Small entities with large impact: microcalcifications and atherosclerotic plaque vulnerability

REVIEW

OPEN

Small entities with large impact: microcalcifications and atherosclerotic plaque vulnerability

Joshua D. Hutcheson, Natalia Maldonado, and Elena Aikawa

Purpose of review
Atherosclerotic plaque rupture and subsequent acute events, such as myocardial infarction and stroke, contribute to the majority of cardiovascular-related deaths. Calcification has emerged as a significant predictor of cardiovascular morbidity and mortality, challenging previously held notions that calcifications stabilize atherosclerotic plaques. In this review, we address this discrepancy through recent findings that not all calcifications are equivalent in determining plaque stability.

Recent findings
The risk associated with calcification is inversely associated with calcification density. As opposed to large calcifications that potentially stabilize the plaque, biomechanical modeling indicates that small microcalcifications within the plaque fibrous cap can lead to sufficient stress accumulation to cause plaque rupture. Microcalcifications appear to derive from matrix vesicles enriched in calcium-binding proteins that are released by cells within the plaque. Clinical detection of microcalcifications has been hampered by the lack of imaging resolution required for in-vivo visualization; however, recent studies have demonstrated promising new techniques to predict the presence of microcalcifications.

Summary
Microcalcifications play a major role in destabilizing atherosclerotic plaques. The identification of critical characteristics that lead to instability along with new imaging modalities to detect their presence *in vivo* may allow early identification and prevention of acute cardiovascular events.

Keywords
microcalcification, plaque rupture, vulnerable atherosclerotic plaque

INTRODUCTION

Clinical studies show that calcium score is an excellent predictor of cardiovascular morbidity and mortality, and coronary calcification is the most widely used marker of the advancement of atherosclerosis [1,2]; however, the link between calcification and plaque rupture is still controversial [3▪]. Moreover, the identification of atheromas prone to rupture and cause subsequent acute cardiovascular events, such as myocardial infarction and stroke, is still challenging.

Formerly, the prevailing view was that the presence of calcification within atherosclerotic plaques acted as a biomechanical stabilizer. Indeed, large calcifications easily detected with coronary computed tomography (CT) do not seem to increase plaque vulnerability [4]. However, recent studies indicate an inverse relationship between cardiovascular risk and calcification density [5▪▪], and spotty or speckled areas of calcification, that can be observed in intravascular ultrasound (IVUS) [6] or optical coherence tomography (OCT) [7] are a good indicator of susceptibility of rupture [8]. These observations provide insights into the role calcification may play in the stability of the atherosclerotic plaque and suggest that it is not only the amount of vascular calcification, but the morphology, size and location that affect plaque vulnerability. A recent biomechanical explanation for the contribution of low density, spotty calcifications to plaque rupture is

Cardiovascular Medicine, Center for Interdisciplinary Cardiovascular Sciences and Center for Excellence in Vascular Biology, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts, USA

Correspondence to Elena Aikawa, MD, PhD, Cardiovascular Medicine, Brigham and Women's Hospital, Harvard Medical School, 77 Avenue Louis Pasteur, NRB-. 741, Boston, MA 02115, USA. Tel: +1 617 730 7755; fax: +1 617 730 7791; e-mail: eaikawa@partners.org

Curr Opin Lipidol 2014, 25:327–332

DOI:10.1097/MOL.0000000000000105

KEY POINTS

- Calcification is a significant predictor of cardiovascular morbidity and mortality.
- Microcalcifications in the fibrous cap of atherosclerotic plaques lead to considerable stress accumulation destabilizing the plaque.
- Emerging imaging modalities may be used to predict the presence of microcalcifications before plaque rupture, potentially identifying patients at risk for myocardial infarction and stroke.

centered on the presence of small microcalcifications that exist within the thin fibrous cap of atherosclerotic plaques [3▪,9–11,12▪▪].

In this review, we will focus on the biomechanical mechanisms by which microcalcifications contribute to plaque instability with special emphasis given to the important characteristics of dangerous microcalcifications. We will then discuss our current understanding of the formation of microcalcifications. Finally, we will discuss emerging imaging techniques that have the potential to identify dangerous microcalcifications forming within atherosclerotic fibrous caps in order to inform clinical decisions prior to an acute vascular event.

