ESC
European Society
of Cardiology

Coronary inflammation: why searching, how to identify and treat it

Francesco Prati[1,2,3]*, Valeria Marco[2], Giulia Paoletti[2], and Mario Albertucci[1,2]

[1]*Ospedale San Giovanni-Addolorata, Rome;*
[2]*Centro per la Lotta contro l'Infarto-CLI Foundation, Rome; and*
[3]*UniCamillus - Saint Camillus International University of Health Sciences, Rome, Italy*

Inflammation plays an important role in the development of atherosclerotic lesions. A variety of stimuli promote atherosclerosis, including increased LDL cholesterol in blood, exposure to tobacco, diabetes mellitus, hypertension, or rheological stress. Inflammatory cells have an established role in the growth of atherosclerotic lesions. Macrophages recognize and internalise ox-LDL to eventually become lipid-laden foam cells, the hallmark cellular component of atheroma. Infiltrating CD4-T cells have a role too, by interacting with ox-LDL and other antigens. Cytokines secreted by inflammatory cells stimulate smooth muscle cells migration whilst macrophages produce metalloprotease that lead to fibrous cap rupture. The necrotic debris of died macrophages and smooth muscle cells help to continue the inflammatory process. The inflammatory response can also directly activate platelets and promote thrombus formation at the surface of complicated coronary plaques. The CANTOS trial can be waived as an innovative study promoting a novel approach of personalized medicine. In patients with previous myocardial infarction, high-sensitivity C-reactive protein level of 2 mg and normal LDL level (<70 mg/dL), canakinumab a therapeutic monoclonal antibody targeting interleukin-1β, at a dose of 150 mg every 3 months, led to a significant reduction of the primary efficacy end point: nonfatal myocardial infarction, nonfatal stroke, or cardiovascular death at 48 months. Based on the CANTOS results, patients on statins and residual inflammatory risk as assessed by means of a high-sensitivity CRP >2 mg/l at baseline have a high risk of future cardiac events, comparable to that of statin-treated patients with suboptimal cholesterol LDL level. The inhibition of interleukin-1β by means of canakinumab, which is only one of many potential anti-inflammatory pathways, open new perspectives, showing that a selective inhibition of the inflammatory pathway may be beneficial in reducing cardiovascular risk. In a process of personalized medicine, there is need to accurately identify patients at high risk of events, to be treated with potent statins or anti-inflammatory drugs. Perhaps in the near future a more specific assessment of coronary inflammations, possibly obtained with imaging modalities (either invasive or non-invasive), will better select patients at risk of events. In this scenario, in the setting of secondary prevention, OCT may serve the scope of identifying vulnerable plaques with local aggregates of inflammatory cells. Future studies are needed to understand the clinical effectiveness of strategies based on invasive coronary assessment.

*Corresponding author. Email: fprati@hsangiovanni.roma.it

Role of inflammation to promote growth of atherosclerosis and plaque disruption

Inflammation plays an important role in the development of atherosclerotic lesions. A variety of stimuli promote atherosclerosis, including increased LDL cholesterol in blood, exposure to tobacco, diabetes mellitus, hypertension, or rheological stress. Inflammatory cells have an established role in the growth of atherosclerotic lesions. Macrophages recognize and internalize ox-LDL to eventually become lipid-laden foam cells, the hallmark cellular component of atheroma. Infiltrating CD4-T cells have a role too, by interacting with ox-LDL and other antigens.[1] Cytokines secreted by inflammatory cells stimulate smooth muscle cells migration whilst macrophages produce metalloprotease that lead to fibrous cap rupture.[1] The necrotic debris of died macrophages and smooth muscle cells helps to continue the inflammatory process. The inflammatory response can also directly activate platelets and promote thrombus formation at the surface of complicated coronary plaques.

