Endothelial Function Testing as a Biomarker of Vascular Disease

Subodh Verma, MD, PhD; Michael R. Buchanan, PhD; Todd J. Anderson, MD

The endothelium is the monolayer of endothelial cells lining the lumen of all blood vessels. These cells function as a protective biocompatible barrier between all tissues and the circulating blood. Endothelial cells also function as a selective sieve to facilitate bidirectional passage of macromolecules and blood gases to and from tissues and blood. The strategic location of the endothelium allows it to “sense” changes in hemodynamic forces and blood-borne signals and “respond” by releasing a number of autocrine and paracrine substances. A balanced release of these bioactive factors facilitates vascular homeostasis. Endothelial cell dysfunction disrupts this balance, thereby predisposing the vessel wall to vasoconstriction, leukocyte adherence, platelet activation, mitogenesis, pro-oxidation, thrombosis, impaired coagulation, vascular inflammation, and atherosclerosis. Our understanding of these endothelial cell responses has led to the development of tests that are believed to reflect endothelial cell dysfunction or integrity in vivo. Given the central role of the endothelium in the development and clinical course of atherosclerosis, endothelial function testing may serve as a useful biomarker of atherosclerosis.

Assessment of Endothelial Function

Assessment of endothelial cell function refers to a measure of endothelial cell response to stimulation—for example, by vasoactive substances released by or those that interact with the vascular endothelium. Endothelium-dependent vasodilatation can be assessed in the coronary and peripheral circulations in humans. In addition, measures of platelet function and inflammation/leukocyte activation (such as C-reactive protein [CRP]) are other measures of endothelial health. Figure 1 shows methods of assessing endothelium-dependent vasomotion.

Coronary Circulation

Quantitative coronary angiography has been used to examine the changes in vascular diameter in response to an infusion of an endothelium-dependent vasodilator such as acetylcholine (Ach), bradykinin, substance P, or serotonin. In healthy
vessels, Ach evokes a NO-mediated vasodilatory response; however, in patients with endothelial dysfunction, this effect is blunted or paradoxical vasoconstriction may occur.\(^5\) Endothelial function of the coronary microvasculature (resistance vessels) has been assessed by using intracoronary Doppler techniques to measure coronary blood flow in response to pharmacological or physiological stimuli.\(^6\) Although considered by many to be the best assessment of endothelial function, this technique is limited by its invasive nature, expense, and relative inaccessibility.

**Peripheral Circulation**

Brachial artery ultrasound is a widely used, noninvasive measure of endothelial cell function.\(^7,8\) The forearm blood flow is occluded for 5 minutes using a blood pressure cuff maintained at a standard pressure. When the pressure is released, reactive hyperemia occurs. This results in shear stress–induced NO release and subsequent vasodilatation (flow-mediated vasodilation). This technique has the advantage of being noninvasive and can readily identify populations with attenuated endothelial function. The major limitations of this technique are the need for ultrasonographic expertise and a significant day-to-day variability (about 25%) due to biological circadian rhythms. Nonetheless, at present, this approach is widely used to assess vasomotion function. Resistance vessel function in the forearm is assessed by strain-gauge venous impedance plethysmography. This methodology examines the change in forearm blood flow in response to direct intraarterial (brachial artery) administration of agonists. This technique is excellent for acute interventions with repeated measurements.\(^9,10\) The major drawbacks, again, are reproducibility and the technique’s more invasive nature compared with ultrasound. Noninvasive measures of arterial compliance and waveform morphology also provide a marker of vascular health that may in part be endothelium dependent.

