Review article

Noninvasive Assessment of Endothelial Function in Clinical Practice

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ABSTRACT

In the fight against cardiovascular diseases, preventive strategies are becoming the focus of attention. One of these strategies proposes to identify individuals who are at a high risk of developing cardiovascular disease. Endothelial dysfunction could improve patient risk stratification and the implementation of preventive strategies. In this review we focus on noninvasive techniques that have recently become available to assess endothelial function: flow-mediated vasodilation as measured by ultrasound of the brachial artery, pulse wave analysis, and finger plethysmography during postischemic hyperemia. We describe the basic principles, the main protocols to perform these techniques, and their clinical value based on the scientific evidence.

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Evaluación no invasiva de la función endotelial en la práctica clínica

En la lucha contra las enfermedades cardiovasculares, las estrategias preventivas están pasando a ser el principal centro de interés. Una de estas estrategias propone identificar a los individuos con un riesgo elevado de sufrir enfermedad cardiovascular. La disfunción endotelial podría facilitar una mejor estratificación del riesgo y la puesta en práctica de estrategias preventivas. En esta revisión nos centramos en las técnicas no invasivas que se han introducido recientemente para evaluar la función endotelial: vasodilatación mediada por flujo con ecografía de la arteria humeral, análisis de la onda del pulso y plethysmografía digital durante la hiperemia postisquémica. Describimos los principios básicos, los principales protocolos para la aplicación de estas técnicas y su valor clínico basado en la evidencia científica existente.

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Abbreviations

CV: cardiovascular
FMD: flow-mediated vasodilation
MRI: magnetic resonance imaging
PAT: peripheral arterial tone
PWV: pulse wave velocity

INTRODUCTION

In the fight against cardiovascular (CV) diseases, preventive strategies are becoming the focus of attention. Comprehensive pharmacological and interventional treatments in recent years have achieved success in certain areas but costs associated with these strategies are high and global results suboptimal. Therefore the fight to achieve meaningful reductions in the incidence of CV events in the general population continues unabated.1 Two different preventive strategies have been suggested: a) to make pharmacological prevention accessible to as many people as possible, ie, the “polypill”2, and b) to identify those individuals who are at a higher risk of developing CV events within 10 years and thus concentrate preventive efforts on these subjects. The latter is generally preferred at present, given the limited resources available to health systems worldwide and the not uncommon occurrence of side effects associated with the administration of pharmacological agents. Unfortunately, current traditional methods for risk prediction based on conventional risk factors have limitations3 and there is a need to identify more effective risk stratification algorithms. These should take into account the pathophysiology of the disease, be cost-effective and easy to apply in clinical practice, and provide information over and above that supplied by conventional risk factors and risk scores. Progress in this regard has been made in recent years with the advent of ultrasound techniques for the assessment of carotid intima-media thickness and atheromatous plaque composition, computed tomography (CT) for detection and quantification of coronary

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artery calcification, Doppler measurement of brachial-ankle index pressure, and the determination of aortic pulse wave velocity (PWV),\textsuperscript{4} among others. Endothelial dysfunction has also been proposed as a marker of CV risk. This manuscript will focus on the different techniques available for the assessment of endothelial function in clinical practice.

**ENDOTHELIAL DYSFUNCTION**

The term endothelial dysfunction is widely used to describe any form of abnormal activity of the endothelium. Most commonly, endothelial dysfunction is characterized by impaired nitric oxide (NO) bioavailability due to reduced production of NO by NO synthase (eNOS), increased NO breakdown by reactive oxygen species, or both. Under normal conditions, NO diffuses to the vascular smooth muscle cells and activates guanylate cyclase, which leads to cyclic guanosine monophosphate-mediated vasodilation. Shear stress is a key activator of eNOS under physiological circumstances and this helps adapt organ perfusion to changes in cardiac output. Other signaling molecules such as bradykinin, adenosine, vascular endothelial growth factor (expressed in response to hypoxia), and serotonin (released during platelet aggregation) can also activate eNOS (Fig. 1).\textsuperscript{5}

