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Reviews

Methods and Devices for Measuring Arterial Compliance in Humans

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This review analyses methods and devices used worldwide to evaluate the arterial stiffness. Three main methodologies are based upon analysis of pulse transit time, of wave contour of the arterial pulse, and of direct measurement of arterial geometry and pressure, corresponding to regional, systemic and local determination of stiffness. They are used in clinical laboratory and/or in clinical departments. Particular attention is given to the reproducibility data in literature for each device. This article summarizes the discussion of the dedicated Task Force during the first Conference of Consensus on Arterial Stiffness held in June 2000 (Paris, France). Am J Hypertens 2002;15:743–753

Key Words: Arterial stiffness, methodology, measurement.

The clinical relevance of arterial stiffness is due to its fundamental role in pulsatile hemodynamics. Systemic arterial stiffness affects the global buffering properties of the arterial system, but for a particular segment or region there is essentially one value of stiffness for one value of blood pressure (BP) for one individual. Invasive, sophisticated clinical measurements have provided data of this kind from recordings of arterial blood flow, pressure, and diameter changes. Such methods, used in experimental animal laboratories, are not entirely suitable for clinical use, but have provided the basis for measurement and interpretation of noninvasive data in the clinical setting. Noninvasive measurement of arterial stiffness entails measurement of surrogate parameters that are intrinsically associated with stiffness. This involves three main methodologies: 1) pulse transit time, 2) analysis of the arterial pressure pulse and its wave contour, and 3) direct stiffness estimation using measurements of diameter and distending pressure. These surrogate parameters are related to the functional effects of arterial stiffness, and as such can be used to quantify changes. A number of computerized devices are now available that enable quantification of global indices of stiffness, regional, and local measurements. This article will not give an exhaustive list and analysis of all the available methods, but focuses on the main specific devices developed and used in different experimental and clinical laboratories worldwide.

Noninvasive Methods for Arterial Stiffness Measurement

Systemic Determination of Arterial Stiffness

Just as arterial BP can be considered as a global value of hemodynamic load, systemic arterial stiffness may reflect the overall opposition of large arteries to the pulsatile effects of ventricular ejection. Its apparent simplicity explains its clinical value. The measurement is based on an approximation of an electrical model and involves a computerized apparatus. They are based on numerous theoretical approximations. In general it requires the direct measurement of a single peripheral, and often distal, parameter: the pressure curve.

Regional Determination of Arterial Stiffness

Regional arterial stiffness is measured at arterial sites of major physiologic importance such as the aorta where the arterial buffering function is principally expressed, or a particular limb such as the arm (a major site of BP recording). In contrast with the systemic determinations of arterial stiffness, regional, and furthermore, local, evaluations are based on direct measurements of parameters strongly linked to wall stiffness. It is one of the major discrepancies between systemic and regional evaluation of stiffness.

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This article expresses views of the attendees of the first Conference of Consensus on Arterial Stiffness held in June 2000, Paris, France.

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Table 1. Devices and methods based on measurement of pulse transit time

Device	Arterial Measurement	Blood Pressure Measurement	Single Site of Measurement
Complior system	Dedicated mechano-transducer Simultaneous Superficial arteries	Not applicable	Not applicable
Sphygmocor system	Tonometer (Millar) Not simultaneous Superficial arteries	Not applicable	Not applicable
Automated ultrasound recording of PWV	Continuous ultrasound probe: aorta	Not applicable	Not applicable
Wall Track System	Ultrasonic echotracking Superficial arteries	Not applicable	Not applicable
QKd system	Brachial pressure cuff	Not applicable	Not applicable

PWV = pulse wave velocity.

Most of the measurement methods are based on the principle of pulse wave velocity (PWV) recording. This parameter[1] is determined by elastic modulus (E) of the arterial wall, arterial geometry (h = thickness; r = radius) and blood density (ρ). During the end of the nineteenth century, Moens and Korteweg formulated this relationship as: $PWV^2 = Eh/2r\cdot\rho$. Bramwell and Hill[2] described the relationship in terms of relative change in volume ($\Delta V/V$) and pressure (ΔP) during ex vivo experiments: $PWV^2 = \Delta P\cdot V/\Delta V\cdot\rho$. The assessment involves measurement of two quantities: transit time of the arterial pulse along the analyzed arterial segment, and distance on the skin between both recording sites. The measurement of transit time on recording paper was manual,[3] but different automatic methods have now been developed to give instantaneous values of PWV. Several assumptions are made regarding the reference points on the arterial pressure curves for transit time estimation, the pulse wave traveling in opposite directions when recording the common carotid and femoral artery pulses, and methods of measurement of the distance on the skin between recording sites (see review in ref. 1). Other methods depend on direct measurements of the relative change in arterial diameter and change in BP following the Bramwell-Hill formula, whereby it is assumed that the length of the arterial segment is constant. Some assumptions are necessary to simplify calculation from the curvilinear relationship between pressure and volume (discussed later).