Relationship between inflammation and acute coronary syndromes

Acute coronary syndrome (ACS) tends to occur in presence of high concentrations of inflammatory markers in the blood, such as C-reactive protein (CRP), neutrophil myeloperoxidase, pro-calcitonin, and white blood cells.[1] There are convincing data on the link between acute infections and their direct inflammatory effects on atherosclerotic plaques. People dying of acute systemic infections have a substantially higher number of macrophages and T cells in the coronary adventitia and peri-adventitial fat, than people who died without infection.[1,2] Furthermore, an increased morbidity and mortality related to ACSs has been observed during influenza epidemics.[1,2] According to a large histology study on 34 000 autopsies by Madjid *et al.*,[2] myocardial infarction is 30% more likely to happen during influenza season. Other observational studies further support this association. Kwong *et al.*[3] studied 364 hospitalizations for acute myocardial infarction that occurred within 1 year before and 1 year after a positive test result for influenza. Incidence ratios for acute myocardial infarction within 7 days after detection of influenza B and influenza A were significantly higher.

Consistently, a large retrospective study[4] showed that early treatment of influenza in patients with established cardiovascular disease was associated with a 60% reduction in the risk of recurrent cardiovascular events. Also, vaccination against influenza may reduce the risk of ACSs.

Utility of C-reactive protein as an inflammatory marker

The role of inflammatory markers in cardiovascular risk assessment and the development of cardiovascular disease has been a topic of discussion for nearly two decades. Inflammatory markers, including high-sensitivity C-reactive protein (hs-CRP), are not yet considered applicable for routine assessment due to lack of measurement standardization, consistency in epidemiological findings, and evidence for additional risk prediction. Despite this in most of published studies, hs-CRP surge is related to a worse clinical outcome in patients with ACS, stable coronary disease, and previous percutaneous coronary intervention.[5] On the same note reduction of PCR values below the threshold level by means of statins and more recently of the anti-inflammatory drug Canakinumab,[6] reduces significantly the risk of cardiovascular events.

On the other hand, CRP use to stratify the risk of cardiovascular events in primary prevention is still a debated issue. A major limitation of CRP titration resides in its low specificity for coronary artery disease as many inflammatory pathologies can increase CRP values. In a recent study on the prevalence of CAD in an indigenous population, the Tsimane aborigines, with the lowest reported levels of CAD in the world high levels of CRP, related to environmental exposure to infections, were found.[7]

The role of CRP itself in the genesis of atherosclerosis and occurrence of acute events is still unclear, and there is on-going debate as to whether CRP should be more than just a disease marker. Based on several reports,[3] hs-CRP may have a role in the causation of atherosclerosis as a number of in vitro and animal studies suggest a pro-atherogenic role for CRP.

At the current stage there is some consensus that CRP testing might improve risk stratification, among intermediate cardiovascular risk patients, as previously reported.[5]

Systemic vs. localized inflammation

What seems rather obvious is that CRP increase does not reflect the high inflammatory contents of a single vulnerable or disrupted plaque causing an acute ischaemic event. Elevation in the baseline concentration of CRP is induced by pro-inflammatory cytokines IL-1, IL-6, and IL-17 in the liver, reflecting therefore a possible generalized widespread inflammation due to atherosclerosis.

Buffon *et al.*[8,9] showed a higher widespread neutrophil activation in patients with ACS as compared with stable patients regardless of the location of the culprit coronary lesion. Data from Buffon are in line with histology post-mortem data obtained in patients with unstable angina. Arbustini *et al.*[10] found multiple plaques with inflammatory-cell infiltrates and with a high content of pro-inflammatory cytokines.

Other pathology and IVUS studies[11,12] identified signs of plaque fissure in many non-culprit sites. Ge *et al.*[13] showed in an IVUS study that signs of ulceration in remote non-ACS culprit sites are uncommon findings. Such findings gave strength to the concept of pan vascular disease, with simultaneous destabilization (rupture) of multiple plaques and tackled the concept of plaque vulnerability, discouraging any preventive strategy based on the transcatheter treatment of the lesions. However, plaque ulceration may persist for months or years as showed by serial studied with OCT[14,15] and fresh acute thrombosis in remote non-culprit ACS sites is a rare finding.[16] In other words, despite presence of multiple ulceration in a coronary tree, the simultaneous plaque rupture seems a rare event.[16]

Recent findings highlighted the role of local inflammation, showing that, even in a contest of widespread inflammatory arousal, culprit plaques of ACS have a higher inflammatory content.

