Atherosclerotic Plaque Rupture
Identifying the Straw That Breaks the Camel’s Back
Yung-Chih Chen, Alex L. Huang, Tin S. Kyaw, Alex Bobik, Karlheinz Peter

The idiom “the straw that breaks the camel’s back” describes scenarios where seemingly minor incidents eventuate in a sudden, unexpected, and often detrimental downfall. In the case of atherosclerosis, over time multiple subclinical cellular events result in the development of unstable, vulnerable atherosclerotic lesions, which leads to the rupture of atherosclerotic plaques, culminating in the often catastrophic clinical manifestation of myocardial infarction or ischemic stroke. In this review, we first summarize lessons learned from autopsy studies, clinical investigations, and animal models mainly published in ATVB. We then present recent experimental studies published in ATVB that shed light on the underlying pathophysiologic development of plaque instability and disruption, and how differential and sometimes maladaptive responses at cellular levels contribute to this complex process. These many publications in ATVB are a testament to the journal’s leading role in research on atherosclerotic plaque instability, an area of research with utmost translational relevance.

Characteristics of Plaque Instability (Vulnerability) in Humans

Our understanding of the pathology of unstable, vulnerable atherosclerotic plaques is mainly based on a limited number of postmortem examinations of human coronary arteries and the analysis of resected surgical specimens from patients who underwent carotid endarterectomy and performed for primary/secondary prevention of transient ischemia attack or stroke.1-3 The histopathologic definition of unstable plaques includes, as the most central features, thin fibrous caps (thickness <65 μm) with paucity of vascular smooth muscle cells, inflammatory cell infiltrates (eg, variable degrees of lymphocyte and particularly macrophage contents although the thin fibrous cap is most often infiltrated), localized proteolytic activity, and large lipid/necrotic cores (which typically account for >40% of the total lesion volume).4-7 Importantly, repeated subclinical plaque ruptures, histologically and potentially macroscopically visible as intraplaque hemorrhage, are described as an additional cause of plaque instability.8 From an autopsy series of 800 cases of sudden coronary death, 3 independent pathogenic mechanisms were identified, namely, plaque rupture (55%-60%), plaque erosion (30%-35%), and calcified nodules (2%-7%).4 However, changes in risk factors (less smoking, more metabolic diseases) and widespread use of statins may result in a shift toward higher prevalence of plaque erosions.5

Although postmortem examinations provide invaluable information on histopathologic characteristics of vulnerable plaques, they are inherently limited by selection bias, and only lesions at the most advanced stage have been studied. Furthermore, they are a snapshot in nature and cannot provide detailed information on the natural history of plaque progression. This deficiency is, in part, bridged by clinical studies that use intracoronary imaging in patients. In the PROSPECT study (The Providing Regional Observations to Study Predictors of Events in the Coronary Tree), 697 patients were followed up for 3.4 years, and multimodality intracoronary imaging was used to interrogate and characterize lesions in all 3 coronary vessels. Investigators have found that thin-cap fibroatheroma indeed confers higher risk of adverse outcomes (4.9% versus 1.3%; P<0.001). However, the fact that only 4.9% of these lesions eventually give rise to clinical events limits the clinical utility of the criterion of plaque vulnerability, as used in PROSPECT, as a risk-stratifying tool. In addition, this further highlights the knowledge gap and the need for a more mechanistic understanding and better identification of characteristics reflecting plaque vulnerability.9

