Abstract: There is a common misperception in the cardiology community that most acute coronary events arise from ruptures of mildly stenotic plaques. This notion has emanated from multiple studies that had measured the degree of angiographic luminal narrowing in culprit plaques months to years before myocardial infarction. However, angiographic studies within 3 months before myocardial infarction, immediately after myocardial infarction with thrombus aspiration or fibrinolytic therapy, and postmortem pathological observations have all shown that culprit plaques in acute myocardial infarction are severely stenotic. Serial angiographic studies also have demonstrated a sudden rapid lesion progression before most cases of acute coronary syndromes. The possible mechanisms for such rapid plaque progression and consequent luminal obstruction include recurrent plaque rupture and healing and intraplaque neovascularization and hemorrhage with deposition of erythrocyte-derived free cholesterol. Moreover, recent intravascular and noninvasive imaging studies have demonstrated that plaques which result in coronary events have larger plaque volume and necrotic core size with greater positive vessel remodeling compared with plaques, which remain asymptomatic during several years follow-up, although these large atheromatous vulnerable plaques may angiographically seem mild. As such, it is these vulnerable plaques which are more prone to rapid plaque progression or are those in which plaque progression is more likely to become clinically evident. Therefore, in addition to characterizing plaque morphology, inflammatory activity, and severity, detection of the rate of plaque progression might identify vulnerable plaques with an increased potential for adverse outcomes. (Circ Res. 2015;117:99-104. DOI: 10.1161/CIRCRESAHA.117.305637.)

Key Words: acute coronary syndrome ■ atherosclerosis ■ coronary artery disease ■ myocardial infarction

Pathological and anatomic features of high-risk or vulnerable plaques have been reviewed extensively in the literature. Briefly, high-risk plaques are characterized by the presence of large plaque burden and necrotic cores that are covered by intensely inflamed, thin fibrous caps; these lesions are typically positively (or outwardly) remodeled. Most of the anatomic features of high-risk plaques are identifiable in vivo using invasive and noninvasive imaging modalities, such as intravascular ultrasound, optical coherence tomography, and coronary computed tomography angiography. Although difficult, inflammation has been identified by intravascular demonstration of thermal heterogeneity and targeting of macrophages by positron emission tomography. Studies over the past 2 decades have demonstrated that high-risk plaques are usually responsible for most acute coronary syndromes (ACS). However, despite extensive interest and excitement regarding the potential of identifying high-risk lesions, plaque characteristics that have been shown to be associated with high-risk plaques have demonstrated a poor positive predictive value for identifying future events.

For more than a decade, the cardiology community has believed that most ACS arise from ruptures of mildly stenotic plaques and that most major adverse events occur independent of the plaque size and the degree of luminal stenosis. This belief emanated from retrospective studies of patients in whom coronary angiography had been performed months to years before myocardial infarction (MI); the lesions responsible for the subsequent infarct were angiographically mild in most cases, that is, at baseline <50% diameter stenosis compared with the adjacent reference vessel lumen. Pathologically, although some coronary events may be caused by rupture of plaques with a mild degree of luminal narrowing, most culprit lesions at the time of the acute event are critically occlusive. A postmortem study of patients...
who died suddenly demonstrated that >70% of ruptured plaques exhibited >75% (mean 78%±14%) cross-sectional area narrowing; only ~5% of the fatal events were caused by the lesions <50% cross-sectional luminal narrowing.17 Studies in patients at the time of MI are consistent with these findings. Following successful fibrinolysis in patients with acute ST-segment elevation MI (STEMI), the average luminal stenosis caused by culprit lesions (excluding those with obvious residual thrombus) as assessed by quantitative coronary angiography was reported to be 61%±17%.25 Similarly, the average stenosis of the infarct related lesion in STEMI patients who underwent thrombus aspiration was reported as 66%±12%.26 (Figure 1). Although other post MI studies in the absence of thrombolytic therapy or thrombus aspiration have also confirmed a significant degree of stenosis of the infarct-related artery, some overestimation of the luminal stenosis caused by residual thrombus cannot be ruled out.27–29