Narula et al.[17] showed in a post-mortem study that macrophage infiltration was significantly higher at the lesion site deemed responsible for the sudden death as compared to vulnerable non-culprit plaque located in the same artery 0.31 ± 0.36 mm^2 vs. 0.53 ± 0.44 mm^2; $P < 0.001$. This finding has been then confirmed by a study carried on with OCT and IVUS-NIRS. Macrophages along with other features of vulnerability were more often detected at the site of culprit ACS lesions.[18] These findings may be in support of the search of vulnerable plaques, containing inflammatory cells.

Imaging detection of inflammation

Detection of coronary inflammation is not a simple task. FDG PET has certainly some potentials. FDG is a radio-labelled glucose analogue which competes with glucose for transport across the sarcolemma and phosphorylation by hexokinase and is avidly accumulated by metabolically active cells. Previous studies have shown that the FDG uptake in the carotid arteries is associated with plaque macrophage infiltration and occurrence of cerebrovascular ischaemic events.[19,20]

MRI is a high-resolution non-invasive imaging modality. The combination of multiple MR sequences can identify the main features of atherosclerotic plaques, such as the fibrous cap, LRNC, intra-plaque haemorrhage, neovascularization, and signs of inflammation.[21,22]

Two MRI strategies have been used to detect macrophage infiltration: (a) dynamic kinetics of tissue enhancement after gadolinium administration (DCE); and (b) ultra-small super-paramagnetic particles of iron oxide (USPIO) targeting macrophages in vivo.

Unfortunately, both FDG PET and MRI at the current stage of development are not suited for coronary assessment. Small vessel size of coronary arteries and cardiac motion are the main obstacle to plaque assessment with either MRI and PET, and confine these two imaging technique to peripheral studies.

CT on the other hand is largely adopted to study the coronary arteries. Unfortunately, CT has not the resolution to detect inflammatory cells, although preliminary experiences have been done in this regard, using targeted nanoparticle contrast agents.[23] In atherosclerotic mice, spectral CT enabled detection of intra-plaque inflammation after injection of gold-labelled high-density lipoprotein nanoparticles designed to target activated macrophages.[24]

The advent of high-resolution intracoronary imaging strategies, have opened a new chapter in plaque characterization. OCT is so far the only commercially available intracoronary technique that is able to characterize plaques and study inflammation.

In the multicentre prospective CLIMA registry on plaque vulnerability,[16] we showed for the first time that an association exists between macrophages presence and higher risk of cardiac events at follow-up. Macrophage clusters were observed in about half of cases, and were related to the risk of adverse event (HR 2.66). More importantly, macrophage plaque infiltration further improved the classification of high-risk plaque phenotype; in fact, when included on the top of MLA, FCT, and lipid arc extension the risk of future adverse events increased from HR 5.40 to HR 7.54.

Intravascular near-infrared fluorescence (NIRF) using targeted molecular agents is a novel promising solution, to study plaque vulnerability and coronary inflammation.[25]

Detection of fluorescence from naturally occurring molecules also known as auto-fluorescence, is closer to clinical application because it can be detected without the administration of exogenous agents that are not yet approved for human use. An auto-fluorescence-OCT probe, has been tested in human plaques ex vivo to identify and showed potential to visualize elastin, collagen, and macrophage accumulation.[25]

Therapeutic implication

The CANTOS trial[6] can be waived as an innovative study promoting a novel approach of personalized medicine. In patients with previous myocardial infarction, high-sensitivity C-reactive protein level of 2 mg and normal LDL level (<70 mg/dL), canakinumab a therapeutic monoclonal antibody targeting interleukin-1β, at a dose of 150 mg every 3 months, led to a significant reduction of the primary efficacy endpoint: non-fatal myocardial infarction, non-fatal stroke, or cardiovascular death at 48 months.

Based on the CANTOS results,[6] patients on statins and residual inflammatory risk as assessed by means of a high-sensitivity CRP >2 mg/L at baseline have a high risk of future cardiac events, comparable to that of statin-treated patients with suboptimal cholesterol LDL level. The inhibition of interleukin-1β by means of canakinumab, which is only one of many potential anti-inflammatory pathways, open new perspectives, showing that a selective inhibition of the inflammatory pathway may be beneficial in reducing cardiovascular risk.