One direction of research is the development of intracoronary imaging methods toward the identification of unstable, rupture-prone coronary plaques. Several elegant examples of this approach have recently been published in ATVB. Near-infrared spectroscopy, as a means to determine the lipid content of a plaque, intravascular ultrasound, as a means to predominantly determine the size of the necrotic core and the thickness of the plaque cap, and optical coherence tomography as a means to predominantly determine the cap thickness and plaque surface microstructures (eg, thrombi on plaque microcrotures), and these technologies in combination, have been investigated in regard to their ability to identify vulnerable plaques.10-11 Whether these measurements of individual morphological characteristics of plaque vulnerability have the prognostic power to be used for clinical risk stratification must be determined in future studies. However, these technologies have been shown to allow monitoring of morphologic changes induced by plaque-stabilizing drugs and, as such, have strong potential as surrogate measures in clinical trials for initial proof of concept for plaque-stabilizing drugs.10 Noninvasive molecular imaging of inflammation, protease activity, or specific cell types is another highly promising approach toward the identification of vulnerable atherosclerotic...
plaques. Magnetic resonance imaging (MRI) and positron emission tomodraphy, and in particular the combination of both, providing soft-tissue structural information and highly sensitive functional imaging, are the technologies with the greatest potential for vulnerable plaque imaging. Examples of this are the imaging of activated macrophages with the positron emission tomodraphy tracer 64Cu-DOTATATE (1,4,7,10-tetraazaacyclodocane-N,N',N″,N‴-tetraacetic acid]-d-Phe1,Tyr3-octreotate)12 in carotid artery plaques in patients, the MRI imaging of ex vivo human carotid plaque—targeting activated platelets with MR contrast particles,13 and the combination of 68Ga-Fucoid imaging of P-selectin and high magnetic strength MRI in mouse plaques.14 Even less specific positron emission tomodraphy tracers such as 18F-sodium fluoride (NaF) and 18F-fluoro-deoxyglucose are able to detect atherosclerotic plaque instability/rupture in patients.15 Overall, technical advances in imaging technologies, combined with advances in biotechnology, chemistry, and isotope production toward the generation of novel functional contrast reagents now offer the opportunity to assess whether the identification of vulnerable plaques can improve the management and treatment, and ultimately the outcomes, of patients with atherosclerotic disease.

**Biomarkers of Plaque Instability**

One of the most controversially discussed areas of atherosclerosis research is the ongoing quest for biomarkers of cardiovascular risk, which primarily aims toward identification of markers that can predict plaque rupture.16 To address this controversy, the American Heart Association has laid out a framework for the establishment of biomarkers of cardiovascular risk.17 Although there are several potential candidates, all of these still need to be further assessed to suit the criteria necessary to guide treatment decisions.

Inflammation is clearly a determinant of plaque instability,18 as seen in many studies demonstrating an association with a vulnerable plaque phenotype19 and the increased incidence of coronary events in patients with autoimmune diseases.20,21 Chronic inflammatory diseases such as asthma are also associated with an increased cardiovascular event rate.20 It is, therefore, no surprise that the inflammation marker C-reactive protein (CRP) has been extensively investigated as a biomarker for cardiovascular risk. Indeed, large-scale epidemiological data have demonstrated that the inflammatory marker CRP predicts cardiovascular events, especially in intermediate-risk patients, and, most importantly, retains its risk-prediction value under therapy.22 However, the role of the high-sensitivity CRP assay for treatment decisions has not been fully established, and high-sensitivity CRP is not broadly applied as a risk marker for the prediction of plaque rupture.22

Several potential new biomarkers of cardiovascular risk have recently been described in ATVB. Plasma levels of soluble interleukin-2 receptor α, which is a marker of T-lymphocyte activation, correlate with cardiovascular mortality.23 Galectin-3 is a potential marker for cardiovascular mortality that, most interestingly, reflects plaque instability rather than overall atherosclerotic lesion growth.24 A recent systematic assessment for potential correlations of adipokines with the histological criterion of carotid artery plaque instability in patients reveals a strong association of chemerin with plaque instability.25 Consistent with the role of matrix metalloproteinases in destabilizing atherosclerotic plaques, elevated plasma levels of matrix metalloproteinase-12, which can degrade elastin, fibroenectin, laminin, and type IV collagen, correlate with an increased rate of coronary events in patients with type 2 diabetes mellitus.26 However, there are also descriptions of plasma biomarkers that correlate with a more stable fibrous plaque phenotype and a lower incidence of cardiovascular events. Rattik et al27 describe smooth muscle cell growth factors (eg, heparin-binding epidermal growth factor) as such markers.