MICROCALCIFICATIONS AND PLAQUE RUPTURE

The fibrous cap that overlies the soft necrotic core characteristic of the fibroatheroma [13] is likely to rupture depending on its mechanical stability. If the tissue stress in the cap exceeds a critical peak circumferential stress (PCS), a vulnerable plaque will rupture at the location in which the stress is maximum [14]. Inflammation, metalloproteinases, macrophage infiltration and cell apoptosis affect mechanical properties of the tissue and result in reduced cap thickness, increased core size and abnormal tissue composition, all leading to increased stress in the fibrous cap of the atheroma [15,16].

Several biomechanical models relate PCS to tissue properties, plaque morphology, cap thickness and necrotic core size, based on the principle that the biomechanical stability of an atheroma determines its vulnerability. Numerical studies using initially two-dimensional [13] and, more recently, three-dimensional finite element analyses [5▪▪] and fluid-structure interaction models [17] indicate that local tissue properties significantly modify plaque stability. However, these criteria are insufficient to explain almost 40% of the ruptures, suggesting that other unforeseen factors may play an important role in distinguishing a lesion prone to rupture from a stable one.

A plausible link between calcification and plaque rupture came with the detection of minute microcalcifications less than 60 μm size embedded right in the fibrous cap of human atheromas [9,18]. The presence of hard inclusions, as microcalcifications, in a much softer hyperelastic layer, the fibrous cap, creates a mismatch in tissue properties and large stress concentrations at the interface between cap and microcalcifications [14], and can lead to sudden rupture of the fibrous cap [9]. This stress concentration effect depends mostly on microcalcification size, along with its location, composition, shape and proximity to other microcalcifications [11,19]. As discussed in the following section, the origin of these dangerous microcalcifications may be the aggregation of calcified matrix vesicles [12▪▪], repeatedly found in human atheromas [20–23]. Even though matrix vesicles, approximately 50–300 nm, initially don't seem to significantly affect plaque vulnerability (an estimated 35% increase in PCS [24]), it is the aggregation of matrix vesicles that form progressively larger microcalcifications, eventually reaching a critical size, 5–60 μm [11], that can trigger the rupture of the fibrous cap by increasing local stresses more than 500% [12▪▪]. Figure 1 shows how microcalcifications observed in both mice (Fig. 1a) and human atheromas (Fig. 1b) have a distinct shape likely due to aggregation of smaller particles and how their presence affects the stress distribution in the cap (Fig. 1c, d).

ORIGIN OF MICROCALCIFICATIONS

The origin of microcalcifications remains largely unknown; however, recent evidence suggests that matrix vesicles released by cells within the plaque may serve as nucleating foci for the formation of microcalcifications [17,25▪,26▪▪,27]. Matrix vesicles have long been observed in the development of bone, wherein the vesicles are released by living resident cells and are enriched in calcium-binding proteins that serve as initiating sites for nucleation of calcium phosphate crystals [28–30]. Bone-derived matrix vesicles have also been shown to contain the enzyme alkaline phosphatase, which converts pyrophosphate into free phosphate ions [31,32]. Mineral has been proposed to form within the matrix vesicles as calcium sequestered within the vesicle membrane and the phosphate generated by the activity of alkaline phosphatase reach sufficient nucleating concentrations [33]. The resultant hydroxyapatite mineral that forms from this process is then deposited along collagen fibers within the