A critical review of the literature suggests that the apparent discordance regarding the severity of culprit lesions may be explained by understanding the time course of the development and maturation of atherosclerotic plaques (Figure 1). The common feature in all of the original studies that linked mild plaques to MI is the long lead time between the baseline angiogram and the acute event (average, 25 months, range 18–40 months) (Figure 1).20–24 More recent studies have demonstrated that plaques progress from mild at baseline to obstructive at the time of MI and clarified that plaque progression occurs before actual plaque rupture.16,31–33 In addition, as described later, angiography often substantially underestimates plaque severity, as revealed by intravascular ultrasound imaging, contributing to the misconception of the mild vulnerable plaque.

The Providing Regional Observations to Study Predictors of Events in the Coronary Tree study (PROSPECT) prospectively found that among 106 nonculprit lesions in 697 patients resulting in subsequent ACS during median 3.4 year follow-up, the average luminal stenosis of culprit lesions resulted in MI in various studies, organized relative to the time of MI. Green bars represent average luminal stenosis of the culprit lesions before MI, whereas red bars signify similar measurement after MI. Both green and red bars represent studies with single measurement. Data from studies with >1 measurement are shown by paired colors (orange, blue, and purple). The common perception that most MI are caused by rupture of mild plaques emerged from studies in 1980s and 1990s (2nd, 3rd, 4th, 6th bar from left)16,17,19,20 which reported that lesions responsible for the subsequent STEMI were angiographically mild at baseline. In studies in which measurements were made >3 months before MI, the mean luminal stenosis by culprit lesion was 35.6%±20.6%. On average, these measurements were done 25 months before MI (range 18–41 months). On the other hand, data emerging from studies that investigated culprit lesion after the MI shows obstructive lesions are responsible for MI with mean luminal stenosis of 66%±15.5% (red bars). (We only included post-STEMI data with successful fibrinolysis or thrombectomy along with postmortem data in this figure to ensure measurements were not significantly affected by the presence of thrombus and accurately reflect plaque size.) The PROSPECT study along with studies by Zaman et al28 and Ojio et al29 shed light on this apparent discrepancy in the literature. PROSPECT (orange bars) demonstrated progression of lesion from 32.3%±20.6% at baseline to 65.4%±16.3% at the time of event (during a median follow-up of 3.4 years). In a study by Zaman et al (blue bars),28 among 41 patients who had STEMI, culprit lesions that were measured >3 months (mean 24 months) before MI had mean luminal stenosis of 36.5%±20.6%, whereas culprit lesions that were measured <3 months before MI had mean luminal stenosis of 59.6%±31.5%. On average, these measurements were done 25 months before MI (range 18–41 months). On the other hand, data emerging from studies that investigated culprit lesion after the MI shows obstructive lesions are responsible for MI with mean luminal stenosis of 66%±15.5% (red bars). (We only included post-STEMI data with successful fibrinolysis or thrombectomy along with postmortem data in this figure to ensure measurements were not significantly affected by the presence of thrombus and accurately reflect plaque size.) The PROSPECT study along with studies by Zaman et al28 and Ojio et al29 shed light on this apparent discrepancy in the literature. PROSPECT (orange bars) demonstrated progression of lesion from 32.3%±20.6% at baseline to 65.4%±16.3% at the time of event (during a median follow-up of 3.4 years). In a study by Zaman et al (blue bars),28 among 41 patients who had STEMI, culprit lesions that were measured >3 months (mean 24 months) before MI had mean luminal stenosis of 36.5%±20.6%, whereas culprit lesions that were measured <3 months before MI had mean luminal stenosis of 59.6%±31.5%. Similarly, in a study by Ojio et al (purple bars),29 the mean luminal stenosis of culprit lesions 10 months before MI was 30%±18%, whereas similar measurement less than a week before MI revealed culprit lesions causing luminal stenosis of 71%±12%. Overall, the totality of the data represented in this figure demonstrates that culprit lesions go through a period of rapid progression weeks to months before MI. This observation can explain the apparent discrepancy in the literature between size of culprit plaques at baseline and at the time of event. The culprit lesions in PROSPECT study (orange bar) and study by Ojio et al (purple bar) resulted in variety of acute coronary syndromes (ACS) presentations, whereas the culprit lesions in the rest of studies represented here resulted in STEMI. MI indicates myocardial infarction; and STEMI, ST elevation myocardial infarction.