Polymarker approaches using a pattern of protein or micro-RNA markers have been described and may indeed have a higher association with plaque instability than single marker approaches. Proteomic approaches are based on peptides that are released from unstable plaques with protease activity (eg, collagen peptides)28 or on micro-RNAs that are potentially integral parts of the pathology of vulnerable plaques.29

**Contribution of Hemodynamics to Plaque Instability/Rupture**

ATVB is the primary forum for original work and discussion of data and concepts on the role of hemodynamic parameters in atherogenesis and particularly plaque rupture, involving scientists of various disciplines. The observation that atherosclerosis, under the same systemic risk factors, preferentially develops in certain parts of the arterial tree where the vessel wall experiences low shear stress or turbulent flow, such as at branches and curvatures, is a long-appreciated indication of a direct role of hemodynamic characteristics in atherogenesis.30-32 Low shear stress has been identified as a major driver of plaque development and plaque instability, via mechanisms such as accumulation of lipids, macrophages, and other inflammatory cells; overexpression of adhesion molecules and proteases; reduction of stabilizing collagen fibers; increase in necrotic core volume; thinning of fibrous caps; and reduction of endothelial cell coverage.33,34 Endothelial cells are the major mechanosensors and a multitude of work demonstrates changes in numerous signaling pathways dependent on the hemodynamic settings experienced by endothelial cells. These changes include altered glucose uptake capacity,35 gene expression,36 epigenetic changes,37,38 and shear-dependent neutrophil adhesion.39 Several recent articles in ATVB elegantly highlight the importance of the shear-sensing function of the endothelium.40-44

However, low shear stress on its own does not seem to be sufficient to induce plaque rupture,45,46 Tensile (wall) stress, which is higher by several magnitudes than wall shear stress, seems to be an important determinant in causing a vulnerable atherosclerotic plaque to rupture.45,46 There is a high prevalence of plaque rupture in the proximal coronary arteries, where the tensile stress is higher than the periphery of the coronary artery system,42 indicating the importance of tensile stress over laminar shear stress. With the technical advances in flow measurements in the catheter laboratory, and also with flow measurements using noninvasive technologies, such as...
computed tomography and MRI, hemodynamic considerations will increasingly become part of clinical decision making as well.

Animal Models of Plaque Rupture and Erosion
Animal models are crucial for research toward the understanding of atherosclerosis. They allow genetic and pharmacological manipulations, thereby elucidating the complex interplay between different genetic and environmental factors, and they offer the opportunity to develop and test novel therapeutic approaches. Ideally, animal models should recapitulate characteristic features of human plaque instability and rupture, and they should respond to clinically used pharmacotherapy displaying the same effects as seen in humans. In addition, they should be easy to apply and inexpensive, thereby allowing for statistically significant numbers of animals for experimental studies. Indeed, for the understanding of the initiation and progression of atherosclerosis, animal models such as ApoE−/− and LDLR−/− mice have been the basis of in-depth knowledge gain. ATVB gives testimony to the successful use of and important findings obtained by these mouse models. However, studies addressing the clinically most relevant pathology of plaque instability and rupture have been severely hampered by the paucity of animal models that reflect the pathology of plaque instability and rupture as seen in humans. ATVB is actively engaged in the development of novel animal models of plaque instability/rupture and provides an engaged forum of debate on the strengths, weaknesses, and translational potential of various models.

Sasaki et al48 proposed a total ligation model in which the common carotid artery was ligated for 4 weeks and then a cuff was placed on top of the artery with no blood flow. Although this model has shown some of the features seen in human atherosclerosis, the pathogenesis of plaque rupture with artificial hemodynamics and cuff-induced inflammation is not widely accepted as a full reflection of human plaque rupture pathology. Williams et al49 report the development of plaque instability/rupture and provides an engaged forum of debate on the strengths, weaknesses, and translational potential of various models.

Cholesterol and Other Lipids Boosting Plaque Instability
Clinical studies have established a close link between low-density lipoprotein cholesterol and plaque instability. Recent studies published in ATVB have identified novel contributors, provided novel mechanistic understandings of clinical observations, and also provided alternate avenues for novel therapies. Edsfeldt et al50 explored the role of sphingolipids. By analyzing 200 carotid plaques, they have shown that sphingolipids, in particular glucosylceramide, are associated with plaque inflammation and instability and may represent a novel therapeutic target.50 Ronsein et al51 have found that niacin, although successfully raising high-density lipoprotein, fails to improve ABCA1 (ATP-binding cassette transporter A1)-specific efflux, the main cholesterol exporters in macrophages. This may explain why niacin is limited in its clinical benefits, as observed in the AIM-HIGH trial (The Aterotherosclerosis Intervention in Metabolic Syndrome with Low HDL/High Triglycerides: Impact on Global Health Outcomes).52 Melchior et al53 used an antisense approach to reduce cholesterol oleate packaging and have shown that hepatic knockdown of sterol-O-acyltransferase 2 not only arrests lesion growth but also remodels lesions into a more stable phenotype. This fits well...
with clinical data reporting that the capacity for cholesterol efflux is inversely correlated with carotid stenosis and strongly associated with advanced carotid atherosclerotic lesion.62