Local Determination of Arterial Stiffness

Local determination of arterial stiffness involves measurement of cross-sectional arterial distensibility. For the corresponding arterial segment, the assumption is that the segment is a cylindrical tube. That means the combination of diameter measurement and simultaneously or within a few minutes, local BP recording. Systems are based on a vascular echotracking device using the Doppler shift principle or on echo imaging. They differ with respect to their ability to obtain continuous recordings of changes in diameter and pressure waveforms from diastole to systole, or only to measure the two extreme points of this range.

Other Assessments

Methods based on flow pulse detection using magnetic resonance imaging have been proposed as noninvasive means of obtaining arterial pulse wave velocity[4,5] or even local distensibility. However, due to the time resolution required for flow detection, the technique presently appears to have limited clinical application.

Table 2. Devices and methods based on analysis of the arterial pressure pulse

Device	Arterial Measurement	Blood Pressure Measurement	Single Site of Measurement
Subclavian pulse tracing Doppler–echocardiography	Mechanical air transmission Subclavian artery	Brachial oscillometric device (Dinamap)	Not applicable
Proximal and distal compliance from a modified windkessel model	Wrist automatic tonometer	Dedicated brachial oscillometric device	Not applicable
Second derivative of the finger plethysmogram	Finger photoplethysmograph	Not applicable	Not applicable
Sphygmocor system (augmentation index variable)	Hand-held tonometer (Millar) Superficial arteries	Brachial sphygmomanometric method	Not applicable

Bland & Altman Repeatability	Experimental Laboratory	Clinical Purpose (practician or nurse)	Epidemiologic Purpose (nurse or technician)	Direct Measure (M)/Systemic Evaluation (E)
Yes	+	+ (one operator)	+ (one operator)	M
Yes	+	+ (one operator)	+ (one operator)	M
No	+	+ (two operators)	+ (two operators)	M
No	+	±	−	M
No	−	+ (one operator)	+ (one operator)	M

Devices and Methods Based on Measurement of Pulse Transit Time

Complior System

The Complior System (Colson, Les Lilas, France) gives an automated measurement of PWV[6] for one or two arterial segments simultaneously,[7] with dedicated mechanotransducers. For the transit time calculation during 15 sec under vision control, only adequate pressure waves are used, which are selected by an in-built quality control processing (Table 1).

SphygmoCor System

Transit time between arterial sites is determined in relation to the R wave of the electrocardiogram (ECG). A single high-fidelity applanation tonometer (Millar, Houston, TX) is used to obtain a proximal and a distal pulse recorded sequentially a short time apart. Then transit time is obtained by subtraction from the delays between ECG and both pulses. To select a fiducial point on the pulse wave curve used as the reference point,[8] the SphygmoCor Pulse Wave Velocity (PWV Medical, Sydney, Australia) system provides the user with a choice of four possible algorithms.

Automated Doppler Ultrasound Recording of PWV

Transit time is determined between flow pulses recorded simultaneously by continuous Doppler probes[9] from the root of the left subclavian artery and abdominal aorta bifurcation. The latter point of recording is located at the umbilicus level on the skin, which is an important approximation, therefore the distance between recording sites is measured between the suprasternal notch and the umbilicus.