In the early stages of the atherosclerotic process, endothelial function may be partly maintained by the compensatory upregulation of prostaclyxin and/or endothelium-derived hyperpolarizing factor(s) (EDHF). Prostacyclin, a product of the cyclooxygenase system, is another endothelium-derived vasodilator that acts independently of NO, but has a limited role in maintaining human vascular tone. The endothelium also mediates the hyperpolarization of vascular smooth muscle cells via an NO-independent pathway, which increases potassium conductance and facilitates the subsequent propagation of depolarization of vascular smooth muscle cells to maintain vasodilator tone. The EDHF involved in this process are only partially understood (such as the cytochrome-derived factors and possibly C-type natriuretic peptide), and may differ between vascular beds.\textsuperscript{6} Endothelial dysfunction has been documented in almost every condition associated with atherosclerosis and CV disease\textsuperscript{7} and has also been related to the presence of conventional CV risk factors like hypertension, dyslipidemia, diabetes mellitus, age, and obesity.\textsuperscript{5,8-13} It has also been described in patients with inflammatory and infectious diseases.\textsuperscript{14,15}

As a consequence of endothelial dysfunction, a range of proatherosclerotic molecular events occur, including increased lipid permeability and the promotion of oxidative and inflammatory environments within atheromatous plaques that favor plaque rupture and pro-thrombotic events, as seen in the acute coronary syndrome. Endothelial function therefore represents an integrated index of both the overall CV risk factor burden and the sum of vasculoprotective factors in a given individual. Given its role in the atherosclerotic process, it is not surprising that many studies demonstrate a prognostic role for endothelial dysfunction, as measured both in the coronary arteries and the circulation.\textsuperscript{16}

**ASSESSMENT OF ENDOTHELIAL FUNCTION**

Coronary endothelial dysfunction is generally assessed using invasive methods, such as the infusion of acetylcholine (ACh) into the coronary artery, where it has been shown to produce a paradoxical vasoconstriction in those arteries affected by atheroma.\textsuperscript{17} ACh promotes the release of NO from vessels with an intact

![Figure 1. The endothelium. Structure and function. The endothelium is a thin layer of cells that lines the interior surface of blood vessels.\textsuperscript{5} It behaves as an autocrine, paracrine, and endocrine gland. Endothelial cells produce several mediators with vasorelaxing, anti-proliferative, anti-thrombotic, and anti-adherent effects, such as nitric oxide, prostacyclin, endothelium-derived hyperpolarizing factor, and C-type natriuretic peptide. The actions of these molecules are balanced by the release of substances with opposing effects, such as endothelin-1, thromboxane A₂, prostaglandin H₂, and superoxide anion. Impairment of endothelium-dependent dilation shifts a net dilator response to a variety of stimuli to a constrictor response that can affect blood flow.\textsuperscript{5} 5-HT, serotonin; ACE, angiotensin-converting enzyme; ACh, acetylcholine; ADP, adenosine diphosphate; AI, angiotensin I; All, angiotensin II; AMP, cyclic adenosine monophosphate; AT₁, angiotensin 1 receptor; B₂, bradykinin receptor 2; BK, bradykinin; ECE, endothelin converting enzyme; eNOS, nitric oxide synthetase; ET₁, endothelin-1; ET₂, endothelin A receptors; ET₄, endothelin B receptors; GMP, cyclic guanosine monophosphate; L-Arg, L-arginine; M, muscarinic receptor; NO, nitric oxide; OH, hydroxyl radical; ONOO⁻, nitric oxide peroxynitrite; P, purine receptor; PGH₂, prostaglandin H₂; PGI₂, prostacyclin, ROS, reactive oxygen species; S₄, serotoninergic receptor; TX, thromboxane receptor; TXA₂, thromboxane. Modified with permission from Flammer et al.\textsuperscript{7}](image-url)
endothelium and this leads to vasodilation. Arteriosclerotic vessels with impaired endothelial function, however, respond with vasoconstriction as a result of a direct vasoconstrictor effect of ACh on the vascular smooth muscle (muscarinic effect) in the absence of NO release. Nitroglycerine is used to test endothelial-independent dilatation. Investigators have also used endothelial agonists that include substance P, adenosine, and bradykinin, and the use of these agents has provided important insights into the vascular effects of risk factors. These methods have also allowed the characterization of the vascular effects of pharmacological agents such as angiotensin-converting enzyme inhibitors and statins. The usefulness of this method, however, is limited by its invasive nature and therefore new techniques have been developed in recent years to assess endothelial dysfunction noninvasively. Nonetheless, because endothelial dysfunction is a systemic process that simultaneously affects different vascular territories, it is accepted that noninvasive approaches assessing endothelial function in peripheral vessels are, albeit indirectly, representative of coronary vascular function. Most of the techniques available at present use endothelial-dependent vasomotion as the clinical endpoint for the assessment of endothelial function. Testing involves pharmacological and/or physiological stimulation of endothelial release of NO and other vasoactive compounds, and often a comparison of vascular responses to endothelium-independent dilators such as nitroglycerine. Determination of local NO bioavailability not only reflects its influence on vascular tone, but also the other important functions of this molecule, which include thromboregulation, cell adhesion, and proliferation. The majority of those techniques exhibit a good correlation with the assessment of coronary endothelial function. Currently the main noninvasive techniques to assess endothelial functions are flow-mediated vasodilation (FMD) as measured by ultrasound of the brachial artery, pulse wave analysis, and finger plethysmography during postischemic hyperemia. Other invasive and noninvasive methods for measuring coronary microvascular function have been recently reviewed, such as magnetic resonance imaging (MRI), positron emission tomography scanning, CT scanning, single photon emission CT, Doppler echocardiography, Doppler flow wire, temperature and pressure sensor tripped coronary wire, or thrombolysis in myocardial infarction frame count and myocardial blush score. A completely different approach has also been proposed and this is based on the measurement of plasma levels of endothelium-related analytes, which can reflect -to a certain extent- overall endothelial activation or dysfunction. Circulating soluble fractions of intercellular adhesion molecule-1, vascular cell adhesion molecule-1, and von Willebrand factor may be regarded as markers of endothelial function. The concentrations of these peptides raise when the endothelium is activated or damaged and they are predictive of the risk, presence, and severity of vascular disease. The assessment of biochemical markers of endothelial dysfunction is beyond the scope of the present review.