**Inflammatory Markers**

Over the past few years, we have witnessed a paradigm shift in our understanding of the underlying principles of atherosclerosis. This new view supports the concept that vascular inflammation is a central orchestrator of atherosclerotic lesion formation, progression, and eventual rupture.\(^11\)
Chronic inflammation results in endothelial dysfunction and facilitates the interactions among modified lipoproteins, monocyte-derived macrophages, T cells, and normal cellular elements of the arterial wall, thus inciting early and late atherosclerotic processes. This paradigm has fueled interest in evaluating inflammatory markers of atherosclerosis, of which high-sensitivity CRP has emerged as one of the most important. As such, CRP is a powerful independent predictor of myocardial infarction, stroke, and vascular death in a variety of settings and appears to be a better prognosticator of cardiovascular events than LDL cholesterol.12–14 Over the past year, much interest has been generated into unraveling the mechanistic basis of the CRP–atherosclerosis connection (Figure 2). Indeed, recent studies, including work from our laboratory, suggest that CRP is not only a predictor but also a mediator of lesion formation.15–25 CRP, at concentrations known to predict vascular disease, has a direct effect to stimulate diverse early atherosclerotic processes, including the expression of endothelial cell adhesion molecules, the production of chemoattractant chemokines, and macrophage LDL uptake. In addition, CRP directly modulates the production of endothelium-derived vasoactive factors, including downregulating endothelial NOS (eNOS)–derived NO while augmenting production of the potent endothelium-derived vasoconstrictor endothelin-1. Additionally, CRP facilitates endothelial cell apoptosis and attenuates angiogenesis, which is an important compensatory mechanism in ischemia. More recently, CRP has also been demonstrated to promote the release of plasminogen activator inhibitor-1 from endothelial cells,20 upregulate angiotensin-mediated neointimal formation, and alter endothelial progenitor cell survival and differentiation.22

Thus, CRP is not only an inflammatory marker of atherosclerosis/coronary events but is also a mediator of the disease because it contributes to the pathogenesis of lesion formation, plaque rupture, and coronary thrombosis by interacting with and altering the endothelial cell phenotype. CRP should be regarded as an indirect, albeit important, measure of endothelial function. The major advantage of biochemical measures of endothelial function is that they are inexpensive and offer excellent reproducibility. However, it is not yet clear what the relationship is between these markers, measures of endothelium-dependent vasodilation, and cardiovascular outcomes, and it is an area that is currently being investigated. Preliminary studies suggest that patients with elevated levels of CRP have impaired endothelium-dependent vasodilatation, which suggests that CRP may be a useful clinical tool for endothelial vasomotion.26

Endothelial Function as a Biomarker of Atherosclerosis
Dysfunction of endothelial cells is probably the earliest event in the process of lesion formation—hence, the concept that
assessments of endothelial function exist; and (6) endothelial dysfunction also decreases cardiovascular events in patients with the lowest tertile of endothelial function had an increase in cardiovascular events over a 3-year follow-up. The most robust of the prognostic studies was reported by Heitzer et al,33 who studied 281 subjects with coronary disease undergoing forearm Ach studies. Two key observations were made. First, subjects with attenuated responses had more events. Second, subjects with a greater acute improvement of endothelial function with vitamin C (suggesting more oxidative stress) had a worse outcome.

Studies of Inflammatory Markers
Studies with thousands of subjects are underway with brachial ultrasound to determine if a single measure of vasoreactivity in an individual patient predicts the development of atherosclerosis or its complications (J. Vita, MD, personal communication, 2002).

Studies of Vasomotion
We demonstrated that endothelial dysfunction was associated with the development of transplantation atherosclerosis as assessed by intravascular ultrasound.28 Those subjects with normal vasodilator responses to Ach immediately after transplantation developed atherosclerosis at a rate one third that of those with endothelial dysfunction during the first year of follow-up. Three retrospective trials have assessed the relationship between Ach-mediated coronary endothelial function and clinical events (Table). Subjects with vasoconstrictor responses to Ach were more likely to develop adverse cardiovascular events during follow-up of 5 to 10 years despite having minimal coronary disease at baseline. Although important, these observations are diminished by the relative low frequency of end point events.29,30 A recently published trial of 308 subjects who underwent coronary endothelial function testing revealed improved survival in those subjects with better conduit and resistance vessel responses to Ach. Endothelial function was a predictor of outcome in a multivariate analysis.31

Perticone and colleagues32 studied 225 hypertensive subjects who underwent Ach testing in the forearm with plethysmography. After correcting for blood pressure, subjects with the lowest tertile of endothelial function had an increase in cardiovascular events over a 3-year follow-up. The most robust of the prognostic studies was reported by Heitzer et al,33 who studied 281 subjects with coronary disease undergoing forearm Ach studies. Two key observations were made. First, subjects with attenuated responses had more events. Second, subjects with a greater acute improvement of endothelial function with vitamin C (suggesting more oxidative stress) had a worse outcome.

Small studies have also suggested a prognostic role for the brachial ultrasound assessment of endothelial function.34 A recently reported prospective study demonstrated that abnormalities of flow-mediated dilation were predictive of postoperative complications in patients undergoing noncardiac vascular surgery.35

All the studies done to date are too small to be definitive. Studies with thousands of subjects are underway with brachial ultrasound to determine if a single measure of vasoreactivity in an individual patient predicts the development of atherosclerosis or its complications (J. Vita, MD, personal communication, 2002).