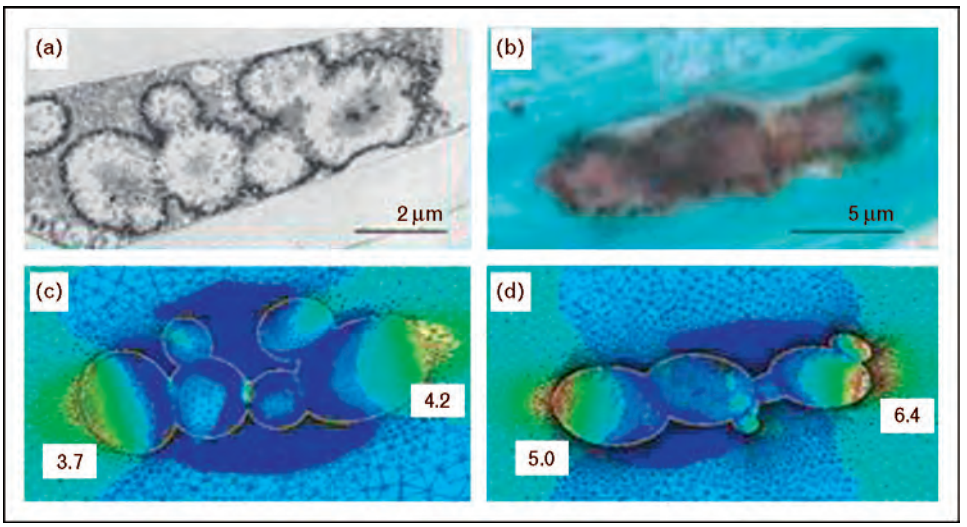

FIGURE 1. Transmission electron microscopy and histology-based finite element analyses. (a) Transmission electron microscopy image of aggregated calcifying matrix vesicles forming microcalcifications in a mouse atheroma. (b) Image of a microcalcification embedded in a human fibrous cap, obtained from nondecalcified histology, and stained with von Kossa. (c and d) Stress distribution at the interface of the microcalcifications in a and b, respectively, assuming that they are embedded in fibrous caps under tension. The numbers indicate the factor by which stress is increased and concentrated at the poles of the microcalcifications. Reproduced with permission from [12▪▪].

developing bone [30]. Vascular calcification has been proposed to involve similar processes, whereby pathologic conditions cause calcifying matrix vesicles to be released from cells within the vascular wall [25▪]. Studies have indicated that both vascular smooth muscle cells [17] and macrophages [26▪▪] have the propensity to release calcifying matrix vesicles, and matrix vesicles have been observed in calcific regions within human and mouse atheromas [20]. Corresponding with the observation that cholesterol and matrix vesicles colocalize within atherosclerotic lesions (Fig. 2a), oxidized forms of cholesterol have been shown to enhance the calcifying activity of matrix vesicles isolated from rabbit aortae [34].

In contrast to bone matrix vesicle processes, in which mineralization is alkaline phosphatase dependent, in-vitro studies indicate that vascular calcification may involve both alkaline phosphatase dependent and independent matrix vesicle-induced mineralization processes [17,25▪]. When macrophages or smooth muscle cells are stimulated with the addition of phosphate ions, vascular matrix vesicle mineralization mechanisms appear to be independent of alkaline phosphatase; smooth muscle cell-derived matrix vesicles have been shown to require the calcium-binding protein annexin A6 for calcification [17], whereas mineralization of macrophage matrix vesicle calcification appears to involve a complex of annexin A5 and another calcium-binding protein, S100A9 [25▪]. When phenotypic switching of smooth muscle cells to an osteogenic phenotype is achieved *in vitro* using a common osteogenic milieu, it involves cell differentiation and expression of alkaline phosphatase to hydrolyze phosphoric acid monoesters into free phosphate ions [35]. *In vivo*, osteogenic reprogramming of vascular smooth muscle cells has been observed [35]; however, as alkaline phosphatase activity generates free phosphate ions, nonosteogenic vesicle populations may serve as additional calcifying foci.

Using advanced microscopic analyses, a recent study demonstrated the pervasiveness of calcifying spherical particles throughout excised human cardiovascular tissues [36▪▪]. The identified spherical structures ranged from the size of dangerous microcalcifications (~5 µm) down to the size of individual matrix vesicles (~100 nm). The detailed progression of mineralization from the nucleating events within matrix vesicles to the development of dangerous microcalcifications is still uncertain because of inadequate techniques to monitor these processes *in vivo*. Further, the differences between large, plaque stabilizing calcifications and dangerous microcalcifications remain unknown. Matrix vesicles may serve as nucleating foci for both types of calcification with the major difference being the aggregation and location of the vesicles (Fig. 2b). Future works focusing on this progression may give new insight into the controllability of this process for clinical intervention and early detection methods that can be used to predict plaque vulnerability.