ASSESSMENT OF BRACHIAL ARTERY FLOW-MEDIATED VASODILATION

At present, FMD is the most commonly used method for measuring endothelial dysfunction, mainly because of its sensitivity and noninvasive nature. It was used for the first time by Celermajer et al. after a physiological study by Anderson and Mark. It is based on the endothelial release of NO and other endothelium-derived relaxing factors in response to an increase in shear stress. In this test, this occurs when the forearm blood flow increases during the reactive hyperemia that follows a brief period of transient ischemia in the distal territories. The ischemia is achieved through a pneumatic cuff, placed on the forearm, distal to the ultrasound image site, and inflated to suprasystolic pressure for 5 min (Fig. 2). On deflation of the cuff, the increased flow results in shear stress, which activates endothelial NO synthase to release NO via the L-arginine pathway. The NO diffuses to the smooth muscle cells, causing them to relax, resulting in vasodilation. Finally, FMD is measured as the percentage change in brachial artery diameter (Fig. 3) from baseline to the maximum increase in diameter (Fig. 4).

Despite being the most frequently used technique, a closer look at the literature reveals that there are wide variations in mean FMD when different studies in similar populations are compared. At present, the lack of scientific consensus regarding a standardized protocol for measuring FMD precludes the accurate comparison of data between centers. There have been efforts to provide guidelines, but a full standardization has not been achieved. Five critical elements of FMD methodology need to be standardized:

- Probe position in relation to cuff: if the cuff is placed proximal to the probe, it is not clear what aspect of endothelial function is being measured. NO-dependent FMD measurement becomes confounded by the presence of additional ischemic (NO-independent) vasodilation. Therefore, if the aim of the study is to assess NO bioavailability, the cuff should be positioned distally to the probe (Fig. 2).
- Shear stimulus (cuff occlusion time): there is general consensus that 5 min is the optimum time to elicit a good reactive hyperemic response and consequent dilation, because a longer period does not guarantee a pure NO-mediated event.
- Image measurement (stereotaxis and automation): it is compulsory to use a stereotactic apparatus to acquire high-quality static images (Fig. 2). To achieve more stable images, a micrometer-adjustable base can be used to reposition the probe to track the artery; alternatively, an anatomical forearm cast helps to preclude pronosupination of the forearm, which is the most important cause of image drifting. Each image should be measured at end diastole, and the maximal dilation should be recorded rather than the dilation at any set time after cuff release; it has been shown that taking a measurement at a set time of 60 s, for example, misses the peak dilation in approximately 70% of subjects. In fact, the moment of maximum dilation is part of the interindividual endothelial response differences, and so far it remains unknown whether it is useful to determine the time to peak diameter. To select the maximal dilation, automatic measurement at each cardiac cycle is desirable, with the additional benefit of avoiding the variability inherent to manual measurements.
- Control of environmental factors: this is important for the longitudinal consistency of FMD measurements. The factors which are known to affect FMD measurements include room temperature, time of day, ingestion of fatty foods and caffeine, concurrent inflammation or infection, and stage of menstrual cycle. Although these factors have been shown to influence FMD and current guidelines have issued clear advice regarding certain conditions, recent data demonstrate that this contribution to the variability of FMD is relatively small and should not be considered a limiting factor when the ideal conditions cannot be achieved.
- Finally, quantification of the reactive hyperemic stimulus has been rarely investigated and the variation in the achieved hyperemia may account for substantial FMD variation. Several variables can affect the transduction of shear stress into conduit artery dilation. These are methodological [eg, cuff position, duration of shear stress, and duration of ischemia] and physiological variables [eg, arterial stiffness, flow pattern and blood viscosity] that have not been fully described or accounted
for. Shear stress can be calculated by recording the Doppler velocity after cuff release. To avoid shear stress variation, a ratio normalization (FMD/shear) has been proposed. Nonetheless, the usefulness of this normalization is controversial and currently it is not possible to recommend a method for correcting for differences in shear stress.

FMD studies reported in the literature differ regarding their adherence to the key methodological issues outlined above. For accuracy and reproducibility, FMD measurements, like many other imaging modalities, require careful training of the operator, a standardized technique, and well-defined analysis protocols. Recently, it has been shown in follow-up studies and interventional trials that FMD may represent a useful surrogate endpoint. Power curves have been published to assist in the design of both crossover and parallel trials and a nomogram for FMD values is also available for use as a reference for various vessel sizes.

Research on the clinical application of FMD techniques is ongoing and new approaches and measurements are being tested, such as the importance of the diameter reduction of the brachial artery during cuff inflation, which has been suggested to correlate with the presence of risk factors.

**Clinical Value of Flow-Mediated Dilation Assessment**

Under standardized conditions, brachial artery FMD is a useful measure of NO-dependent endothelial function. In apparently healthy individuals it may serve as a marker for cardiac risk factor exposure and their functional effects. Over a 6-year follow-up, FMD has been reported to correlate with the progression of preclinical carotid artery disease, showing a closer relationship with progression than conventional risk factors. In secondary prevention, it provides long term prognostic information both in patients with peripheral vascular disease and acute coronary syndrome as well as short term prognostic information in patients undergoing vascular surgery. These are promising studies but the clinical application of FMD is currently limited by the lack of standardized protocols and reference values. Thus FMD testing remains confined to research, where it is a valuable and important tool, mainly for the study of populations rather than individuals. The additive value of brachial ultrasound FMD over and above established traditional clinical tools remains to be proven and ongoing studies are currently addressing this issue.

**PULSE WAVE VELOCITY AND PULSE WAVEFORM ANALYSIS**

PWV was first described by the Moens-Korteweg equation derived in the 1920s that relates PWV to vessel distensibility, $c0\sqrt{Eh/2R\rho}$, where $c0$ is the wave speed, $E$ is the Young modulus in the circumferential direction, $h$ is wall thickness, $R$ is vessel radius, and $\rho$ is the density of fluid. Normal values vary from vessel to vessel and are described in Table 1. Aortic PWV is usually measured between the carotid and femoral artery by synchronically detecting the arrival of the wave at both locations and measuring the distance. This method renders an average velocity value.
Another parameter of interest which is related to PWV is the pressure waveform. The pressure waveform in any artery is the result of the summation of the forward transmission of the cardiac pressure impulse and a backward reflection generated by the peripheral vascular system at the interface between large arteries and resistance vessels (arteries and arterioles). The pressure wave travels at such high velocity that it is reflected back to the central arteries during the same ejection cycle and overlaps part of the forward wave. Pressure recorded anywhere in the arterial system is thus the sum of the forward wave and the reflected wave and is dependent on 3 factors: the amplitude and duration of ventricular ejection, the amplitude of the reflected wave, and the PWV.47

Using either applanation tonometry or photoplethysmography, pressure vs time data can be acquired in different arteries, such as the radial, femoral or carotid arteries. Several measurements can be obtained using peripheral waveform analysis.48 By applying a validated integral transfer function, the central aortic waveform can be derived.49 In particular, central pressures can be inferred and the augmentation index can be calculated as an index of arterial stiffness. Using the electrocardiogram as time reference, readings from arteries at different locations can be compared to measure PWV.