**Intraplaque Hemorrhage as a Consequence and Amplifier of Plaque Instability**

Intraplaque hemorrhage is one of the cardinal histological features of vulnerable plaques63–65 and is thought to result either from microruptures with intraplaque bleedings or from leaky neovascularization within the plaque.66 Recent studies suggest that intraplaque hemorrhage could also be a trigger, rather than just a marker, of plaque instability. It plays a major role in plaque progression through accumulation of erythrocyte membranes, production and retention of cholesterol crystals, erythropagocytosis, and enlargement of necrotic cores. In addition, it promotes oxidative and proteolytic activities, as well as leukocyte infiltration and inflammation in plaques.67–71 One of the key regulators of intraplaque hemorrhage and plaque instability may be hepcidin. Hepcidin degrades the iron transporter ferroportin 1, resulting in retention of iron, accumulation of intracellular lipids, and apoptosis of macrophages.72 Adenoviral-overexpressed hepcidin enhanced macrophage infiltration and destabilized plaques.72 Inhibition of hepcidin via the bone morphogenetic protein pathway in liver limits atherosclerosis progression by upregulating ABCA1 and ABCG1 (ATP-binding cassette subfamily G member 1).73 These reports provide mechanistic insights into how erythropagocytosis drives lesion vulnerability. Intraplaque hemorrhage may also release free heme, which is a strong activator for nicotinamide adenine dinucleotide phosphate oxidase and a major source of reactive oxygen species.74 Mehta et al74 have shown that hemopexin, a ligand for heme, plays a protective role in heme elimination and modulates macrophage polarization. An interesting connection between blood pressure and prevalence of intraplaque hemorrhage in carotid plaques in patients (up to ~22%) was recently reported.75 The stiffer the arterial system, the more intraplaque hemorrhages were found.76 The latter 2 reports indicate the relevance of intraplaque hemorrhage in human plaque instability.

**Platelets as Therapeutic Targets in Plaque Instability?**

Platelets play a pivotal role in atherogenesis. Their binding to the endothelium precedes the appearance of leukocytes in plaques and, as such, platelets are early players in atherogenesis.77 Also infusion of activated platelets accelerates atherosclerosis.78 Furthermore, platelets are clearly involved in the often fatal event of thrombotic vessel occlusion occurring with plaque rupture. However, there are only a few studies available that address the role of platelets in plaque instability. Platelets clearly adhere to inflamed endothelial cells that cover atherosclerotic plaques.13 They induce monocyte extravasation and foam cell formation, and thereby contribute indirectly to plaque destabilization.79 Platelets are central players not only in thrombosis and hemostasis but also in inflammation and the innate immune system. The latter is also indicated by the finding that human platelets express all of the TLR1 (Toll-like receptor-1) to TLR10 transcripts.80 Interestingly, women have higher expression levels of TLRs on platelets than men,81 a difference that might contribute to sex-dependent differences in the cardiovascular risk profile.81 Furthermore, aspirin intake is associated with decreased platelet TLR1, TLR3, and TLR4, and lipid treatment increased platelets TLR1, TLR2, TLR3, and TLR9, indicating a distinct association of cardiovascular risk factors with specific platelet TLR expression.82 This study also demonstrates the association of TLR gene expression and the serum biomarkers of CRP, intercellular adhesion molecule-1, interleukin (IL)-6, MCP-1 (monocyte chemoattractant protein 1), tumor necrosis factor receptor, and P-selectin, which suggests a sex-specific link between thrombosis, immunity, infection, and cardiovascular disease.83 Pathogens such as human cytomegalovirus also activate platelets in a TLR2-dependent manner and may ultimately contribute to atherosclerosis and plaque instability through this platelet-dependent mechanism.82 TLRs on platelets but also other cells may thus contribute to the association of infection and plaque instability.83

In general, the cardiovascular risk reduction, as undoubt edly seen with antiplatelet therapy, is generally seen as an effect of platelet inhibition in the event of plaque rupture. However, as plaque rupture may be a repeated event resulting in microthrombi, which in turn increase plaque instability and the risk of further plaque rupture, platelets may well have direct involvement in plaque instability. It may be the inhibition of the repeated plaque ruptures or additional mechanisms of not yet identified plaque-stabilizing effects of platelets that also contribute to the reduction of cardiovascular events seen with antiplatelet therapy.