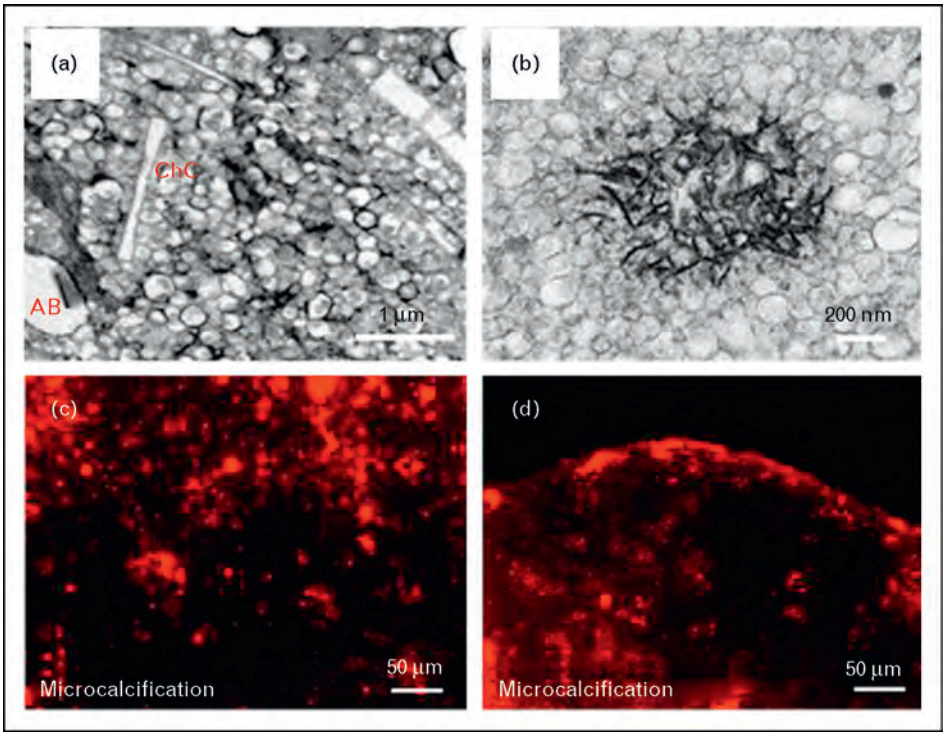

FIGURE 2. Matrix vesicles and microcalcifications in atherosclerotic plaques. (a) Transmission electron microscopy image of matrix vesicles aggregating within a plaque in close proximity to ChC. An AB is shown for size comparison. (b) Transmission electron microscopy of aggregating matrix vesicles nucleating mineralization. (c) NIRF staining of microcalcifications within a mouse plaque. (d) NIRF staining of microcalcifications at the plaque border. AB, apoptotic body; ChC, cholesterol crystals; NIRF, near-infrared fluorescent. Reproduced with permission from [26▪▪].