Recently, arterial stiffness has been assessed using MRI. Unlike PWV, which is an average measure of overall arterial stiffness, MRI enables the detection of more subtle changes in regional stiffness. In MRI, full 3-dimensional visualization of the vessel is possible, enabling an image-measuring plane to be placed perpendicular to the vessel in a reproducible location. Moreover, velocity data can be acquired simultaneously in 2 aortic locations and the distance between them can be measured precisely.50

Radial artery applanation tonometry, as opposed to carotid or femoral artery tonometry, is easier to use in the clinical setting and causes less discomfort to the patient.51 Tonometry of the radial artery provides an accurate, reproducible, noninvasive assessment of the central pulse pressure waveform. Radial artery applanation tonometry is carried out by placing a handheld tonometer (strain gauge pressure sensor) over the radial artery and applying mild pressure to partially “flatten” the artery (Fig. 5). The radial artery pressure is then transmitted from the vessel to the sensor (strain gauge) and is recorded digitally (Fig. 6).47

Recently, a new method of pulse wave analysis using oscillometric data obtained from an arm cuff inflated to suprasystolic pressure has been validated, showing a strong correlation (Pearson’s correlation 0.91; P<.001) with measurements obtained during cardiac catheterization.52 This new technique has the advantage of having a high level of automation, which provides better reproducibility.53

However, depending on the method, results regarding the reproducibility of PWV are still controversial.54–56 In general, we could say that when the PWV is recorded by methods like Doppler or tonometry, it is more time-consuming and above all the reproducibility depends on operator skill, whereas when using the

Figure 3. Diameter and blood velocity curves as a function of time in a typical flow-mediated dilation test. The solid black line depicts diameter. The dotted gray line depicts blood velocity. The dotted horizontal line indicates the reference baseline diameter. Distal ischemia period is denoted as CUFF. NTG indicates the instant of nitroglycerin administration. FMD, flow-mediated dilation; NTG, nitroglycerine. Modified with permission from Laclaustra et al.29

Figure 4. Nomogram for flow-mediated dilation according to the vessel baseline diameter. A negative linear association exists between baseline diameter and flow-mediated dilation. For a specific baseline diameter, flow-mediated dilation can be estimated. The black line shows the 75th percentile, the circular dashed line the 50th percentile, and the rectangular dashed line the 25th percentile of the population. FMD, flow-mediated dilation. Modified with permission from Charakida et al.27

Table 1
Normal Values of Pulse Wave Velocity in the Typical Middle-Aged Adult

<table>
<thead>
<tr>
<th>Location</th>
<th>Normal values (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending aorta</td>
<td>4</td>
</tr>
<tr>
<td>Abdominal aorta and carotids</td>
<td>5</td>
</tr>
<tr>
<td>Brachial artery</td>
<td>7</td>
</tr>
<tr>
<td>Iliac arteries</td>
<td>8</td>
</tr>
</tbody>
</table>

Reproduced with permission from Zambanini et al.46
new oscillometric techniques (Fig. 7) the procedure is found to be much more simple and reproducible. Nevertheless, strict adherence to standard processes is necessary to ensure that clinically sound data are obtained. Blood pressure should be measured according to the guidelines set forth in the seventh report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure. Given that vasoactive supplements, decongestants, caffeine, nicotine, or exercise can influence vascular reactivity, heart rate, and blood pressure, these should be avoided before blood pressure measurement so as not to invalidate the results.

**Clinical Value of Pulse Wave Velocity**

Although not the only contributor, endothelial function plays an important role in arterial stiffness. All the factors that reduce distensibility of the vessel (ie, increase "stiffness" of the wall) lead to a faster PWV. Atherosclerotic risk factors cause vascular remodeling, producing arterial "stiffness" within the aorta and other large arteries.