Wall Track System

The Wall Track System (Pie Medical, Maastricht, The Netherlands) can permit the aortic PWV measurement by echotracking the changes in arterial diameter: transit time is obtained by subtraction between both delays between ECG and time of the 10% arterial diameter increase with pulse.[10]

QKd System

This totally ambulatory method is developed as an add-on software for the ambulatory BP monitoring (ABPM) recording device Diasys (Novacor, Rueil-Malmaison, France).[11] It permits an upper limb artery stiffness evaluation while the ABPM recording is active. Transit time is measured between the onset of ventricular electrical ac-

Bland & Altman Respectability	Experimental Laboratory	Clinical Purpose (practician or nurse)	Epidemiologic Purpose (nurse or technician)	Direct Measure (M)/Systemic Evaluation (E)
Yes	+	−	−	E
Yes	+	+	+	E
Yes	+	+	+	E
Yes	+	+ (one trained operator)	+ (one trained operator)	E

Table 3. Devices and methods based on direct stiffness calculation using measurements of diameter

Device	Arterial Measurement	Blood Pressure Measurement	Single Site of Measurement
Beta index model	Ultrasonic phase-locked echotracking device Superficial arteries	Brachial oscillometric computerized device	No
Suprasternal view echocardiography	Standard B-mode echocardiography of ascending aorta	Brachial sphygmomanometric measure	No
NIUS 2	High resolution ultrasonic echotracking Radial artery	Simultaneous finger optoplethysmograph	Yes
Wall Track System	High resolution ultrasonic echotracking Superficial arteries	Nonsimultaneous applanation tonometer	Yes
Brachial artery transmural pressure modulation device	High resolution ultrasonic echotracking B mode ultrasound	Applanation tonometer of radial artery	No
Transesophageal echocardiography	B mode ultrasound Aorta	Mechanical air transmission of subclavian artery calibrated from brachial artery	No
Vascular echography frame grabber processing (Devereux group)	B mode ultrasound Local reading Carotid artery	Simultaneous applanation tonometer	Yes
Vascular echography frame grabber processing (ARIC study)	B mode ultrasound Centralized reading Carotid artery	Brachial oscillometric device	No

NIUS = noninvasive ultrasound system; ARIC = the Atherosclerosis Risk in Communities study.
See text for references.

tivity (recorded with cutaneous electrodes) and the phase of diastole during recording of BP using the brachial cuff.

Devices and Methods Based on Analysis of the Arterial Pressure Pulse

Subclavian Pulse Tracing and Doppler–Echocardiography Method

Arterial pressure and aortic flow velocity recordings are computerized to calculate arterial compliance using an electrical three-element model.[12,13] Pulsatile arterial pressure is measured at the level of the subclavian artery using a strain-gauge transducer (mechanical air transmission within a Silastic tube). Aortic blood velocity and aortic annulus diameter are recorded with a Doppler echocardiographic measurement simultaneously (apical view) and echography (parasternal axis), respectively (Table 2).

Proximal and Distal Compliance From a Modified Windkessel Model

This technique is based on the arterial pulse recording at the level of the radial artery (CR-2000, Research Cardiovascular Profiling System, Eagan, MN)[14] following modified windkessel[15] model allowing determination of proximal "capacitive" compliance (C1) and distal "oscillatory" compliance (C2). A tonometer sensor is strapped on the wrist and calibrated with an oscillometric BP. The appropriate hold down force of the sensor is obtained with an external screw attachment under visual inspection of the waveform. Then the pulse is obtained without the aid of the operator.

Second Derivative of the Finger Plethysmogram (SDPTG)

The amplitude ratios of the second derivative of the peripheral BP pulse waveform obtained by finger plethysmography permit evaluation of the effects of aging and vasoactive agents on arterial system.[16–18] The parameter $|b/a|$ designates the ratio of the amplitudes of the second (b) and first (a) inflection of the second derivative of the plethysmogram obtained from a photoplethysmographic device (Fukuda Electric Co., Tokyo, Japan).

SphygmoCor System

The SphygmoCor device (PWV Medical, Sydney, Australia) performs pulse wave analysis to estimate the central augmentation index (AI) derived from the peripheral arterial pulse wave by means of a transfer function.[19] The relationship between AI and arterial stiffness per se are complex and AI could represent a global surrogate index of arterial behavior with influence of arterial function, including wall properties and wave reflection, body height, and ventricular vascular coupling with a significant influence of heart rate.