**Monocytes/Macrophages as Central Players in Plaque Instability**

The atherosclerotic lesion burden has been demonstrated to be positively correlated with the number of circulating monocytes in mice and the presence of coronary artery disease in patients.84,85 Vulnerable, rupture-prone plaques have abundant monocytes/macrophages, particularly in the shoulder region of thin caps, indicating their causative role in plaque rupture and also rendering macrophages good drug targets.86 These activated macrophages release proinflammatory molecules such as IL-6 and tumor necrosis factor-α, proatherosclerotic chemokines, metalloproteinases, mi-RNAs, and reactive oxygen species.86,87 The role of monocytes in plaque destabilization is further supported by experimental inhibition of chemokine effects, such as the blockade of CCR-5 (C-C chemokine receptor 5), CX3CR1 (CX3C chemokine receptor 1), and CCL2 (chemokine C-C motif ligand 2), which are involved in the recruitment of both Ly6C+ and Ly6C+ monocytes. This inhibition almost fully abolishes atherosclerotic plaque development.88,89 In patients with chronic kidney disease, monocyte subtype blood counts, in particular of intermediate CD14++CD16−, correlates with an increase in cardiovascular events, suggesting a role of specific monocyte subtypes in plaque instability.90 This role of the intermediate monocyte subtype CD14++CD16− in plaque instability had also been suggested by the finding that this monocyte subset is a predictor of cardiovascular events in patients.91 In addition, previous imaging studies show an association of CD16+ monocytes with characteristics of plaque instability, as
visible in computed tomography or optical coherence tomography in patients, and reversal of this association under statin therapy. In a recent human autopsy study, another subtype, the M4 macrophage subtype, has been found to be associated with features of plaque instability.

Overall, monocytes/macrophages are clearly a driving force of plaque instability and, as such, represent a potent therapeutic target for plaque stabilization. However, further mechanistic studies must clearly define mechanisms of targeting and the subpopulation to be targeted. Depletion of circulating monocyte populations, inhibiting monocyte recruitment, and inhibiting macrophage proliferation within atherosclerotic plaques are potential therapeutic strategies.

**Emerging Role of Lymphocytes in Plaque Instability**

Multiple lymphocyte populations are found in vulnerable plaques. Natural killer T (NKT) cells, which bridge the gap between innate and adaptive immunity, accumulate in human rupture-prone shoulder regions of vulnerable plaques, together with dendritic cells. In ApoE−/− mice, Li et al showed that NKT cells, in particular CD4+ NKT cells, exert their effects on atherosclerotic lesions via cytotoxic mechanisms, mostly via perforin and granzyme B, stimulating apoptosis and large increases in necrotic cores. NKT cells are activated by many mechanisms, including lipid antigen presentation via CD1d expressed by dendritic cells, which may explain their colocalization in lesions, or via IgG antibodies activating NKT cell Fcgamma RIII. IgG auto-antibodies can be active mediators of atherosclerotic plaque instability. Selanthari et al have also shown that NK cells can contribute to lesion vulnerability by increasing necrotic core size via essentially similar cytotoxic mechanisms. In cytomegalovirus seropositive patients, the NKGC2c+ NK cell subset has been associated with high-risk carotid atherosclerotic plaques.