In different studies, PWV correlates with the number of CV risk factors, the fitness level, CV events, and mortality in patient populations with end-stage renal disease, diabetes, or metabolic syndrome, and in healthy elderly adults as well as in those patients with a higher baseline risk, as recently published in a large meta-analysis.

However, due to the lack of bigger studies proving reproducibility, PWV is confined, like FMD, to use as a research tool, applied mainly to study populations rather than individuals.

**FINGER PLETHYSMOGRAPHY**

In 1937 Alrick Hertzman produced a “photoelectric plethysmograph,” which he described as a device that “takes advantage of the fact that the absorption of light by a transilluminated tissue varies with its blood contents.” This is a consequence of the Lambert–Beer law, which relates light absorption to optical density. There is still uncertainty about what the photoplethysmographic pulse actually represents at different body sites, but the continuous component is attributed to light absorption by tissue and fixed blood volume, and the pulsatile component is attributed to changes in the blood volume during the cardiac cycle. Photoplethysmography, once calibrated with a blood pressure measurement, can be used on the finger to provide continuous finger blood pressure monitoring (Fig. 8).

A different technology is also available to measure the same phenomenon. A finger pneumatic plethysmographic cuff has recently been made available, and provides an additional method for a “beat to beat” blood flow volume assessment by recording finger arterial pulsatile volume changes (EndoPAT®) (Fig. 9). With these instruments, blood pulsatile volume changes are used as a surrogate for baseline blood flow. Given that peripheral flow depends on small vessels tone, these procedures are known as peripheral arterial tone (PAT) measurements.

To assess endothelial function, postischemic (hyperaemic) blood flow is compared to baseline blood flow. One finger from each hand is monitored and a pressure cuff is placed on one of the upper arms to produce a transient ischemia, while the other arm serves as a control. After measuring baseline flow, the blood pressure cuff is inflated above systolic pressure during 5 min to induce a postischemic reactive hyperemia. The calculated index (Fig. 10) between the flow in the arm with reactive hyperemia and the control arm represents a measure for endothelial function. Similar flow changes after administering nitroglycerin can be measured to assess the nonendothelium dependent response.

**Clinical Value of EndoPAT®**

PAT measurements in patients with chest pain and coronary artery disease seem to correlate well with the assessment of endothelial function performed by both intracoronary infusion of acetycholine during angiography and FMD brachial artery ultrasound, although the strength of the correlation varies between studies.

The main advantage of EndoPAT® as opposed to the aforementioned techniques is its high reproducibility, mainly because of the simplicity of the procedure itself that leads to very few interoperator variables. A study carried out to compare reproducibility of these techniques indicated that EndoPAT® provides more reproducible results than brachial artery ultrasound assessment of FMD, even when this is performed by a qualified brachial artery ultrasound sonographer. However, the flow increase and subsequent increase of the finger pulse volume during reactive hyperemia is a complex response to ischemia and is only partly dependent on NO. In that sense, another study found that while the reactive hyperemia index is relatively stable for 2 h, even when measured at 30 min intervals, interday reproducibility was low. This might be due to the daily variability of endothelial responses, but also to other factors that may have affected the peripheral vascular responses to ischemia. Once again, it appears as a compulsory requirement to adhere to a strict protocol when performing these assessments.

As with other techniques to assess endothelial dysfunction, EndoPAT® has been correlated with multiple traditional CV risk factors, such as: male sex, body mass index, waist circumference, LDL cholesterol, diabetes, smoking, hypertension, and family history of coronary artery disease. More importantly, a study of...
270 patients with a follow-up period of 5.8 years demonstrated that this diagnostic procedure adds incremental value to the Framingham risk score. Additionally, EndoPAT® assessment of endothelial dysfunction has been reported to be able to detect improvements after different therapies, including smoking cessation.

USEFULNESS OF NONINVASIVE ENDOTHELIAL ASSESSMENT TECHNIQUES

Given the noninvasive nature of the procedures, these methods can be used in most people and measurements can be repeated to monitor changes in status. These aspects, in addition to the high reproducibility of measurements, mainly due to the high level of automation of at least some of the methods described above, make the techniques useful for clinical practice.