DETECTION OF MICROCALCIFICATIONS AND CLINICAL IMPLICATIONS

In order for our increased understanding of the significant contribution of microcalcifications to atherosclerotic plaque vulnerability to impact clinical decisions, imaging modalities must first be developed to identify the presence of dangerous microcalcifications prior to plaque rupture. The small size of microcalcifications presents a major challenge for imaging modalities to detect potential regions of vulnerability *in situ*. Calcification is traditionally imaged using CT, which can give an accurate measure of overall calcium burden, and improved risk prediction is possible through the identification of spotty calcifications with IVUS or OCT. However, CT lacks the resolution to identify specific dangerous microcalcifications within arterial walls [37], IVUS requires an invasive catheterization procedure, and standard OCT is limited by tissue penetration depth. Recent advancements using PET/CT with 18F-sodium fluoride (18F-NaF), an established PET tracer for bone formation and remodeling, may provide new strategies for honing in on regions of plaque vulnerability [38]. Coronary uptake of 18F-NaF was found overlaying, adjacent to and distal from regions of CT identified calcifications [39]. Additionally, large areas of calcification with no 18F-NaF uptake were observed. This suggests that, as with bone, 18F-NaF uptake in the vasculature is a marker of ongoing calcific remodeling [39]. Large, stable calcifications do not exhibit 18F-NaF uptake, whereas active regions of biomineralization accumulate 18F-NaF. The 18F-NaF signals far away from the CT identified calcific regions may represent the dangerous microcalcifications that cannot be detected by traditional imaging modalities [39]. In support of this hypothesis, a prospective clinical trial showed high 18F-NaF accumulation in the culprit coronary plaques in cases of myocardial infarction and in ruptured carotid artery plaques [40▪▪]. Histological evaluation of these plaques revealed active calcification processes. These PET/CT techniques exhibit promise in identifying particularly vulnerable regions within the vasculature; however, they still do not have the resolution necessary to identify specific microcalcifications that may contribute to plaque rupture. One strategy may be to use PET/CT imaging to identify potentially vulnerable regions followed by more invasive catheter-based imaging of these regions to assess plaque and calcification morphology. In this way, clinicians may be able to implement the size and

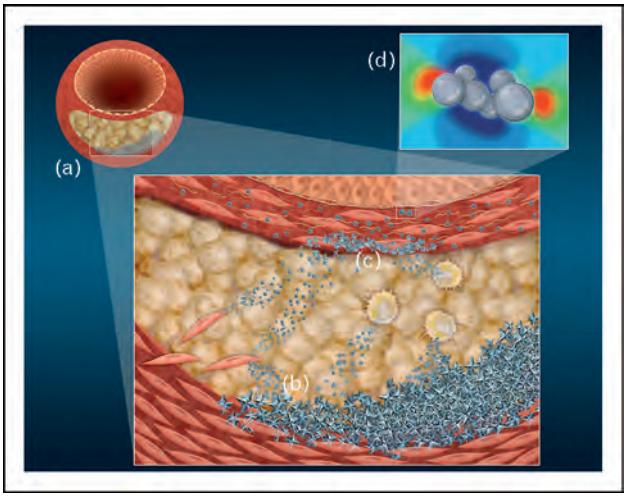

FIGURE 3. Schematic of our current understanding of the vesicle-derived calcification process. (a) Typical cross section of a fibroatheroma with a thin fibrous cap and large calcification. (b) Smooth muscle cells and macrophages release vesicles that contribute to large calcifications and (c) microcalcifications within the fibrous cap. (d) Vesicles accumulating in the fibrous cap form microcalcifications creating stress concentrations as shown by finite element analysis that can lead to cap rupture.

morphology criteria established by biomechanical modeling to make informed treatment decisions.

In addition to the advent of promising techniques to identify vulnerable plaques *in situ*, fluorescent probes already in use offer the resolution to identify microcalcifications in preclinical animal models and pathological analyses of resected tissues (Fig. 2c, d). Near-infrared fluorescent (NIRF) probes for hydroxyapatite, the calcium phosphate-based mineral involved in calcification, allow earlier detection of calcification in human plaques than light microscopy techniques currently used by pathologists [41]. These tracers are based on the conjugation of a NIRF moiety attached to a bisphosphonate backbone. Bisphosphonates have a similar structure to pyrophosphate, irreversibly bind calcium and accumulate in regions of calcium-based mineralization. NIRF tracers have been successfully used in intravital microscopy to detect vascular calcification in mice [41–43]; therefore, this technique can be utilized to monitor the progression of calcification in longitudinal animal studies and diagnose microcalcifications on histological sections. This enhanced resolution due to NIRF signal amplification may allow researchers to understand the nucleation of microcalcifications and allow pathologists to readily identify the presence of microcalcifications in subclinical atherosclerotic plaques. The formation of calcified plaques may also give insight into the nucleation and aggregation mechanisms that lead to large calcifications.

