The vascular endothelium plays a critical role in the regulation of arterial function through the synthesis and elaboration of a number of antiatherogenic factors such as nitric oxide (NO). “Endothelial dysfunction” represents a pathophysiological state in which normal homeostatic properties of the vasculature are impaired or lost, thereby supporting a vasospastic, prothrombotic, and proinflammatory atherogenic milieu. Impaired arterial function is associated with multiple cardiac risk factors and is detectable early in the progression of atherosclerosis, thus making it an ideal target for primary preventive intervention. It is also fundamental to mechanisms of advanced disease playing a critical role in the pathophysiology of acute cardiovascular syndromes such as myocardial infarction and stroke. The concept that endothelial phenotype serves as an overall barometer of vascular pathophysiology of acute cardiovascular syndromes such as myocardial infarction and stroke. The concept that endothelial phenotype serves as an overall barometer of vascular function in the coronary circulation, relates to traditional risk factors, improves with targeted treatment, and predicts risk of future cardiovascular events. As such, this technique, available since 1992, is presently viewed as the gold standard for noninvasive interrogation of peripheral conduit artery vaso-reactivity. Despite its clinical relevance, several limitations have precluded its integration into clinical practice, partly owing to technical limitations that require extensive sonographer training, expensive equipment, labor-intensive image analysis, and lack of methodological standardization that have prompted a search for techniques inherently faster and easier to perform. One such newer methodology involves digital pulse amplitude tonometry (PAT), which measures volumetric changes in the fingertip, using a probe that quantifies pulse amplitude in response to reactive hyperemia using a commercially available device (EndoPAT, Itamar Medical, Ltd). Signals in the contralateral hand not experiencing hyperemia are simultaneously recorded, controlling for systemic effects. Proprietary software provides a reactive hyperemia PAT ratio in relation to the control arm that is expressed after natural log transformation owing to skewed variable distribution. The potential advantage of this technique relates to use of an automated, computerized analysis system that minimizes operator dependency and interobserver variability. Small-scale preliminary studies show that PAT hyperemic responses depend on NO and are reduced in the presence of coronary artery disease or its risk factors, suggesting that clinically important group differences can be detected using this method. Another device that is fairly quick and simple to use involves fingertip infrared light transmission photoplethysmography (PulseTrace, Micro Medical, Ltd), which performs digital pulse volume waveform analysis and generates an automated reflection index (RI). The response shows decrement with cardiac risk factors but exhibits somewhat low reproducibility, and its ability to detect changes with intervention is unknown.

In this issue of Circulation: Cardiovascular Imaging, Schnabel and colleagues report their findings in 5000 individuals followed in the community-based Gutenberg Heart Study, examining the associations between these 3 contemporary noninvasive methods described above (FMD, PAT, and RI) and their relation to classic cardiovascular risk factors. The authors are to be commended because this represents the largest comparative study to date of differing methodologies in endothelial function assessment. In this

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From the Department of Medicine and Whitaker Cardiovascular Institute, Boston University School of Medicine, Boston, MA.

Correspondence to Noyan Gokce, MD, Boston Medical Center, 88 East Newton St, D-8, Cardiology, Boston, MA, 02118. E-mail Noyan.Gokce@bmc.org

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sex-balanced, unselected cohort ages 34 to 74 years, the primary novel findings were that different techniques correlated weakly with each other, differed significantly in their relation to traditional risk factors, and response profiles were influenced by sex, particularly for PAT and FMD. In general, all techniques related to age and sex, but FMD also correlated with body mass index, hypertension, dyslipidemia, and C-reactive protein. PAT ratio was additionally associated with smoking status, plasma glucose, and diabetes but unexpectedly correlated positively with blood pressure. RI demonstrated the weakest relationship with measured risk factors, with a model $R^2$ of only 3.2%. Overall, hyperemic parameters correlated more weakly than baseline variables such as brachial artery size. As such, for the entire study, measured risk factors explained only a fraction (<16%) of the variability in hyperemic responses for any of the 3 techniques, demonstrating that traditional risk factors were more predictive of anatomic changes than physiological responses.

The overall findings of the present study by Schnabel and coworkers are similar to data published very recently by the Framingham Heart Study group demonstrating lack of correlation between PAT and FMD and differing patterns in risk factor associations. The findings from both studies are clinically important because they show that fingertip and brachial measures of endothelial function are not interchangeable and clearly provide different information about distinct aspects of vascular biology. This is not surprising because brachial FMD examines macrovascular conduit artery vasodilator capacity, whereas fingertip changes measure microvascular function in a terminal vascular bed. Additionally, different stages of disease processes may have disparate effects on different vascular beds. As such, the closer association of glycemic parameters with PAT may reflect microvascular impairment in early phases of metabolic vascular disease.

