Which method is better to measure arterial stiffness; augmentation index, pulse wave velocity, carotid distensibility?
Arterial stiffness

- Arterial stiffness is inversely related to arterial distensibility (D). Arterial distensibility and arterial volume (V) are related to arterial compliance (C):
  - C = D x V

- Arterial stiffness is determined by
  - Vascular function (vascular smooth muscle tone)
  - Vascular structure (elastin/collagen content)
  - Depends on arterial pressure

- Stiffness is not a static but a dynamic property
Arterial stiffening and destiffening
Parameters of large artery stiffness are not interchangeable

- Local Distensibility (eg aortic, carotid)
- Regional Distensibility (PWV)
- System Measures
  - Systemic Arterial Compliance
  - Augmentation Index

Note: Arterial Stiffness is Pressure Dependent
### Definition and units of the various indices of arterial stiffness

<table>
<thead>
<tr>
<th>Index</th>
<th>Definition</th>
<th>Formula</th>
<th>Units</th>
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<tbody>
<tr>
<td>Arterial distensibility</td>
<td>Relative diameter (or area) change for a pressure increment; the inverse of elastic modulus</td>
<td>$\frac{\Delta D}{\Delta P \cdot D}$ (mmHg$^{-1}$)</td>
<td></td>
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<tr>
<td>Arterial compliance</td>
<td>Absolute diameter (or area) change for a given pressure step at fixed vessel length</td>
<td>$\frac{\Delta D}{\Delta P}$ (cm/mmHg) or cm$^2$/mmHg</td>
<td></td>
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<tr>
<td>Volume elastic modulus</td>
<td>Pressure step required for (theoretical) 100% increase in volume</td>
<td>$\frac{\Delta P}{(\Delta V/V)}$ (mmHg) = $\frac{\Delta P}{(\Delta D /D)}$ (mmHg)</td>
<td></td>
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<tr>
<td>Elastic modulus</td>
<td>Where there is no change in length The pressure step required for (theoretical) 100% stretch from resting diameter at fixed vessel length</td>
<td>$\frac{\Delta P \cdot D}{\Delta D}$ (mmHg)</td>
<td></td>
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<tr>
<td>Young's modulus</td>
<td>Elastic modulus per unit area: the pressure step per square centimeter required for (theoretical) 100% stretch from resting length</td>
<td>$\frac{\Delta P \cdot D}{\Delta D \cdot h}$ (mmHg/cm)</td>
<td></td>
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<tr>
<td>Pulse wave velocity</td>
<td>Speed of travel of the pulse along an arterial segment</td>
<td>Distance/$\Delta t$ (cm/s)</td>
<td>(mm Hg or as % of pulse pressure)</td>
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<td>Pressure augmentation</td>
<td>Increase in aortic or carotid pressure after the peak of blood flow in the vessel</td>
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<td>Characteristic impedance</td>
<td>Relationship between pressure change and flow velocity in the absence of wave reflections</td>
<td>$\frac{\Delta P}{\Delta V}$ [(mmHg/cm)/s]</td>
<td></td>
</tr>
<tr>
<td>Stiffness index</td>
<td>Ratio of logarithm (systolic/diastolic pressures) to (relative change in diameter)</td>
<td>$\beta = \ln (P_s/P_d) / [D_s – D_d]/D_d]$ (nondimensional)</td>
<td></td>
</tr>
<tr>
<td>“Large artery elasticity index”</td>
<td>Relationship between pressure fall and volume fall in the arterial tree during the exponential component of diastolic pressure decay</td>
<td>$\frac{\Delta V}{\Delta P}$ (cm$^3$/mmHg)</td>
<td></td>
</tr>
<tr>
<td>Small artery elasticity index</td>
<td>Relationship between oscillating pressure change and oscillating volume change around the exponential pressure decay during diastole</td>
<td>$\frac{\Delta V}{\Delta P}$ (cm$^3$/mmHg)</td>
<td></td>
</tr>
</tbody>
</table>
Methods/devices of arterial stiffness

<table>
<thead>
<tr>
<th>Method/Device</th>
<th>Systemic</th>
<th>Regional</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compliance</td>
<td>Distensibility</td>
<td>Compliance</td>
</tr>
<tr>
<td></td>
<td>OP</td>
<td>IC</td>
<td>OP</td>
</tr>
<tr>
<td>Applanation tonometry</td>
<td>PCA</td>
<td></td>
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<tr>
<td>Cine MRI Complior CR-2000</td>
<td></td>
<td>PWV</td>
<td></td>
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<tr>
<td>Nius 02 SphygmoCor WTS</td>
<td>PCA</td>
<td>PWV</td>
<td>SA</td>
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</tbody>
</table>

- OP at operating pressure; IC under isobaric conditions; cine MRI cine magnetic resonance imaging; PCA pulse contour analysis; PWV pulse wave velocity; DA deep arteries like the thoracic and abdominal aorta; SA superficial arteries like the common carotid, common femoral, brachial and radial artery; WTS wall track system; CR-2000 HDI/PulseWave*CR-2000 Research CardioVascular Profiling System.
Large elastic arteries

• Expand and recoil with cardiac pulsation and relaxation
  – To buffer the rise in systolic pressure
  – To convert pulsatile cardiac ejection into continuous blood flow in capillary beds

• Reductions in compliance and increases in stiffness
  – Independent risk factors for CVD

• Increased arterial stiffness
  – Development & progression of HTN, LVH, MI and CHF
Pulse Wave Velocity
The Compliant Vessel vs the Noncompliant Vessel

Compliant
Systole Diastole

Constant Stroke Volume

Aorta

Noncompliant
Systole Diastole

Pulse Pressure

Change in brachial systolic pressure with age

O'Rourke *Am J Hypertens* 2002;15:426-44
Age-related changes of PWV in normals; central elastic >> peripheral muscular artery

O'Rourke Am J Hypertens 2002;15:426-44
Reflection and cf–PWV

- Relationship between time from wave foot to initial systolic inflection of the carotid pressure waveform (ordinate), and carotid–femoral pulse wave velocity (abcissa).