Bland & Altman Repeatability	Experimental Laboratory	Clinical Purpose (practician or nurse)	Epidemiologic Purpose (nurse or technician)	Direct Measure (M)/Systemic Evaluation (E)
No	+	−	−	M
No	+	−	−	M
Yes	+	−	−	M
Yes	+	±	±	M
Yes (for Wall track system)	+	−	−	M
No (for B mode ultrasound)	+	−	−	M
No	+	−	−	M
No	+	−	+	M

Devices and Methods Based on Direct Stiffness Calculation Using Measurements of Diameter

Beta Index Model

From a vascular ultrasonic phase-locked echotracking device and an oscillometric computerized brachial artery pressure measurement (irrespective of where the diameter is measured), the regional evaluation of arterial stiffness is based on the change in pressure and in diameter.[20] The curvilinear relationship between pressure and diameter is approximated with a logarithmic transformation, resulting in the beta index reflecting the stiffness, although only the extreme points of the pressure and diameter curves are considered in the calculation. The same principle was used for the evaluation of the stiffness of the thoracic aorta,[21] with suprasternal incidence echocardiography and brachial artery BP recordings. The fact that pressure and diameter are measured at different locations is at variance with the aim to focus on the coherence of recordings, although brachial BP measurement is simpler than more accurate techniques requiring optimal training and expertise. But coherent data provide a better understanding of arterial mechanics, particularly due to the pressure amplification from aorta to periphery (Table 3).

Noninvasive Ultrasound System (NIUS 2)

NIUS 2 (Asulab, Marin, Switzerland) measures simultaneously as continuous function of time radial artery internal diameter and intima–media thickness (IMT) with a high resolution ultrasonic echotracking device and finger BP by a Finapres system with a customized software correcting the time delay between both sites.[22,23] All along the range between end-diastole and end-systole limits, the pressure–diameter curve is analyzed according to the Langewouter's mathematical model,[24] resulting in estimates for the compliance, distensibility, and for the incremental elastic modulus given as isobaric, either for the actual observed "operating" mean BP or for an arbitrary point of the BP curve usually set at 80 or 100 mm Hg.[25] However, at the present time, this device and the Finapres system, are no longer developed by the manufacturers, which limits new developments.

Wall Track System

The Wall Track System (Pie Medical), is a high resolution vascular echotracking device that measures internal diameter at diastole and the pulsatile change of the artery diameter. From the same ultrasound data, the IMT is extracted.[26] Blood pressure has to be measured separately, usually derived from a applanation tonometer (Millar)[27] recording of the local carotid artery BP after an appropriate calibration based on pressure–time integral of the brachial BP or automatic calculation using transfer function processing (Sphygmocor, PWV Medical, Sydney Australia).[19] The estimates are based on the end-diastolic and end-systolic values of pressure and diameter, but the calculation for any specific reference pressure remains pos-

Table 4. Reproducibility of devices and methods based on measurement of pulse transit time

Device	Bland & Altman Repeatability Coefficient (SD of diff.)	Mean Value of Population Sample (measure1/measure2)	Number of Subjects
Complior system (aortic)	0.89 m/sec*	10.8 ± 2.39 m/sec 10.96 ± 2.69 m/sec	56
Sphygmocor (aortic)	1.25 m/sec* 1.17 m/sec†	8.15 ± 3.01 m/sec	24
Automated ultrasound pulse wave velocity			
QKd system			

* Interobserver reproducibility; † Intraobserver reproducibility.

sible although not automatically.[28] The elastic modulus of the arterial wall can be available with the assumption of linearity of the strain–stress relationship.[29] All the superficial arteries are suitable for the geometrical investigation.

Brachial Artery Transmural Pressure Modulation Device

Based on the same technical principle (Wall Track System), the addition of a pressure-adjusted water-filled cuff permits the manipulation of the transmural arterial wall pressure at the level of radial artery[30] together with the IMT measurement (Phase 2, Biosound Inc., Indianapolis, IN) and arterial pressure range (tonometer N500, Nellcor Inc., Pleasanton, CA).

Transesophageal Echocardiography

Transesophageal echocardiography enabled the measure of the ascending aorta wall thickness and changes in diameter.[31] The combination with the subclavian BP[12] permits to calculate the elastic modulus of this local part of aorta.