CONCLUSION

Emerging evidence suggests that microcalcifications play a critical role in determining atherosclerotic plaque vulnerability (Fig. 3). Model-based biomechanical analyses of plaques indicate that the size, morphology, size and location of calcification within the plaque are more important indicators of plaque stability than the presence of calcification solely. The presence of small microcalcifications within the fibrous cap of the plaque can greatly increase the amount of stress in the cap. When this stress exceeds the threshold required for cap failure, the plaque ruptures, leading to thrombus formation and vessel occlusion. The rupture of asymptomatic plaques and vessel occlusion are silent contributors to sudden stroke and myocardial infarction, the leading causes of cardiovascular morbidity and mortality. Studies suggest that vascular calcifications form as part of an active process wherein cellular-derived vesicles within the plaque serve as nucleating foci for the formation of calcium phosphate mineral. This active mechanism provides hope that therapeutic strategies may be developed to target dangerous microcalcifications. As future studies progress our understanding of the nucleating events of mineralization, the development of preventive strategies for calcification or therapeutic interventions that may reduce calcification or shift it to a more favorable phenotype may be within reach.

Acknowledgements

Dr Aikawa is supported by grants from the National Institutes of Health (R01HL114805; R01HL109506). Other authors have no disclosures to report.

Conflicts of interest

There are no conflicts of interest.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:

- ■ of special interest
- ■■ of outstanding interest

1. Vliegenthart R, Oudkerk M, Hofman A, *et al.* Coronary calcification improves cardiovascular risk prediction in the elderly. Circulation 2005; 112:572–577.
2. Janssen CH, Kuijpers D, Vliegenthart R, *et al.* Coronary artery calcification score by multislice computed tomography predicts the outcome of dobutamine cardiovascular magnetic resonance imaging. Eur Radiol 2005; 15:1128–1134.
3. Otsuka F, Sakakura K, Yahagi K, *et al.* Has our understanding of calcification ■ in human coronary atherosclerosis progressed? Arterioscler Thromb Vasc Biol 2014; 34:724–736.

This recent review nicely summarizes the different calcification morphologies observed within atherosclerotic plaques.

4. Lin TC, Tintut Y, Lyman A, *et al.* Mechanical response of a calcified plaque model to fluid shear force. Ann Biomed Eng 2006; 34:1535–1541.
5. ■■ Criqui MH, Denenberg JO, Ix JH, *et al.* Calcium density of coronary artery plaque and risk of incident cardiovascular events. JAMA 2014; 311:271–278.

This clinical study is the first to demonstrate the importance of calcification density as a risk factor for acute cardiovascular events. Prior to this study, calcium score was considered the most important predictor. These new findings corroborate the biomechanical analysis of the role of microcalcifications in plaque vulnerability.

6. Thilo C, Gebregziabher M, Mayer FB, *et al.* Correlation of regional distribution and morphological pattern of calcification at CT coronary artery calcium scoring with noncalcified plaque formation and stenosis. Eur Radiol 2010; 20:855–861.
7. Kume T, Okura H, Kawamoto T, *et al.* Assessment of the coronary calcification by optical coherence tomography. EuroIntervention 2011; 6:768–772.
8. Ehara S, Kobayashi Y, Yoshiyama M, *et al.* Spotty calcification typifies the culprit plaque in patients with acute myocardial infarction: an intravascular ultrasound study. Circulation 2004; 110:3424–3429.
9. Maldonado N, Kelly-Arnold A, Vengrenyuk Y, *et al.* A mechanistic analysis of the role of microcalcifications in atherosclerotic plaque stability: potential implications for plaque rupture. Am J Physiol Heart Circ Physiol 2012; 303:H619–628.
10. Rambhia SH, Liang X, Xenos M, *et al.* Microcalcifications increase coronary vulnerable plaque rupture potential: a patient-based micro-CT fluid-structure interaction study. Ann Biomed Eng 2012; 40:1443–1454.
11. Maldonado N, Kelly-Arnold A, Cardoso L, Weinbaum S. The explosive growth of small voids in vulnerable cap rupture; cavitation and interfacial debonding. J Biomech 2013; 46:396–401.
12. ■■ Kelly-Arnold A, Maldonado N, Laudier D, *et al.* Revised microcalcification hypothesis for fibrous cap rupture in human coronary arteries. Proc Natl Acad Sci U S A 2013; 110:10741–10746.