In a process of personalized medicine, there is need to accurately identify patients at high risk of events, to be treated with potent statins or anti-inflammatory drugs. Perhaps in the next future a more specific assessment of coronary inflammations, possibly obtained with imaging modalities (either invasive or non-invasive), will better select patients at risk of events. In this scenario, in the setting of secondary prevention, OCT may serve the scope of identifying vulnerable plaques with local aggregates of inflammatory cells. Future studies are needed to understand the clinical effectiveness of strategies based on invasive coronary assessment.

Conflict of interest: none declared.

References

1. Corrales-Medina V, Madji M, Musher DM. Role of acute infection in triggering acute coronary syndromes. *Lancet Infect Dis* 2010;**10**: 83-92.
2. Madjid M, Vela D, Khalili-Tabrizi H, Casscells SW, Litovsky S. Systemic infections cause exaggerated local inflammation in

atherosclerotic coronary arteries: clues to the triggering effect of acute infections on acute coronary syndromes. *Tex Heart Inst J* 2007;**34**:11–18.

3. Kwong JC, Schwartz KL, Campitelli MA, Chung H, Crowcroft NS, Karnauchow T, Katz K, Ko DT, McGeer AJ, McNally D, Richardson DC, Rosella LC, Simor A, Smieja M, Zahariadis G, Gubbay JB. Acute myocardial infarction after laboratory-confirmed influenza infection. *New Engl J Med* 2018;**378**:345–353.

4. Casscells SW, Granger E, Kress AM, Linton A, Madjid M, Cottrell L. Use of oseltamivir after influenza infection is associated with reduced incidence of recurrent adverse cardiovascular outcomes among military health system beneficiaries with prior cardiovascular diseases. *Circ Cardiovasc Qual Outcomes* 2009;**2**:108–115.

5. Pearson TA, Mensah GA, Alexander RW, Anderson JL, Cannon RO, Criqui M, Fadl YY, Fortmann SP, Hong Y, Myers GL, Rifai N, Smith SC, Taubert K, Tracy RP, Vinicor F. Markers of inflammation and cardiovascular disease: application to clinical and public health practice: a statement for healthcare professionals from the Centres for Disease Control and Prevention and the American Heart Association. *Circulation* 2003;**107**:499–511.

6. Ridker PM, Everett BM, Thuren T, MacFadyen JG, Chang WH, Ballantyne C, Fonseca F, Nicolau J, Koenig W, Anker SD, Kastelein JJP, Cornel JH, Pais P, Pella D, Genest J, Cifkova R, Lorenzatti A, Forster T, Kobalava Z, Vida-Simiti L, Flather M, Shimokawa H, Ogawa H, Dellborg M, Rossi PRF, Troquay RPT, Libby P, Glynn RJ. Antiinflammatory therapy with canakinumab for atherosclerotic disease. *N Engl J Med* 2017;**377**:1119–1131.

7. Kaplan H, Thompson RC, Trumble BC, Wann LS, Allam AH, Beheim B, Frohlich B, Sutherland ML, Sutherland JD, Stieglitz J, Rodriguez DE, Michalik DE, Rowan CJ, Lombardi GP, Bedi R, Garcia AR, Min JK, Narula J, Finch CE, Gurven M, Thomas GS. Coronary atherosclerosis in indigenous South American Tsimane: a cross-sectional cohort study. *Lancet* 2017;**389**:1730–1739.

8. Buffon A, Biasucci LM, Liuzzo G, D'Onofrio G, Crea F, Maseri A. Widespread coronary inflammation in unstable angina. *N Engl J Med* 2002;**347**:5–12.

9. Liuzzo G, Biasucci LM, Gallimore JR, Caligiuri G, Buffon A, Rebuzzi AG, Pepys MB, Maseri A. Enhanced inflammatory response in patients with preinfarction unstable angina. *J Am Coll Cardiol* 1999;**34**: 1696–1703.

10. Arbustini E, Grasso M, Diegoli M. Coronary atherosclerotic plaques with and without thrombus in ischemic heart syndromes: a morphologic, immunohistochemical, and biochemical study. *Am J Cardiol* 1991;**68Suppl**:36B–50B.