Figure 1. Do plaques rapidly progress before myocardial infarction? This figure illustrates average luminal stenosis of culprit lesions resulted in MI in various studies, organized relative to the time of MI. Green bars represent average luminal stenosis of the culprit lesions before MI, whereas red bars represent similar measurement after MI. Both green and red bars represent studies with single measurement. Data from studies with >1 measurement are shown by paired colors (orange, blue, and purple). The common perception that most MI are caused by rupture of mild plaques emerged from studies in 1980s and 1990s (2nd, 3rd, 4th, 6th bar from left) which reported that lesions responsible for the subsequent STEMI were angiographically mild at baseline. In studies in which measurements were made >3 months before MI, the mean luminal stenosis by culprit lesion was 35.6%±20.6%. On average, these measurements were done 25 months before MI (range 18–41 months). On the other hand, data emerging from studies that investigated culprit lesion after the MI shows obstructive lesions are responsible for MI with mean luminal stenosis of 66%±15.5% (red bars). (We only included post-STEMI data with successful fibrinolysis or thrombectomy along with postmortem data in this figure to ensure measurements were not significantly affected by the presence of thrombus and accurately reflect plaque size.) The PROSPECT study along with studies by Zaman et al and Ojio et al shed light on this apparent discrepancy in the literature. PROSPECT (orange bars) demonstrated progression of lesion from 32.3%±20.6% at baseline to 65.4%±16.3% at the time of event (during a median follow-up of 3.4 years). In a study by Zaman et al (blue bars), among 41 patients who had STEMI, culprit lesions that were measured >3 months (mean 24 months) before MI had mean luminal stenosis of 36.5%±20.6%, whereas culprit lesions that were measured <3 months before MI had mean luminal stenosis of 59.6%±31.5%. Similarly, in a study by Ojio et al (purple bars), the mean luminal stenosis of culprit lesions 10 months before MI was 30%±18%, whereas similar measurement less than a week before MI revealed culprit lesions causing luminal stenosis of 71%±12%. Overall, the totality of the data represented in this figure demonstrates that culprit lesions go through a period of rapid progression weeks to months before MI. This observation can explain the apparent discrepancy in the literature between size of culprit plaques at baseline and at the time of event. The culprit lesions in PROSPECT study (orange bar) and study by Ojio et al (purple bar) resulted in variety of acute coronary syndromes (ACS) presentations, whereas the culprit lesions in the rest of studies represented here resulted in STEMI. MI indicates myocardial infarction; and STEMI, ST elevation myocardial infarction.
follow-up, there was progression from a mean angiographic diameter stenosis of 32%±21% at baseline to 65%±16% at the time of occurrence of the acute event. In the Dynamic Registry of the National Heart, Lung, and Blood Institute, 31 3,747 patients undergoing percutaneous coronary intervention were retrospectively studied. In this cohort, 216 patients required an additional percutaneous coronary intervention of a nonculprit lesion within 1 year. The mean diameter stenosis of the (originally) nonculprit lesion progressed from a baseline value of 41.8%±20.8% to 83.9%±13.9% at the time of the subsequent percutaneous coronary intervention. Thus, these studies clearly demonstrate plaque progression from the time of initial angiography to the acute event. Another set of studies32,33 in STEMI patients wherein previous angiographic data were available has further clarified the dynamics and rate of plaque progression before MI. The average diameter stenosis of lesions that eventually led to STEMI (28) and were identified on angiography >3 months before the acute event was 36.5%±20.6% by quantitative coronary angiography. Conversely, the average diameter stenosis of the lesions that resulted in STEMI within the next 3 months was 59.1%±31.5%32 (Figure 1). A similar study segregated patients who had undergone coronary angiography either within days before their MI or more remotely.33 If the elective diagnostic coronary angiography was performed within 1 week before MI (mean, 3±3 days), the mean diameter stenosis of the fateful lesions was 71%±12% compared with 30%±18% in patients who underwent coronary angiography 6 to 18 months before MI (mean, 28±49 days; Figure 1). It is thus reasonable to hypothesize that lesions leading to MI enlarge in the months to weeks before MI, helping to explain why plaques causing MI are mild many months before the acute event but obstructive at the time of the event.