Vascular Echography Coupled With Frame Grabber Processing

The carotid arterial diameter and IMT are assessed after connecting an echograph to a frame grabber processing. The images are shown on a high resolution video display. Measurement of diameter was manual under the control of vision (with a screen or caliper resolution of 0.2 mm) together with tonometer measurement of the carotid artery BP (Millar)[32] or with a centralized reading in a designated center to evaluated the carotid artery diameter characteristics and BP measured with an oscillometric apparatus at the level of the brachial artery (Dinamap, Critikon, Tampa, FL).[33]

Validation and Reproducibility

There are large differences in validation procedures and

Table 5. Reproducibility of devices and methods based on analysis of the arterial pressure pulse

Device	Bland & Altman Repeatability Coefficient	Mean Value of Population Sample (measure1/measure2)
Subclavian pulse tracing Doppler–echocardiography (1st publication)	Peak systolic pressure: 5 mm Hg (=2 ∗ SD of difference) Mean diastolic pressure: 10 mm Hg Aortic volume flow: 15 to 90 cm^3/sec	Aortic volume flow: 329 ± 47 cm^3/sec
Subclavian pulse tracing Doppler–echocardiography (2nd publication)	Systolic pressure: 12 mm Hg (=1.96 ∗ SD of difference) Diastolic pressure: 10 mm Hg Arterial compliance: 0.8 cm^3/mm Hg	110 ± 15 mm Hg 64 ± 11 mm Hg −2.1 ± 0.59 cm^3/mm Hg
Proximal and distal compliance from a modified windkessel model	C1: 0.38 mL/mm Hg C2: 0.014 mL/mm Hg	1.86 mL/mm Hg 0.078 mL/mm Hg
Second derivative of the finger plethysmogram	[b/a] index: 0.08 units Age index (SDPTGAI): 0.16 U	−0.78 ± 0.08 U −0.88 ± 0.14 U
Sphygmocor device	Augmentation index: 5.37% (intraobs), 3.8% (interobs)	19.6% ± 12.0%

SDPTGAI = second derivative of the finger plethysmogram age index.

References	Variability Coefficient (SD/Mean)	Number of Subjects	References
6			
47			
	Young adults: 10% Elderly normals 13.7% (1 month), 14.4% (3 months)		9
	4% (15 days)	30	11

reproducibility evaluation of all these techniques (see Tables 4, 5, and 6). There is no gold standard method for local or regional in vivo measurement of arterial stiffness. Direct comparison with other in vitro or in vivo techniques is always limited due to the major role of mediator systems and autonomic nervous control. Furthermore, the major discrepancy between a full noninvasive conscious in vivo experiment and other techniques is the role of pulsatile flow and pulsatile pressure, which clearly interact with the arterial mechanic behavior.[34] Evaluation of a single series of measurements with the classic coefficient of variation (SD/mean), series comparison, or regression analysis is unsuited for validation studies. At present, the British Standard Institution recommended well-accepted statistical procedures to validate techniques. Particularly, Bland and Altman[35] suggested the analysis of agreement between two methods and of reproducibility by means of the repeatability coefficient, ie, the standard deviation of the difference between measurements. The scatterplot of this difference in comparison with the average value of both series of measures can also be given. Reproducibility data are shown in Tables 4, 5, and 6.

Complior System

Validation of the device (version 1) was performed by comparison between manual measurement of aortic PWV and automatic calculation of the arterial wave transit time. In 56 subjects, agreement assessed by the repeatability coefficient, was 0.94 m/sec for a mean value of 11.05 $\pm$ 2.58 m/sec.

SphygmoCor System

The augmentation index was analyzed in terms of its relationship to pulse wave reflection and global arterial stiffness. Comparison between AI and aortic PWV has shown a significant association,[36] but relatively low positive correlation ($r = 0.29$, $P < .005$), which increased when gender was accounted for. This could be related to the role of height, heart rate, BP, and a possible heritable component evaluated in twins.[37]

QKd System

Validation of the PWV between subclavian artery and radial artery with respect to the measurement of PWV with Doppler probes was assessed through regression analy-

Number of Subjects	References	Variability Coefficient (SD/Mean)	Number of Subjects	References
86	12			
18	13			
20	14			
53	K. Takazawa: unpublished data			
33				

Table 6. Reproducibility of devices and methods based on direct stiffness calculation using measurements of diameter

