Regional vs ,local measures

Gold standard: flow or pressure probes

2D PC acquisitions generally provide a temporal resolution on the order of 10-30 ms.

Fourier velocity encoded (FVE) M-mode imaging is another MR method of deriving PWV. This method uses NMR excitation of a “pencil” beam aligned along a straight segment of a vessel, such as the aorta, to produce M-mode phase contrast images as shown in *Figure 7* (47,48).

Simpler 1D projection velocity methods have been proposed that provide a temporal resolution of ~2 ms (51-53). The

high temporal resolution of this technique allows for both regional and global measurements of PWV. While FVE M-mode imaging provides superior temporal resolution compared to other MR-based methods, the need to image along a straight vessel segment is a limitation, especially because vessels burdened with atherosclerotic disease tend to become tortuous over time

Westenberg method

Kröner ES, van der Geest RJ, Scholte AJ, et al. Evaluation of sampling density on the accuracy of aortic pulse wave velocity from velocity-encoded MRI in patients with Marfan syndrome. J Magn Reson Imaging 2012;36:1470-6.

Westenberg JJ, de Roos A, Grotenhuis HB, et al. Improved aortic pulse wave velocity assessment from multislice two- directional in-plane velocity-encoded magnetic resonance imaging. J Magn Reson Imaging 2010;32:1086-94.

**206 Wentland et al. MRI-based measurements of pulse wave velocity** © Cardiovascular Diagnosis and Therapy. All rights reserved. *Cardiovasc Diagn Ther* 2014;4(2):193-206 www.thecdt.org

acquired double obliquely to the aorta (similar to the view in *Figure 4A*) and are encoded with both anterior-posterior and superior-inferior velocity encoding (39,56). A center line is drawn along the aorta that provides both distance measurements as well as points along which velocity waveforms are derived via the combination of values from the two velocity encoding directions. The acquisition provides an effective temporal resolution of 6-10 ms. This PWV method has the advantage of high temporal resolution with the potential for regional PWV measurements. This method also has greater coverage of the vasculature compared to the FVE M-mode method. It should be noted that the acquisition time is relatively long—up to 14 minutes in duration depending on the subject’s heart rate.

## Cross sectional area:

It is prudent to briefly discuss the analysis of vessel cross-sectional area as a marker for vascular stiffness (26,57). The principle behind this technique is that the change in vessel area is related to the vessel compliance; compliance is lower in vessels burdened with atherosclerosis. A time-resolved slice orthogonal to a vessel is acquired; the area of the vessel is measured in both systole and diastole. Compliance, C, is then measured by dividing the change in area, ΔA, by pulse pressure, ΔP, as measured by a sphygmomanometer, such that *C=*Δ*A/*Δ*P*. This method of measuring arterial stiffness does not require sophisticated software; additionally, highly focal points of the vasculature can be assessed. However, the highly focal nature of this technique can be a disadvantage, because the technique is more subject to sampling error such that the results can either under- or over-estimate disease burden depending on the particular plane of analysis. Furthermore, the technique requires high spatial resolution to accurately assess changes in vessel area. A more thorough discussion of methodsfor quantifying compliance is discussed by Oliver and Webb (58)

26. Mohiaddin RH, Firmin DN, Longmore DB. Age-related changes of human aortic flow wave velocity measured noninvasively by magnetic resonance imaging. J Appl Physiol (1985) 1993;74:492-7.

57. Mohiaddin RH, Underwood SR, Bogren HG, et al. Regional aortic compliance studied by magnetic resonance imaging: the effects of age, training, and coronary artery disease. Br Heart J 1989;62:90-6.

58. Oliver JJ, Webb DJ. Noninvasive assessment of arterial stiffness and risk of atherosclerotic events. Arterioscler Thromb Vasc Biol 2003;23:554-66.

## QA method

Compliance also can be used to derive PWV such that *PWV=*Δ*Q/*Δ*A*; this is termed the QA method (59-61). PWV is calculated by plotting vessel area versus flow as measured in a time series of a 2D PC slice through a vessel. A best fit line is fitted to the early systolic portion of this plot to calculate slope; the slope is equivalent to PWV. Ibrahim *et al*. showed good agreement between multi-

59. Vulliémoz S, Stergiopulos N, Meuli R. Estimation of local aortic elastic properties with MRI. Magn Reson Med 2002;47:649-54.