This study provides detailed size, location and morphological criteria required for microcalcification-induced plaque rupture. The analyses presented in this study clearly demonstrate the potential stress accumulation caused by the presence of microcalcifications within the fibrous cap. The resulting stability criteria could lead to clinical parameters that can be used to identify vulnerable atherosclerotic plaques.

13. Finn AV, Nakano M, Narula J, *et al.* Concept of vulnerable/unstable plaque. Arterioscler Thromb Vasc Biol 2010; 30:1282–1292.
14. Richardson PD, Davies MJ, Born GV. Influence of plaque configuration and stress distribution on fissuring of coronary atherosclerotic plaques. Lancet 1989; 2:941–944.
15. Akyildiz AC, Speelman L, van Brummelen H, *et al.* Effects of intima stiffness and plaque morphology on peak cap stress. Biomed Eng Online 2011; 10:25.
16. Cheng GC, Loree HM, Kamm RD, *et al.* Distribution of circumferential stress in ruptured and stable atherosclerotic lesions. A structural analysis with histopathological correlation. Circulation 1993; 87:1179–1187.
17. Kapustin AN, Davies JD, Reynolds JL, *et al.* Calcium regulates key components of vascular smooth muscle cell-derived matrix vesicles to enhance mineralization. Circ Res 2011; 109:e1–e12.
18. Vengrenyuk Y, Carlier S, Xanthos S, *et al.* A hypothesis for vulnerable plaque rupture due to stress-induced debonding around cellular microcalcifications in thin fibrous caps. Proc Natl Acad Sci U S A 2006; 103:14678–14683.
19. Cardoso L, Kelly-Arnold A, Maldonado N, *et al.* Effect of tissue properties, shape and orientation of microcalcifications on vulnerable cap stability using different hyperelastic constitutive models. J Biomech 2014; 47:870–877.
20. Bobryshev YV, Killingsworth MC, Lord RS, Grabs AJ. Matrix vesicles in the fibrous cap of atherosclerotic plaque: possible contribution to plaque rupture. J Cell Mol Med 2008; 12:2073–2082.
21. New SE, Aikawa E. Molecular imaging insights into early inflammatory stages of arterial and aortic valve calcification. Circ Res 2011; 108:1381–1391.
22. Relucenti M, Heyn R, Petruzziello L, *et al.* Detecting microcalcifications in atherosclerotic plaques by a simple trichromic staining method for epoxy embedded carotid endarterectomies. J Cell Mol Med 2010; 54:e33.
23. Roijers RB, Debernardi N, Cleutjens JP, *et al.* Microcalcifications in early intimal lesions of atherosclerotic human coronary arteries. Am J Pathol 2011; 178:2879–2887.
24. Wenk JF, Papadopoulos P, Zohdi TI. Numerical modeling of stress in stenotic arteries with microcalcifications: a micromechanical approximation. J Biomech Eng 2010; 132:091011.
25. ■ New SE, Aikawa E. Role of extracellular vesicles in de novo mineralization: an additional novel mechanism of cardiovascular calcification. Arterioscler Thromb Vasc Biol 2013; 33:1753–1758.

This review explains our current understanding on the role of matrix vesicles in nucleating calcification within cardiovascular tissues.

26. ■■ New SE, Goettsch C, Aikawa M, *et al.* Macrophage-derived matrix vesicles: an alternative novel mechanism for microcalcification in atherosclerotic plaques. Circ Res 2013; 113:72–77.

This study demonstrated that macrophages can also play a direct role in vascular calcification through the release of calcifying matrix vesicles. Prior to this study, vascular smooth muscle cells were thought to be the cellular culprit behind calcification. Therefore, this study established a new paradigm in which the role of macrophages in the formation of plaque destabilizing microcalcifications must also be considered.