The understanding of the complex dynamics of plaque progression before MI is of paramount importance. Most studies of plaque progression with serial coronary angiography have found the process to be nonlinear and variable with an unpredictable course.34–36 A unique Japanese study has illustrated this hypothesis in a serial angiographic evaluation. Yokoya and colleagues performed 4 coronary angiograms within a 1-year period, at 4 month intervals (ie, at mean time 0, 4, 8, and 12 months).37 They observed 3 different types of plaque progression (Figure 2). Type I plaques (n=14; Figure 2, blue line) did not have significant progression in the initial 3 angiograms followed by a very rapid and sudden progression between the third and fourth angiogram; 70% of these patients developed unstable angina or acute MI. Type II plaques (n=22; Figure 2, red line) showed a steady and slow progression over the entire 1-year length of the study, and no MI was reported in this group; 14% of patients, however,
developed angina pectoris when the diameter stenosis became severe (Figure 2). There were no significant differences in the use of medications, smoking status, obesity, or family history of premature coronary disease between the 2 groups.37 The third type of plaque (control lesions, n=50) did not change from the baseline during the year (Figure 2, green line); new onset angina developed in only 1 of these patients (2%), and none developed MI. This study demonstrates that there are different patterns of plaque progression and, in concert with the prior studies (Figure 1), suggests that sudden, rapid plaque progression precedes MI in the majority of cases.

The pioneering work of Glagov and colleagues39 using invasive and noninvasive imaging2,38 confirmed that the growth of the lipid-rich atherosclerotic plaques initially manifests with outward plaque expansion (positive remodeling) to preserve luminal dimensions and coronary flow reserve. It seems that further outward expansion is limited when the plaque occupies ≈40% of the cross-sectional luminal area, after which further plaque progression necessarily encroaches on the lumen.39 It should be noted that during the time of outward expansion, if plaque progression is assessed solely by luminal narrowing measurements (eg, coronary angiography), a plaque that is actively expanding outwardly might be mistakenly considered a stable, nonprogressive and mild plaque (Figure 3). The misconception of the angiographically mild vulnerable plaque was first prospectively exposed in the PROSPECT study. By radiofrequency intravascular ultrasound imaging, plaques that were responsible for ACS during 3-year follow-up were more likely at baseline to have large plaque burden and a small minimal lumen area (in addition to being classified as a thin-cap fibroatheroma), despite appearing angiographically mild.13

The exact mechanism of rapid plaque progression is not yet fully understood. It is known that mildly obstructive plaques with vulnerable features can rupture and heal subclinically, and these cycles of rupture and healing can lead to progressive plaque expansion until symptoms and vessel occlusion occur.30,40 In addition, neovascularization at the borders of necrotic core commonly accompanies plaque growth with mural hypoxia. These nascent vessels are not enveloped by smooth muscle cells and leak macromolecules into the plaque microenvironment, including erythrocytes. The red blood cells are rich in free cholesterol and contribute to the expansion of the necrotic core region41 (Figure 3). These neovascularure are fragile and may result in intraplaque hemorrhage with plaque expansion.42,43 Increasing inflammation within the plaque with consequent increase in cytokines and matrix alterations can not only contribute directly to the plaque expansion but may