60. Peng HH, Chung HW, Yu HY, et al. Estimation of pulse wave velocity in main pulmonary artery with phase contrast MRI: preliminary investigation. J Magn Reson Imaging 2006;24:1303-10.

61. Herold V, Parczyk M, Mörchel P, et al. In vivo measurement of local aortic pulse-wave velocity in mice with MR microscopy at 17.6 Tesla. Magn Reson Med 2009;61:1293-9.

QA in PA: 62. Ibrahim el-SH, Shaffer JM, White RD. Assessment of pulmonary artery stiffness using velocity-encoding magnetic resonance imaging: evaluation of techniques. Magn Reson Imaging 2011;29:966-74.

Long processing times for QA

33. Ibrahim el-SH, Johnson KR, Miller AB, et al. Measuring aortic pulse wave velocity using high-field cardiovascular magnetic resonance: comparison of techniques. J Cardiovasc Magn Reson 2010;12:26.

## Avolio 2018

see fig 10.6 age dependence of PWV

PWV

is selected as an index of vascular stiffness, as it is

solely dependent on the properties of the arterial

system.

Overall arterial function is essentially determined

by the compliance of the large arteries and resistance

of the peripheral vessels, as characterized

by the Windkessel model. Peripheral muscular

arteries are stiffer than central aorta. As such,

the increased stiffness found in hypertensive

patients is mostly due to reduced compliance in

the aorta rather than that in peripheral arteries,

(e.g., radial or femoral arteries). The elastic modulus

is much higher in these peripheral arteries

than in the central aorta, for both sexes [26]. Thus,

a change in increased PWV is less if measured in

the radial artery of hypertensive patients than that

in the central aorta.

## Nichols 2015

As the arterial system becomes stiffer,

there is a marked increase in central systolic and pulse

pressures and wasted LV energy, along with a decrease in

pulse pressure amplification.

## Withlock 2015 JACC

Great paper to introduce biomechanics

Arterial compliance represents the

change in the diameter of a vessel divided by the

change in the distending pressure within the vessel.

Arterial distensibility is similar to compliance but is normalized for the size of the vessel.

Equation 2:

Distensibility

\_

1

mmHg \_ 103

\_

¼

ðSA \_ DAÞ

DA \_ ðSBP \_ DBPÞ

where SA is the maximal systolic area, DA is the

minimal diastolic area, SBP is systolic blood pressure

millimeters of mercury (mm Hg), and DBP is diastolic

blood pressure.

Figure 1 is awesome

Descriptively, PWV represents

the measure of how fast the systolic pulse from

a volume of blood being ejected from the left

ventricle travels down the aorta. In general, a stiffer

more rigid vessel transmits the pulse faster (higher

PWV). PWV and distensibility are inversely related to

one another by the Bramwell-Hill equation (23):

PWV ¼ 3:57

Ffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffi

Distensibility

In clinical practice, PWV is calculated by recording

(commonly using transducers located at the carotid

artery and femoral artery, hence carotid-femoral PWV

[cfPWV]) 2 locations separated by a known distance.

Accurate PWV determinations rely on several factors.

First, one must accurately measure the distance

along the blood vessel that the pulse wave has traversed.

Body surface estimations can be affected by

body habitus, such as obesity, or by tortuosity of the

blood vessels that is unknown when simply estimating

the path by looking at the body surface. Second,

the fact that blood is flowing in opposite

directions in the carotid and femoral arteries needs to

be taken into account either by measurement technique

or converted via formula (24). Finally, cfPWV is

considered a global measure of aortic stiffness; however,

the ascending aorta from the root to the takeoff

of the right brachiocephalic is not included due to

measuring from the peripheral sites of the carotid

and femoral arteries. This area may represent a clinically

important source of aortic stiffening in certain

disease states.

## Fortier 2018

PWV and pressure are related nonlinearly.

## Calvacante 2011

Awesome paper. Good definitions

Cite paper that compares MRI measures and tonometry!!!!!!!! Better data for MRI

Great future direction section!!