Method of calculating time delay is illustrated as Δt. PP = pulse pressure.

O'Rourke Am J Hypertens 2002;15:426-44
Augmentation index

Augmentation Index

TIME

AP

PP
Aortic and radial pressure wave

Aortic pressure wave
- $PP = (P_s - P_d) = (P_i - P_d) + (P_s - P_i)$.
- $Al_a = (P_s - P_i)/(P_s - P_d)$
- Wasted LV pressure energy $(E_w) = 2.09\Delta tr (P_s - P_i)$

Radial artery pressure wave
- $Al_r = P_2/P_1$
- Arterial stiffness $= \Delta T_{DVP}$, the difference between the first two peaks of the pressure wave

Nichols *Am J Hypertens* 2005;18:3S–10S
Age-related changes in wave reflection and pressure wave shapes

- Radial artery (left) and aortic pressure waves (right) in 3 healthy individuals
- **Solid arrows** identify the peak of the reflected waves, and **broken arrows** indicate the beginning upstroke of the reflected waves

Nichols *Am J Hypertens* 2005;18:3S–10S
Radial and carotid pressure waveforms

- Radial (left) and carotid (right) pressure waveforms, plotted as ensemble-averaged waveforms by decade, in a cohort of 1004 normal Australian subjects.

O'Rourke *Am J Hypertens* 2002;15:426-44
Age–related changes in radial and aortic augmentation indices (%) and their relationship

Nichols *Am J Hypertens* 2005;18:3S–10S
Ascending aortic augmentation index

- Ascending aortic augmentation index (augmentation pressure/pulse height) in a combined group of US and Japanese patients with chest pain syndrome and normal coronary arteries, undergoing cardiac catheterization.

O'Rourke *Am J Hypertens* 2002;15:426-44
Change in augmentation index

Change in augmentation index (augmentation/pulse height) in the radial artery (bottom line) and carotid artery (center line), calculated from data in B, compared to the regression line for aortic augmentation index in C.

O'Rourke Am J Hypertens 2002;15:426-44
Arterial Stiffness, Wave Reflections, and the Risk of Coronary Artery Disease

Effects of atenolol & losartan on central and peripheral arterial pressure wave in a HTN patient

- Noninvasive recordings of radial artery pressure waves (left) and synthesized aortic pressure waves (right)
- Different effects of a β-blocker (atenolol) and an ARB (losartan) on central and peripheral arterial pressure wave shapes in a HTNsive patient.
- **Arrows** denote the beginning of the reflected wave. The waves are scaled to the pressures published in LIFE trial

Nichols *Am J Hypertens* 2005;18:3S–10S
Comparative effects of GTN and amyl nitrite on pulse wave reflection and augmentation index

- **Figure 1** Schematic of the effect of arterial stiffness on the peripheral wave form. P₁ represents the initial systolic pressure wave, traveling from the heart to the periphery.
- Figure a: In compliant large arteries (as in healthy young subjects), P₂, composite of the forward wave and reflected pressure waves, arrive back at the central aorta in diastole, augmenting diastolic blood pressure and coronary filling.
- Figure b: In stiff arteries (as in age with increasing CV risk), wave reflection occurs earlier and thus the systolic peak is augmented.
- Augmentation index; as the difference between P₁ and P₂ expressed as a percentage of the pulse pressure (PP)

Distensibility
Diurnal variation in arterial distensibility

- subjects, 12 healthy young volunteers; standard meals were served at 9 AM, 1 PM, and 7 PM. Subjects stayed in bed from 11 PM until 7 AM.
Association Between Local Pulse Pressure, Mean Blood Pressure, and Large-Artery Remodeling

- 43 healthy subjects and 124 never-treated hypertensive patients.
- Intima-media thickness and internal diameter of the carotid and radial arteries
- noninvasively high-definition echo-tracking devices.

Carotid PP was a strong independent determinant of carotid artery enlargement and wall thickening, whereas mean blood pressure and brachial pulse pressure were not, indicating the prominent influence of local pulsatile mechanical load on arterial remodeling.

These relationships were observed at the site of an elastic artery but not at the site of a muscular artery, suggesting the contribution of cyclic stretching to the pulse pressure–induced arterial remodeling.

Boutouyrie Circulation 1999;100:1387-1393
Association Between Local Pulse Pressure, Mean Blood Pressure, and Large-Artery Remodeling

- Univariate relationship between carotid internal diameter and IMT and either carotid PP (A), measured with applanation tonometry, or brachial PP (B), measured with Dinamap, in the entire population.

*Boutouyrie Circulation 1999;100:1387-1393*
Conclusion

- To estimate arterial stiffness
  - Systemic arterial stiffness
    - Augmentation Index
    - Systemic Arterial Compliance
  - Regional or segmental stiffness
    - Pulse Wave Velocity
  - Local Distensibility (eg aortic, carotid)

- Drugs to improve stiffness should be developed.