So, which method do we use, and where do we go from here? As with any new biomarker or test that stands to gain clinical acceptance, a number of key criteria must be met, which include ease of use, standardization, low cost, reproducibility, firm relation to disease pathophysiology, and ability to predict cardiovascular risk and improve existing stratification tools. Additionally, interventions should alter the marker, and alterations in the marker should ideally predict change in risk. At the present time, none of the 3 above-mentioned techniques of endothelial function assessment meet all these benchmarks. Brachial artery FMD has been most subject to analytic scrutiny because it has been around longer and investigated most extensively. As such, prospective outcome studies in varying populations by and large show that brachial FMD independently predicts risk of future cardiovascular events. We now also recognize that measures of resistance vessel function such as forearm reactive hyperemia may provide incremental prognostic information. Recent outcome studies using these end points are summarized in the Table. Despite its predictive value, brachial reactivity testing has not been adopted into the clinical arena. The technique remains operator-dependent, is highly variable between centers (ie, cuff positioning, software analysis), and is without established sex-specific normal values or cutoff points that define increased risk. Nevertheless, clinical studies with these methods continue to accrue, and there is also growing evidence that combining markers of vascular structure and function may provide complementary information. Recent data also demonstrate that both forearm FMD and reactive hyperemia (RH) correctly reclassify up to a third of patients with intermediate Framingham Risk Scores, providing incremental discriminatory power beyond existing algorithms. Perhaps most interesting are data demonstrating that endothelial interrogation may identify patient responses and gauge treatment efficacy. For example, in hypertensive women, failure to restore endothelial function with blood pressure lowering was strongly associated with increased cardiovascular risk. Similarly, lack of improvement in FMD with antiatherosclerotic treatment identified coronary artery disease patients prone to future events. The notion that endothelial phenotype may capture the biological effects of unmeasured risk factors is an evolving concept that deserves further investigation, and serial vascular assessments with targeted therapy may prove useful in monitoring treatment effects. Nevertheless, these proof-of-principle studies need confirmation in larger and varying cohorts because these types of investigations are likely to move the field forward.

<table>
<thead>
<tr>
<th>Author</th>
<th>Mean Follow-Up Duration</th>
<th>No. of Events</th>
<th>Event Rate, %</th>
<th>FMD Predictive</th>
<th>RH Predictive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modena</td>
<td>2002</td>
<td>400 67 mo</td>
<td>47</td>
<td>11.7</td>
<td>+</td>
</tr>
<tr>
<td>Brevetti</td>
<td>2003</td>
<td>131 23 mo</td>
<td>39</td>
<td>29.8</td>
<td>+</td>
</tr>
<tr>
<td>Gokce</td>
<td>2003</td>
<td>199 1.2 y</td>
<td>35</td>
<td>17.6</td>
<td>+</td>
</tr>
<tr>
<td>Chan</td>
<td>2003</td>
<td>152 34 mo</td>
<td>22</td>
<td>14.5</td>
<td>+</td>
</tr>
<tr>
<td>Fathi</td>
<td>2004</td>
<td>444 24 mo</td>
<td>70</td>
<td>15.8</td>
<td>-</td>
</tr>
<tr>
<td>Frick</td>
<td>2005</td>
<td>398 39 mo</td>
<td>44</td>
<td>11.1</td>
<td>-</td>
</tr>
<tr>
<td>Yeboah</td>
<td>2007</td>
<td>2792 5 y</td>
<td>674</td>
<td>24.1</td>
<td>+</td>
</tr>
<tr>
<td>Huang</td>
<td>2007</td>
<td>267 309 d</td>
<td>50</td>
<td>18.7</td>
<td>+</td>
</tr>
<tr>
<td>Yeboah</td>
<td>2009</td>
<td>3026 5 y</td>
<td>182</td>
<td>6</td>
<td>+</td>
</tr>
<tr>
<td>Kitta</td>
<td>2009</td>
<td>251 36 mo</td>
<td>42</td>
<td>16.7</td>
<td>+</td>
</tr>
<tr>
<td>Anderson</td>
<td>2011</td>
<td>1574 7.2 y</td>
<td>111</td>
<td>7.1</td>
<td>-</td>
</tr>
</tbody>
</table>

FMD indicates flow-mediated dilation; RH, reactive hyperemia.
will eventually be gained as the Gutenberg and Framingham Heart Study databases continue to mature. The 2010 American College of Cardiology Foundation/American Heart Association Task Force guidelines for assessment of cardiovascular risk in asymptomatic adults did not recommend brachial/peripheral flow-mediated dilation studies for clinical use at the present time. Although brachial reactivity testing is further along the path of potential clinical utility, it remains affected by several limitations mentioned above. Even less is known about the utility of fingertip PAT and RI methodologies, which lack outcome data. Nevertheless, the ability to measure endothelial function noninvasively remains a valuable tool for identification of novel risk factors, elucidating mechanisms of vascular dysfunction, and use as a surrogate of cardiovascular risk for intervention studies using novel therapies in groups of patients. Reversal of endothelial dysfunction represents an attractive goal for therapeutic intervention, and whether any of these noninvasive measures of vascular health will eventually carve a clinical niche remains to be seen.

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Clinical Assessment of Endothelial Function: Ready for Prime Time?
Noyan Gokce

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