Figure 6. The upper long panel shows the radial pressure waveform above the derived central pressure waveform. The bottom left panel demonstrates a magnified radial arterial waveform. Systolic and diastolic pressures are 117/85 mmHg. The bottom right panel provides a magnified derived central pressure waveform. Central pressure is 105/85 mmHg. Modified with permission from Nelson et al.67 ms, milliseconds.

Figure 7. Oscillometric device for assessing pulse wave velocity.

Figure 8. A modern photoplethysmograph incorporating a light-emitting diode and sensor within a finger clip. A typical waveform (solid line) is shown, together with a radial pressure waveform (obtained using a tonometer) in the same individual. Modified with permission from Millaseau et al.66
At present, these techniques are mainly used for research purposes in projects assessing disease mechanisms in humans but they show a remarkable potential as surrogate endpoints and may prove useful in the assessment of pharmacological and non-pharmacological intervention and trials dealing with disease prevention. Assessed of endothelial function may help in patient risk stratification in primary and secondary prevention, the evaluation of vascular responses to specific therapies, and longitudinal patient monitoring.16

**PRESENT AND FUTURE DIRECTIONS**

Noninvasive techniques have become available which might help in the assessment of endothelial dysfunction in clinical practice. There are however many unresolved issues in relation to the utility of these techniques in everyday clinical practice. From a technical perspective, several issues should be investigated thoroughly before these techniques can be recommended for routine use. Firstly, we need to establish whether they are truly and precisely assessing endothelial function or whether they reflect the combined effect of the many variables—endothelial and nonendothelial dependent—that affect vascular responses. Secondly, it is important to study whether they will truly show a direct correlation with the effects of intervention. As most of these techniques assess endothelial function in an indirect way and are affected by the presence of external agents, protocols should be defined rigorously to minimize the effects of these confounding factors. Efforts should focus on automation to make the results more technician-independent and improve the reproducibility of their measurements.

Conceivably, the use of these techniques in clinical practice could improve patient risk stratification, help in the implementation of preventive strategies, and also improve treatment monitoring. Although several studies have already been performed (Table 2), further research is required in large clinical studies using the appropriate gold standards for the assessment of the role of this methodology in relation to diagnosis and intervention. So far, there is not enough evidence to support the use of endothelial function assessment in clinical practice. Prospective, well designed, clinical studies involving real-life subjects should be performed to clarify whether the endothelial function, as assessed by the techniques described in this manuscript, represent an independent risk factor and/or an independent marker of risk that provides additional information over and above that afforded by the classic CV risk factors. Comparisons among the different tools for risk assessment currently used in clinical practice and the assessment of endothelial function should also be carried out.

Other potential clinical applications include the dynamic monitoring of treatment as, in contrast to conventional CV risk factors, endothelial function is a dynamic event. Hence, these novel techniques should allow a better short-term assessment. Evidence to document that this is the case would require 2 steps. First, it should be established—in long-term observational open-label interventions—whether endothelial function assessment can identify, better than the use of conventional risk factors, successful and ineffective preventive treatments. Second, studies should be performed to demonstrate that intensification of treatment leading to improved endothelial function improves patients’ clinical outcomes.

Future areas of interest also include the relationship of endothelial dysfunction to circulating endothelial progenitor cells number and function and their therapeutic modulation, as well as

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**Figure 9.** EndoPAT® device.

**Figure 10.** Differences between normal endothelial function and endothelial dysfunction assessed by EndoPAT®.
Table 2
Studies Using Noninvasive Techniques to Assess Endothelial Function