Although relatively poorly studied, CD4+ T helper and cytotoxic CD8+ T cells are also increased in thin-cap fibroatheromas compared with stable lesions, with the largest increases in cytotoxic CD8+ T cells. Kyaw et al have shown that in atherosclerotic mice, CD8+ T cells contribute to apoptosis of key lesion cell types, including smooth muscle cells and macrophages, as well as increasing necrotic core size. Despite CD8+ T-cell–derived tumor necrosis factor-α being capable of inducing apoptosis, only CD8+ T-cell–derived granzyme B and perforin stimulate apoptosis and so contribute to necrotic core size in developing vulnerable lesions. The role of CD4+ helper T cells in vulnerable plaque development and rupture is less clear and may be indirect via cytotoxic CD8+ T cells, rather than direct, as the cytotoxic effects of CD8+ T cells are substantially diminished in the absence of CD4+ helper T cells. CD4+ helper T cells are required for both development of cytotoxic CD8+ T cells and also sustaining cytotoxic CD8+ T-cell responses. Although cytotoxic CD8+ T cells clearly contribute to plaque instability, it is unclear whether these cells represent effector or memory cells, knowledge essential for effective therapeutic targeting of these cells for plaque stabilization. Several studies in humans also indicate that CD4+CD28− T cells seem to be important in acute coronary syndromes and plaque instability. Their development is associated with premature aging of the immune system, and they may be particularly important in promoting plaque instability and rupture in patients with other inflammatory disorders, such as rheumatoid arthritis, end-stage renal disease, and type 2 diabetes mellitus, where their numbers are increased. Functionally these cells infiltrate target tissues, are highly cytotoxic, expressing cytotoxins including granzymes and perforin, and are resistant to apoptosis and the suppressive effects of Foxp3+ regulatory T cells. Unlike CD4+ helper T cells, these cells most likely directly contribute to plaque instability via cytotoxic mechanisms. Given the elevated numbers of circulating CD4+CD28− T cells in patients with acute coronary syndromes, together with their high activation status and ability to kill endothelial cells, these cells may also be critically important in plaque erosion. As the latter has attracted increased attention as a cause of myocardial infarction, research addressing the roles of these cells in atherosclerosis might be of particular interest.

**Artery Tertiary Lymphoid Organs: A Future Focus of Plaque Instability**

It has been known for >30 years that adventitial immune cell infiltrates are associated with advanced human atherosclerotic plaques, with structural organizations that suggest generation of local humoral responses. In ruptured plaques, the infiltrates seem to be greater in number than in nonruptured human atherosclerotic plaques, suggesting involvement in the pathology of plaque instability. More recent studies have identified similar adventitial infiltrates, now referred to as artery tertiary lymphoid organs (ATLO), associated with aortic atherosclerotic lesions in aged hyperlipidemic ApoE−/− mice. In a recent ATVB publication, Srikakulapu et al focused on defining the B-cell populations within such structures, demonstrating the presence of effector B cells and plasma cells, as well as several immunosuppressive B-cell subtypes. B2 cells, which are proatherogenic, including transitional, follicular, and germinal center B cells, and multiple types of B1 cells were identified, including IgM+ cells. The identified plasma cells include IL-10–producing plasma cells, which may represent regulatory plasma cells. Follicular T cells have also been shown to be present, raising the possibility that artery tertiary lymphoid organs represent an effective T-follicular helper-germinal center B-cell axis that may drive local proatherogenic antibody production. CD8+ regulatory T cells are important in their regulation, as artery tertiary lymphoid organs development is increased when CD8+ regulatory T-cell function is impaired, and this is associated with enhanced disease development. The role of artery tertiary lymphoid organs in the development of advanced atherosclerotic lesions, plaque instability, and rupture promises to be a highly interesting area of research in the future.

**Therapeutic Approaches for Plaque Stabilization**

Despite a multitude of studies often based on gene deletion in mice, which has helped to provide in-depth knowledge of
mechanisms responsible for the initiation and progression of atherosclerosis, therapeutic antiatherosclerotic approaches are rarely described. The lack of novel therapies for plaque stabilization is even more apparent and at the same time worrisome, as this clearly reflects a major medical need.

Nevertheless, a few promising therapeutic approaches toward plaque stabilization are available and have been published in *ATVB*. A recent human study provides evidence that treating blood pressure has the potential to reduce intraplaque hemorrhage as seen in MRI in carotid plaques in patients. DNA/RNA therapeutics hold great promise and initial promising approaches toward plaque stabilization have been published. These include micro-RNA, anti–micro-RNA, and a type B CpG oligodeoxynucleotide TLR9 agonist.