27. Shanahan CM, Crouthamel MH, Kapustin A, Giachelli CM. Arterial calcification in chronic kidney disease: key roles for calcium and phosphate. Circ Res 2011; 109:697–711.
28. Cmoch A, Strzelecka-Kiliszek A, Palczewska M, *et al.* Matrix vesicles isolated from mineralization-competent Saos-2 cells are selectively enriched with annexins and S100 proteins. Biochem Biophys Res Commun 2011; 412:683–687.
29. Thouverey C, Malinowska A, Balcerzak M, *et al.* Proteomic characterization of biogenesis and functions of matrix vesicles released from mineralizing human osteoblast-like cells. J Proteomics 2011; 74:1123–1134.
30. Wuthier RE, Lipscomb GF. Matrix vesicles: structure, composition, formation and function in calcification. Front Biosci (Landmark Ed) 2011; 16:2812–2902.
31. Anderson HC. Matrix vesicles and calcification. Curr Rheumatol Rep 2003; 5:222–226.
32. Anderson HC, Sipe JB, Hessle L, *et al.* Impaired calcification around matrix vesicles of growth plate and bone in alkaline phosphatase-deficient mice. Am J Pathol 2004; 164:841–847.
33. Anderson HC, Garimella R, Tague SE. The role of matrix vesicles in growth plate development and biomineralization. Front Biosci 2005; 10:822–837.
34. Hsu HH. In vitro effect of cholesterol on calcifying activity of vesicles isolated from rabbit aortas. Biochim Biophys Acta 2003; 1638:235–240.
35. Steitz SA, Speer MY, Curinga G, *et al.* Smooth muscle cell phenotypic transition associated with calcification: upregulation of Cbfa1 and downregulation of smooth muscle lineage markers. Circ Res 2001; 89:1147–1154.
36. ■■ Bertazzo S, Gentleman E, Cloyd KL, *et al.* Nano-analytical electron microscopy reveals fundamental insights into human cardiovascular tissue calcification. Nat Mater 2013; 12:576–583.

Using advanced microscopic techniques, this study demonstrated the pervasiveness of microcalcifications throughout cardiovascular tissues. The structures demonstrated ranged from the size of dangerous microcalcifications down to the size of single matrix vesicles.

37. Dweck MR, Joshi FR, Newby DE, Rudd JH. Noninvasive imaging in cardiovascular therapy: the promise of coronary arterial (1)(8)F-sodium fluoride uptake as a marker of plaque biology. Expert Rev Cardiovasc Ther 2012; 10:1075–1077.
38. Chen W, Dilsizian V. Targeted PET/CT imaging of vulnerable atherosclerotic plaques: microcalcification with sodium fluoride and inflammation with fluorodeoxyglucose. Curr Cardiol Rep 2013; 15:364.
39. Dweck MR, Chow MW, Joshi NV, *et al.* Coronary arterial 18F-sodium fluoride uptake: a novel marker of plaque biology. J Am Coll Cardiol 2012; 59:1539–1548.
40. ■■ Joshi NV, Vesey AT, Williams MC, *et al.* 18F-fluoride positron emission tomography for identification of ruptured and high-risk coronary atherosclerotic plaques: a prospective clinical trial. Lancet 2014; 383:705–713.

This is a prospective study that follows up on the findings from [39]. The authors demonstrate that 18F-NaF can identify vulnerable atherosclerotic plaques and is associated with the presence of microcalcifications. The results from this study may lead to new clinical practice to identify rupture prone plaques in at-risk patients.

41. Aikawa E, Nahrendorf M, Figueiredo JL, *et al.* Osteogenesis associates with inflammation in early-stage atherosclerosis evaluated by molecular imaging in vivo. Circulation 2007; 116:2841–2850.
42. Aikawa E, Aikawa M, Libby P, *et al.* Arterial and aortic valve calcification abolished by elastolytic cathepsin S deficiency in chronic renal disease. Circulation 2009; 119:1785–1794.
43. Aikawa E, Nahrendorf M, Sosnovik D, *et al.* Multimodality molecular imaging identifies proteolytic and osteogenic activities in early aortic valve disease. Circulation 2007; 115:377–386.