Device	Bland & Altman Repeatability Coefficient	Mean Value of Population Sample (measure1/measure2)	Number of Subjects
Beta index model (1)			
Beta index model (2)			
NIUS 2 (1)	Radial artery IMT: 47.6 μm (10 min apart)	399 ± 61 μm	10
NIUS 2 (2)	Radial artery IMT: 15 μm (9 months apart)	229 ± 48 μm	13
NIUS 2 (3)			
Wall Track System	Carotid art. Diastolic diameter: 0.36 * mm	6.42 ± 0.90 mm	13
	Carotid art. change in diameter: 60 μm	381 ± 117 μm	
Applanation tonometer (Millar)	Carotid art. pulse pressure: 5.1 mm Hg (15 min apart)	51.1 mm Hg	15
Brachial artery transmural pressure modulation device	Echotracking (WTS): see above		
	Tonometer of radial artery: see above		
Transesophageal echocardiography			
Echography + frame grabber processing			
Vascular echography frame grabber processing (ARIC study)			

Pres. = pressure; IMT = intima–media thickness; WTS = wall tracking system; diam = diameter; other abbreviations as in Table 3.
* Correlation coefficient between pair of measures.

sis.[11] Although significant, the low correlation (r = 0.55, $P < .01$, $n = 37$) is probably partly due to a slight discrepancy between analyzed arterial territories.

Subclavian Pulse Tracing and Doppler–Echocardiography Method

The method was validated[12] by comparison with invasive determination of aortic flow and BP. The Bland–Altman coefficient used (2× standard deviation of the difference) was from 5 mm Hg (peak systolic pressure) to 10 mm Hg (mean diastolic pressure) and from about 15 cm^3/sec to 90 cm^3/sec for aortic volume flow depending on the time to ejection (mean value of about 329 ± 47 cm^3/sec). The feasibility was 81% in 86 subjects (20 to 81 years of age).

Proximal and Distal Compliance From a Modified Windkessel Model

Agreement evaluation (Bland–Altman coefficient) of the radial artery BP obtained with the N500 (Nellcor Inc.) by comparison with invasive measurement (SD of difference: invasive minus noninvasive determination) were, respectively, 8.5 mm Hg and 6.1 mm Hg for the systolic (133 mm Hg) and diastolic (71 mm Hg) BP.[14] Agreement (repeatability coefficient) for cardiac output, was obtained from a customized algorithm, following comparison with indocyanine green dye dilution was 0.94 L/min (mean value, around 5.5 L/min). Agreement was only within 25% in 92% of the pairs of recordings.

Second Derivative of the Finger Plethysmogram

The association of the parameter |b/a| with arterial distensibility[17] and pulse wave velocity[38] has been demonstrated. In 524 subjects with essential hypertension and 140 subjects with proven atherosclerosis, aortic PWV is superior to the Second Derivative of the Finger Plethysmogram method for detection of changes in arterial stiffness with age, BP, and atherosclerosis. However, the Second Derivative of the Finger Plethysmogram was found as appropriate for evaluation of vascular aging in hypertensives[17]: correlations between |b/a| (y) and age (x, years) was $y = 0.8656 - 0.0072x$ ($r = 0.790$, $P < .01$) and between distensibility (dis, as change in diameter/change in pressure, 1/Pa) was: $y = 0.1564 + 0.1145dis$ ($r = 0.892$, $P < .01$).

References	Variability Coefficient (SD/Mean)	Number of Subjects	References
	Systolic pres.: 1.7% Diastolic pres.: 2% Arterial diam: 2% Beta index: 6.69%	1	20
39	Beta index: 6.5%	24	21
48			
	Radial artery diameter: 1.9% ± 0.5% (2 weeks apart) Radial artery IMT: 3.0% ± 0.9%		23
48		—	—
49			
	15%		31
	(R = 0.84)*	20	50

NIUS 2

The echotracking device was validated through in vivo/in vitro comparison of the same radial artery segment in patients undergoing coronary bypass graft with radial artery material.[39] Expressed in terms of arterial wall cross-sectional area, the agreement between both IMT measurement procedures showed correlation coefficient as 0.929 (n = 11 determinations), and repeatability coefficient with the Bland–Altman approach as 0.93 mm^2 (for a mean value of 3.782 ± 1.055 mm^2).