With increasing knowledge of the specific cell types that mediate plaque rupture and advances in biotechnology providing cell-specific therapeutic approaches, selective plaque stabilization might be possible in patients. Preclinical approaches have been successful by targeting monocytes via the relative selective phagocytosis of drug-loaded nanoparticles. Another recent example of these promising developments is cell type–specific anticytokine effects achieved by a bifunctional antibody that combines cell-specific targeting against F4/80 surface molecules on myeloid cells and tumor necrosis factor inhibition. Recombinant antibody technology will allow cell-specific blockade of secreted proteins and also receptors, and this represents a new direction in atherosclerotic therapy.

Despite the association of CRP with cardiovascular risk and potentially with plaque rupture, the pentameric form of CRP has not been associated with a direct causal role and thus the development of drugs that target pentameric form of CRP has not been pursued. Nevertheless, newer data indicate that the dissociated conformation of pentameric form of CRP, the monomeric CRP, clearly possesses proinflammatory effects. Indeed, the inhibition of monomeric CRP has recently been proven to exhibit a strong anti-inflammatory effect. Therefore, monomeric CRP might be worthwhile to be assessed as a potential plaque-stabilizing therapeutic target. An alternative approach targeting inflammation, as a major force leading to plaque instability and rupture, is to choose targets that are upstream of CRP, such as IL-6 or IL-1. Several smaller clinical trials and 2 large-scale clinical trials are currently testing this hypothesis: the large trials are the CIRT (Cardiovascular Inflammation Reduction Trial), which is testing low-dose methotrexate as an inhibitor of the CRP/IL-6/IL-1 axis, and the CANTOS (Canakinumab Anti-Inflammatory Thrombosis Outcomes Study), testing the monoclonal antibody canakinumab and targeting IL-1β. Overall, despite the current paucity of antiatherosclerotic therapy, novel targets and innovative biotechnological approaches justify the hope that plaque-stabilizing therapies are in reach.

**Summary**

It is easy to see the breaking of the camel’s back, as it is typically an obvious, final, and dramatic scene that catches everyone by surprise. Yet it is difficult to see the straw itself and to understand all the strain that silently builds up and contributes to the final event. Similarly, the rupture of unstable atherosclerotic plaques is a complex process ultimately representing a maladaptive response to hemodynamic conditions, lipid accumulation, arterial injury, necrosis, and inflammation. Growing understanding of the many facets of this pathological process offers multiple opportunities for early detection of unstable plaques with biomarkers and novel molecular imaging technologies, and hopefully will ultimately lead to the development of utterly needed plaque-stabilizing drugs.

**Sources of Funding**

Y.-C. Chen was supported by a National Heart Foundation (NHF) of Australia Postdoctoral Fellowship. A.L. Huang was supported by a NHF of Australia Postgraduate Scholarship. K. Peter was supported by a National Health and Medical Research Council (NHMRC) Principal Research Fellowship. The Bobik and Peter laboratories are funded by the NHMRC of Australia.

**Disclosures**

None.

**References**

by guest on August 30, 2017 http://atvb.ahajournals.org/ Downloaded from

Chen et al Atherosclerotic Plaque Rupture e69


43. Murphy PA, Hynes RO. Alternative splicing of endothelial fibronectin is induced by disturbed hemodynamics and protects against hemorrhage of the vessel wall. Arterioscler Thromb Vasc Biol. 2014;34:2042–2050. doi: 10.1161/ATVBAHA.114.303879.


Downloaded from http://atvb.ahajournals.org/ by guest on August 30, 2017
Cholesterol efflux capacity, carotid atherosclerosis, and cerebrovascular


with features of plaque instability.


**Key Words:** atherosclerosis  ■  atherosclerotic plaque  ■  biomarkers  ■  C-reactive protein  ■  interleukins
Atherosclerotic Plaque Rupture: Identifying the Straw That Breaks the Camel's Back
Yung-Chih Chen, Alex L. Huang, Tin S. Kyaw, Alex Bobik and Karlheinz Peter

Arterioscler Thromb Vasc Biol. 2016;36:e63-e72
doi: 10.1161/ATVBAHA.116.307993
Arteriosclerosis, Thrombosis, and Vascular Biology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2016 American Heart Association, Inc. All rights reserved.
Print ISSN: 1079-5642. Online ISSN: 1524-4636

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://atvb.ahajournals.org/content/36/8/e63

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Arteriosclerosis, Thrombosis, and Vascular Biology can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Arteriosclerosis, Thrombosis, and Vascular Biology is online at:
http://atvb.ahajournals.org//subscriptions/