Studies of Inflammatory Markers
Studies by Ridker37 have demonstrated a relationship of cardiovascular outcomes with interleukin-6, tumor necrosis.
factor-α, soluble P selectin, and soluble intercellular adhesion molecule-1. However, high-sensitivity CRP has emerged as the most powerful predictor of future cardiovascular events.12–14

In both men and women, CRP levels in the upper quartile increase risk of adverse clinical events by 2- to 4-fold and are at least as prognostic as lipid parameters. Of great interest is the fact that subjects with elevated levels of CRP seem to gain more benefit from pharmacological therapies such as aspirin or statin therapy. Given the direct effects of CRP to destabilize eNOS mRNA in endothelial cells,16 it is logical to propose that CRP is a sensitive marker of endothelial dysfunction; it remains to be determined whether the predictive value of endothelial vasomotion assessments will be independent of CRP levels.

An alternative approach to measuring endothelial cell function in response to assorted agonists is to measure changes in endothelial cell biocompatibility. In support of this possibility, Brister et al38 found that the lipoxygenase pathway–derived monohydroxide, 13-hydroxyoctadecadienoic acid (13-HODE) decreases with age in patients with coronary artery disease undergoing coronary artery bypass grafting and that this decrease is associated with increased endothelial cell thrombogenicity.38 More recently, 13-HODE plasma levels have been shown to dramatically increase in patients with confirmed atherosclerosis and were higher in coronary artery bypass grafting patients who suffered a cardiovascular event during the 2-year follow-up.39

Several other surrogate markers of endothelial cell activation and inflammation are being investigated, including lipoprotein-associated phospholipase A2,40 CD40 receptor/CD40-ligand interaction,41 LOX-1,42 and measurement of circulating endothelial progenitor cells.43,44

Implications for Practice
Atherosclerotic vascular disease remains the leading cause of morbidity and mortality among adults in developed countries and is increasing at an alarming rate in developing nations. The concept of risk introduced by the Framingham Heart Study more than 50 years ago serves as the “gold standard” in risk assessment.45 Enthusiasm for risk assessment46 and prevention are based on the demonstration that aggressive medical therapy reduces the likelihood of recurrent coronary events in patients with established coronary heart disease. A similar potential exists for primary prevention.

Patients at high risk (those with diabetes, other vascular disease, or multiple risk factors) clearly benefit from pharmacological therapy. In addition, patients without traditional risk factors are at low risk of events over both the short and long term. It is estimated however, that 40% to 50% of adults fall into the intermediate risk group according to National Health and Examination Survey (NHANES) III data. Patients in this intermediate risk group do not currently qualify for the most intensive risk factor interventions. The problem with this approach is that the treatment algorithms take into account short-term (10 years) rather than long-term risk (30 years), and there is a wide range of risk within this large group. It is this group that could potentially benefit from further risk stratification with endothelial function testing. If prospective studies confirm the predictive nature of endothelial markers for cardiovascular outcomes, then incorporation of these measures into risk factor models would lead to more effective prevention. A positive test in a subject at low to moderate risk would identify an individual whose risk would warrant pharmacological treatment.47 Other proposed markers of risk, including coronary calcium score (electron beam computed tomography), carotid intimal-medial thickness, ankle-brachial index, and stress testing, are also being evaluated carefully. The optimal diagnostic/therapeutic approach is not known at this time but will be better defined in the next decade. These data will come from ongoing prospective studies of endothelial function and the National Institutes of Health–sponsored MESA study (Multi-Ethnic Study of Atherosclerosis). Given the increasing atherosclerosis pandemic, advances in diagnostic modalities, and health economics issues, the time is right to define the most effective prevention strategies for subjects at risk of atherosclerotic events.48

Summary
At the present time, measures of endothelial cell function and biocompatibility have advanced our understanding of the pathophysiology of atherosclerosis and its treatment. They are quickly becoming well-established surrogates of disease activity; however, the ideal test(s) of endothelial function have yet to be established. As we incorporate new biomarkers into global risk assessment, the endothelium is the logical target of study, given its unique position as both a sensor and participant in the atherosclerosis process. Recent evidence suggests that the mechanistic basis for the powerful predictive value of inflammatory biomarkers such as CRP may also reside at the level of the endothelium.16 Although endothelial function testing remains a research tool at the present time, it is our contention that this technology will figure prominently in risk assessment strategies in the future.

References
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