11. Falk E, Shah PK, Fuster V. Coronary plaque disruption. *Circulation* 1995;**92**:657–671.

12. Davies MJ, Thomas A. Thrombosis and acute coronary-artery lesions in sudden cardiac ischemic death. *N Engl J Med* 1984;**310**: 1137–1140.

13. Ge J, Chirillo F, Schwedtmann J, Gorge G, Haude M, Baumgart D, Shah V, von Birgelen C, Sack S, Boudoulas H, Erbel R. Screening of ruptured plaques in patients with coronary artery disease by intravascular ultrasound. *Heart* 1999;**81**:621–627.

14. Souteyrand G, Arbustini E, Motreff P, Gatto L, Di Vito L, Marco V, Amabile N, Chisari A, Kodama T, Romagnoli E, Tavazzi L, Crea F, Narula J, Prati F. Serial optical coherence tomography imaging of ACS-causing culprit plaques. *EuroInterv* 2015;**11**:319-324.

15. Di Vito L, Prati F, Arbustini E, Crea F, Maseri A. A "stable" coronary plaque rupture documented by repeated OCT studies. *J Am Coll Cardiol Cardiovasc Imaging* 2013;**6**:835-836.

16. On behalf of CLIMA Investigators. Relationship between coronary plaque morphology of the left anterior descending artery and long term clinical outcome. *Eur Heart J*

17. Narula J, Nakano M, Virmani R, Kolodgie FD, Petersen R, Newcomb R, Malik S, Fuster V, Finn AV. Histopathologic characteristics of atherosclerotic coronary disease and implications of the findings for the invasive and noninvasive detection of vulnerable plaques. *J Am Coll Cardiol* 2013;**61**:1041–1051.

18. Prati F, Gatto L, Romagnoli E, et al. In vivo vulnerability scoring system of coronary plaques causing acute coronary syndromes: an intravascular imaging study. *Int J Cardiol* 2018.

19. Rudd JHF, Warburton EA, Fryer TD, Jones HA, Clark JC, Antoun N, Johnström P, Davenport AP, Kirkpatrick PJ, Arch BN, Pickard JD, Weissberg PL. Imaging atherosclerotic plaque inflammation with [18F]-fluorodeoxyglucose positron emission tomography. *Circulation* 2002;**105**:2708–2711.

20. Tawakol A, Migrino RQ, Bashian GG, Bedri S, Vermylen D, Cury RC, Yates D, LaMuraglia GM, Furie K, Houser S, Gewirtz H, Muller JE, Brady TJ, Fischman AJ. In vivo 18F-fluorodeoxyglucose positron emission tomography imaging provides a noninvasive measure of carotid plaque inflammation in patients. *J Am Coll Cardiol* 2006;**48**: 1818–1824.

21. van den Bouwhuijsen QJ, Vernooij MW, Hofman A, Krestin GP, van der Lugt A, Witteman JC. Determinants of magnetic resonance imaging detected carotid plaque components: the Rotterdam study. *Eur Heart J* 2012;**33**:221–229.

22. Hyafil F, Cornily JC, Feig JE, et al. Noninvasive detection of macrophages using a nanoparticulate contrast agent for computed tomography. *Nat Med* 2007;**13**:636–641.

23. Cormode DP, Roessl E, Thran A, Skajaa T, Gordon RE, Schlomka J-P, Fuster V, Fisher EA, Mulder WJM, Proksa R, Fayad ZA. Atherosclerotic plaque composition: analysis with multicolor CT and targeted gold nanoparticles. *Radiology* 2010;**256**:774–782.

24. Ughi GJ, Wang H, Gerbaud E, Gardecki JA, Fard AM, Hamidi E, Vacas-Jacques P, Rosenberg M, Jaffer FA, Tearney GJ. First-in-human dual-modality OCT and near-infrared autofluorescence imaging of coronary artery disease. *J Am Coll Cardiol Cardiovasc Imaging* 2016; **9**:1304-1314.

25. Ughi GJ, Wang H, Gerbaud E, Gardecki JA, Fard AM, Hamidi E, Vacas-Jacques P, Rosenberg M, Jaffer FA, Tearney GJ. First-in-human dual-modality OCT and near-infrared autofluorescence imaging of coronary artery disease. *JACC Cardiovasc Imaging* 2016;**9**:1304-1314.