Wall Track System

To calculate a stiffness index, the Wall Track System device requires measurement of BP. This measure with the applanation tonometer was studied first by comparison with the mercury sphygmomanometer on the brachial artery in 105 patients, followed by correlation analysis: r = 0.97, slope = 0.98, intercept = 1.4 mm Hg.[40] Second, the shape of the pressure curve recorded with the applanation tonometer was analyzed by comparison with an invasive measurement of carotid artery with a micromanometer-tipped catheter. Spectral analysis over 10 harmonics showed no difference in moduli percentage of power and phase angle.[41]

Summary

Validation was generally quite acceptable when studied. At the present time, assessment of reproducibility has been recommended by using robust analysis taking into account the weight of each individual pair of measurements with the Bland–Altman methodology as suggested by the British Medical Association.[42] Therefore, except for a few devices, the methods of validation and reproducibility are acceptable[47–50] (see Tables). However, some discrepancies deserve attention when comparing data presented by different groups of investigators.

Application and Feasibility

Not all devices are suitable for all studies. Physiologic and physiopathologic studies, particularly in specialized laboratories, require accurate and reproducible systems and here, the simplicity of use is not a relevant criterion. The most suitable devices are those with direct calculation of surrogate measures of arterial stiffness, such as PWV, arterial compliance, or distensibility, followed by systems with off-line calculation after data acquisition. Furthermore, some studies require a global evaluation of the entire arterial system. Clinical, epidemiologic, or pharma-

cologic studies may require a device that is easy to use for a technician or nurse in clinical departments and that incorporates patient data management. The CR-2000 system measuring C1 and C2, the Complior device and SphygmoCor device appear particularly suitable for that purpose. Although the first system provides a global compliance evaluation, the latter two provide direct evaluation of the regional arterial stiffness, suitable for epidemiologic[43,44] or pharmacologic studies. SphygmoCor can also provide data on global arterial system through the augmentation index variable. They can assess prognosis. The place of QKd[11] device is yet not well established in large clinical studies. Because the structure and composition, and hence the mechanical properties, gradually change along the arterial tree, local assessment of wall thickness, the diameter, and BP, particularly as a continuous function of time, should be preferred to study the (patho-)physiology of the vessel wall. Finally, the multicenter Atherosclerosis Risk in Communities (ARIC) study performed on more than 7000 individuals, shows the feasibility to measure arterial diameter on a video monitor by trained and certificated observers in a central location.[33] Recently, the Wall Track system or Complior device also demonstrated their ability in different population-based studies.

Agreement Between Techniques

Data on agreement between different techniques are scarce.[45] Which agreement? All the validated techniques measure global or some specific aspect of arterial stiffness, therefore an agreement between them is logical and expected. To reveal differences between groups of patients or between arterial territories and to evaluate the effects of drug treatment, precision rather than the accuracy (bias in the estimate) is of importance. To understand exactly the intrinsic arterial mechanism may require a very accurate and precise apparatus or group of devices.

Some investigators found correlations between regional and local measurements of arterial stiffness in hypertensive patients or in hemodialyzed patients. Aortic PWV (carotid to femoral arteries) was correlated with local common carotid artery cross-sectional compliance or distensibility. This is possible because of the accuracy of both methods to evaluate stiffness and because the arterial wall structure is very similar for the carotid artery and at least the initial part of the aorta. Studies on systemic and local or regional arterial stiffness are not yet available, but will probably show the same relationship due to the major role of aorta compliance in the global systemic compliance. Agreement will probably be less clear between peripheral artery compliance and systemic arterial stiffness because of the different clinical determinants for each arterial site.[46]

Conclusion

Advantages and limitations of arterial stiffness devices, available for hemodynamic laboratories or clinical departments and health care institutions, are linked to the purpose of their utilization. We must choose the device that is most adapted to our medical training and reason for performing the investigation. In summary, there are two global different concepts: either systemic arterial stiffness is evaluated by adapting an electrical model to calculate a single index from one peripheral measurement of arterial BP curve, or arterial stiffness is evaluated from a direct measure of a surrogate parameter of stiffness. It is not clear whether each of these technical principles reveal the same information for any purpose such as epidemiologic, comprehensive mechanical, or pharmacologic studies. The most widely used devices are accurate and reproducible enough to allow scientific researchers or clinicians to deepen their understanding of arterial mechanics and arterial physiopathology. Technological developments have provided new tools that can be applied to test a working hypothesis almost without limitations. Future technical and software progress will certainly further enhance knowledge of the cardiovascular system. At each step, validation and reproducibility procedures should be as rigorous as possible and should be conducted independently in different laboratories worldwide.

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