<table>
<thead>
<tr>
<th>Method of assessment</th>
<th>Number of patients</th>
<th>Population</th>
<th>Type of study</th>
<th>Follow-up</th>
<th>Findings</th>
<th>First author</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMD</td>
<td>500</td>
<td>Asymptomatic subjects</td>
<td>Observational, retrospective</td>
<td>–</td>
<td>Reduced FMD is related to the presence of classic CVRF</td>
<td>Celermajer et al.</td>
<td>1994</td>
</tr>
<tr>
<td>FMD</td>
<td>213</td>
<td>Non-smoking subjects</td>
<td>Observational, prospective</td>
<td>6 years</td>
<td>Reduced FMD is related to progression of preclinical carotid arterial disease</td>
<td>Witte et al.</td>
<td>2009</td>
</tr>
<tr>
<td>FMD</td>
<td>199</td>
<td>Patients with peripheral artery disease</td>
<td>Observational, prospective</td>
<td>1.2 years</td>
<td>Reduced FMD independently predicted short and long-term CV events</td>
<td>Gokce et al.</td>
<td>2002-2003</td>
</tr>
<tr>
<td>FMD</td>
<td>92</td>
<td>Survivors of ACS without ST-segment elevation</td>
<td>Observational, prospective</td>
<td>2.06 years</td>
<td>Reduced FMD independently predicted CV events</td>
<td>Karatzis et al.</td>
<td>2006</td>
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<tr>
<td>PWV</td>
<td>465</td>
<td>Patients with suspected CAD</td>
<td>Descriptive</td>
<td>–</td>
<td>Aix was an independent risk marker for premature CAD</td>
<td>Weber et al.</td>
<td>2004</td>
</tr>
<tr>
<td>PWV</td>
<td>146</td>
<td>Healthy volunteers</td>
<td>Descriptive</td>
<td>–</td>
<td>Reduced Aix was related to higher physical conditioning status (High VO$_{2\max}$)</td>
<td>Vaitkevicius et al.</td>
<td>1993</td>
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<tr>
<td>PWV</td>
<td>1045</td>
<td>Hypertensive patients</td>
<td>Observational, prospective</td>
<td>5.7 years</td>
<td>Increasing level of PWV was an independent predictor of primary coronary events</td>
<td>Boutouyrie et al.</td>
<td>2002</td>
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<td>PWV</td>
<td>565</td>
<td>Diabetics and non-diabetics</td>
<td>Observational, prospective</td>
<td>10 years</td>
<td>Aortic PWV is a powerful independent predictor of mortality</td>
<td>Cruickshank et al.</td>
<td>2002</td>
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<tr>
<td>PWV</td>
<td>364</td>
<td>Healthy subjects</td>
<td>Descriptive</td>
<td>–</td>
<td>PWV was increased according to the number of MS components present</td>
<td>Kim et al.</td>
<td>2006</td>
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<tr>
<td>PAT</td>
<td>89</td>
<td>Patients with and without CVRF</td>
<td>Descriptive</td>
<td>–</td>
<td>PAT ratio was more impaired in patients with CVRF</td>
<td>Kuvim et al.</td>
<td>2003</td>
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<td>PAT</td>
<td>60</td>
<td>Patients with CVRF</td>
<td>Descriptive</td>
<td>–</td>
<td>PAT ratio was related to the extension of CAD</td>
<td>Kuvim et al.</td>
<td>2007</td>
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<tr>
<td>PAT</td>
<td>94</td>
<td>Patients without obstructive artery disease</td>
<td>Descriptive</td>
<td>–</td>
<td>PAT ratio was lower in patients with coronarymicrovascular endotelial function assessed by ACh test</td>
<td>Bonetti et al.</td>
<td>2004</td>
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<tr>
<td>PAT</td>
<td>22</td>
<td>Healthy subjects</td>
<td>Descriptive</td>
<td>–</td>
<td>Repetitive PAT measurements in 30 min, 1 and 2h have no carry over effects. Interday reproducibility is relatively low</td>
<td>Liu et al.</td>
<td>2009</td>
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<tr>
<td>PAT</td>
<td>1957</td>
<td>General population</td>
<td>Descriptive</td>
<td>–</td>
<td>PAT ratio was related to multiple traditional metabolic and CVRF.</td>
<td>Hamburg et al.</td>
<td>2008</td>
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<tr>
<td>PAT</td>
<td>270</td>
<td>Patients with CVRF</td>
<td>Observational, prospective</td>
<td>7 years</td>
<td>Low PAT ratio was related to higher incidence of CV adverse events</td>
<td>Rubinshtein et al.</td>
<td>2010</td>
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</table>

Aix, augmentation index; CAD, coronary artery disease; CV, cardiovascular; CVRF, cardiovascular risk factors; FMD, flow-mediated dilation; MS, metabolic syndrome; PAT, peripheral arterial tone; PWV, pulse wave velocity.

REFERENCES

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CONFLICTS OF INTEREST

None declared.


