cap fibroatheroma
Minimal luminal area (MLA)
Plaque burden (PB)

Representative Case of Plaque Rupture. A 57-year-old man presenting with ST-segment elevation myocardial infarction was treated with thrombolysis. (A) The coronary angiogram shows the culprit lesion in the mid left anterior descending coronary artery (dashed line indicates the ruptured site corresponding to B). Plaque rupture is identified on cross-sectional (B) and longitudinal (C) optical coherence tomography images by the disrupted fibrous-cap (arrowheads) and a cavity (arrow formation) inside the plaque.

Representative Case of Probable OCT-Erosion. A 37-year-old male smoker presented with ST-segment elevation myocardial infarction. The angiographic image (bottom panel) shows a mild stenosis in the proximal left anterior descending coronary artery. Serial optical coherence tomography (OCT) cross-sectional images from proximal to distal of the culprit lesion show absence of detectable rupture (A to D). Underlying plaque morphology is not well visualized, due to the presence of residual red thrombus (A to C, arrows). The OCT images in the distal and proximal segments of the thrombotic lesions show the absence of superficial lipid and calcification (A and D).

In Vivo Diagnosis of Plaque Erosion and Calcified Nodule in Patients With Acute Coronary Syndrome by Intravascular Optical Coherence Tomography.

Incidence of Plaque Rupture, OCT-Erosion, and OCT-CN in Patients With ACS. Among the 126 culprit lesions, 55 (44%) lesions were classified as plaque rupture, 39 (31%) lesions were classified as optical coherence tomography (OCT) erosion, 10 (8%) lesions were classified as OCT-calcified nodule (CN), and 22 (17%) lesions were classified as others. ACS = acute coronary syndrome.

Plaque rupture causes primarily ST Segment Elevation MI (STEMI)

STEMI

N=39

Rupture

Erosion

NSTEMI

N=24

N=15

Contrasting mechanisms of plaque disruption

<table>
<thead>
<tr>
<th>Plaque Rupture</th>
<th>Plaque “Erosion”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth muscle cell apoptosis</td>
<td>Endothelial cell apoptosis</td>
</tr>
<tr>
<td>Macrophage predominance</td>
<td>Neutrophil involvement</td>
</tr>
<tr>
<td>Interstitial Collagen breakdown</td>
<td>Non-fibrillar collagen breakdown</td>
</tr>
</tbody>
</table>

Mechanisms of plaque disruption and thrombosis

<table>
<thead>
<tr>
<th>Plaque Rupture</th>
<th>Plaque “Erosion”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Many inflammatory cells</td>
<td>Few inflammatory cells</td>
</tr>
<tr>
<td>Lipid rich</td>
<td>Lipid poor</td>
</tr>
<tr>
<td>Collagen Poor</td>
<td>Proteoglycan and glycosaminoglycan rich</td>
</tr>
<tr>
<td>Male predominance</td>
<td>More common in women</td>
</tr>
<tr>
<td>High LDL</td>
<td>High TG, Low HDL</td>
</tr>
</tbody>
</table>

We tend to face battle prepared to fight the last war

❤ We understand the pathophysiology of plaque rupture
❤ We understand how lipid lowering limits plaque rupture
❤ Let’s now address residual risk in statin-treated patients with the current risk factor profile