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**Figure 3. Possible mechanism for rapid plaque progression before MI.** This figure illustrates a biologically plausible mechanism for rapid plaque progression before MI. The plaque depicted here is going through outward expansion (positive remodeling) in the first 6 measurements (A–F). During this time, the degree of luminal narrowing is relatively stable, despite active plaque growth, emphasizing that a stable degree of luminal narrowing is not equivalent to lack of plaque growth. Between stages F and G, the plaque reaches the limit of outward expansion (dotted line) and intraluminal growth ensues causing accelerated luminal narrowing. The possible mechanisms for this rapid expansion include intraplaque neovascularization with incompetent vessels that leak red blood cells at the borders of the necrotic core (F–H), intraplaque hemorrhage (G–I), and subclinical cycles of rupture and healing (H) causing accelerated plaque growth. Finally, a rapidly grown plaque ruptures and causes intraluminal thrombus formation resulting in a myocardial infarction (I). It should be noted that histological and behavioral features that allow plaques to undergo such rapid progression are the same features that are known to be characteristics of vulnerable plaques. It is also known that most MIs are result of ruptures of plaques with these features. Therefore, in order for a plaque to grow rapidly before causing MI, it should already possess or acquire these features of vulnerability. MI indicates myocardial infarction.
also lead to progressive fibrous cap thinning and likelihood of subclinical or overt plaque rupture.44,45

Although it is well established that plaques with vulnerable features are responsible for most MI, not all plaques with such features lead to an acute event. In a postmortem study,12 one of the major differences between the ruptured plaques and high-risk plaques with similar histological features was significantly larger size of ruptured plaques. In a prospective coronary computed tomographic angiography,14 only 22% of patients with plaques with 2 vulnerable features (positive remodeling and large necrotic cores) developed acute events. These plaques had a significantly larger remodeling index (126.7±3.9 versus 113.4±1.6), total plaque volume (134.9±14.1 mm³ versus 57.8±5.7 mm³), and necrotic core volume (20.4±3.4 mm³ versus 11.1±4.2 mm³) compared with uneventful plaques with high-risk features. Another serial computed tomography angiography study demonstrated that the high-risk plaques only resulted in an acute event if they were associated with plaque progression46 suggest that among plaques with features of vulnerability, those with a higher degree of progression have much greater likelihood to result in ACS.

Conclusions

Although a small proportion of truly mild plaques might rupture and become symptomatic, most plaques that are destined to cause events typically undergo rapid plaque progression in the weeks to months before MI and have large atheroma volume with large necrotic cores at the time of event. Asymptomatic lesion progression of milder plaques might result from subclinical cycles of rupture and healing and intraplaque neovascularization and hemorrhage. Given that only a minority of plaques with vulnerable features will result in coronary events and that such plaques have larger volume and necrotic core size with greater expansive remodeling compared with those which do not become symptomatic in the intermediate time, we propose that rapid plaque progression of moderately severe vulnerable plaques is the critical step before MI in most cases. It is conceivable that in addition to characterizing plaque morphology and inflammatory activity, detection of the rate of plaque progression might identify vulnerable plaques with an increased potential for adverse outcomes. With rapid plaque progression having been demonstrated as a prerequisite to MI in most patients, we further think that it is time to shift perspective from plaque size as a static concept to more of a dynamic one, as the rate of progression might prove to be as or more important than the absolute degree of plaque burden and luminal narrowing. As the data available to support this perspective emerge from small studies, larger studies to further investigate these concepts are warranted.

Disclosures

None.

References


Do Plaques Rapidly Progress Prior to Myocardial Infarction?: The Interplay Between Plaque Vulnerability and Progression
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