Whole-body vs. regional arterial stiffness: implications for a single Windkessel model of the circulation

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Objectives

The objectives of the present work were to:

1. Evaluate whether the stiffness of the Windkessel derived from radial arterial tau and systemic vascular resistance is related to central or peripheral arterial stiffness (pulse wave velocity squared)
2. Identify factors affecting radial arterial tau

Background

Tau

A time constant characterizing any rate of exponential decay, as for arterial pressure: P = A + B[exp(-t/tau)]

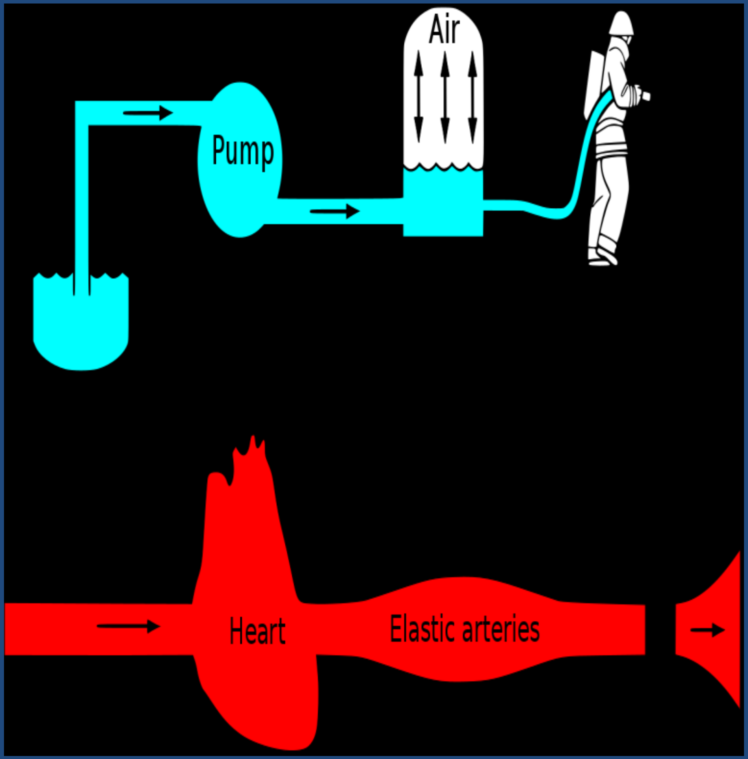
Windkessel (WK)

• German for '**air chamber,**' a rigid air-filled tank used in fire fighting, with intermittent well pumps, etc.) to damp the variation in water flow and make it more constant (Upper panel).

• In physiology, an '**elastic reservoir**' that damps BP pulsatility, making peripheral blood flow more constant (Lower panel).

• A WK has a characteristic "stiffness:"

Stiffness = tau/resistance



Methods

Experimental cohort

- **Selected cohort** to match the age-BP relationship in U.S. cross-sectional (NHANES) data.

***Hemodynamic determinations*:**

- **BP** - oscillometry
- **Stroke volume and systemic vascular resistance** - echocardiography
- **Central and peripheral arterial stiffness** (Heart-femoral and femoral-ankle PWV; from Colin VP1000).
- **Radial pressure waveform (tonometry)** - Sphygmocor.

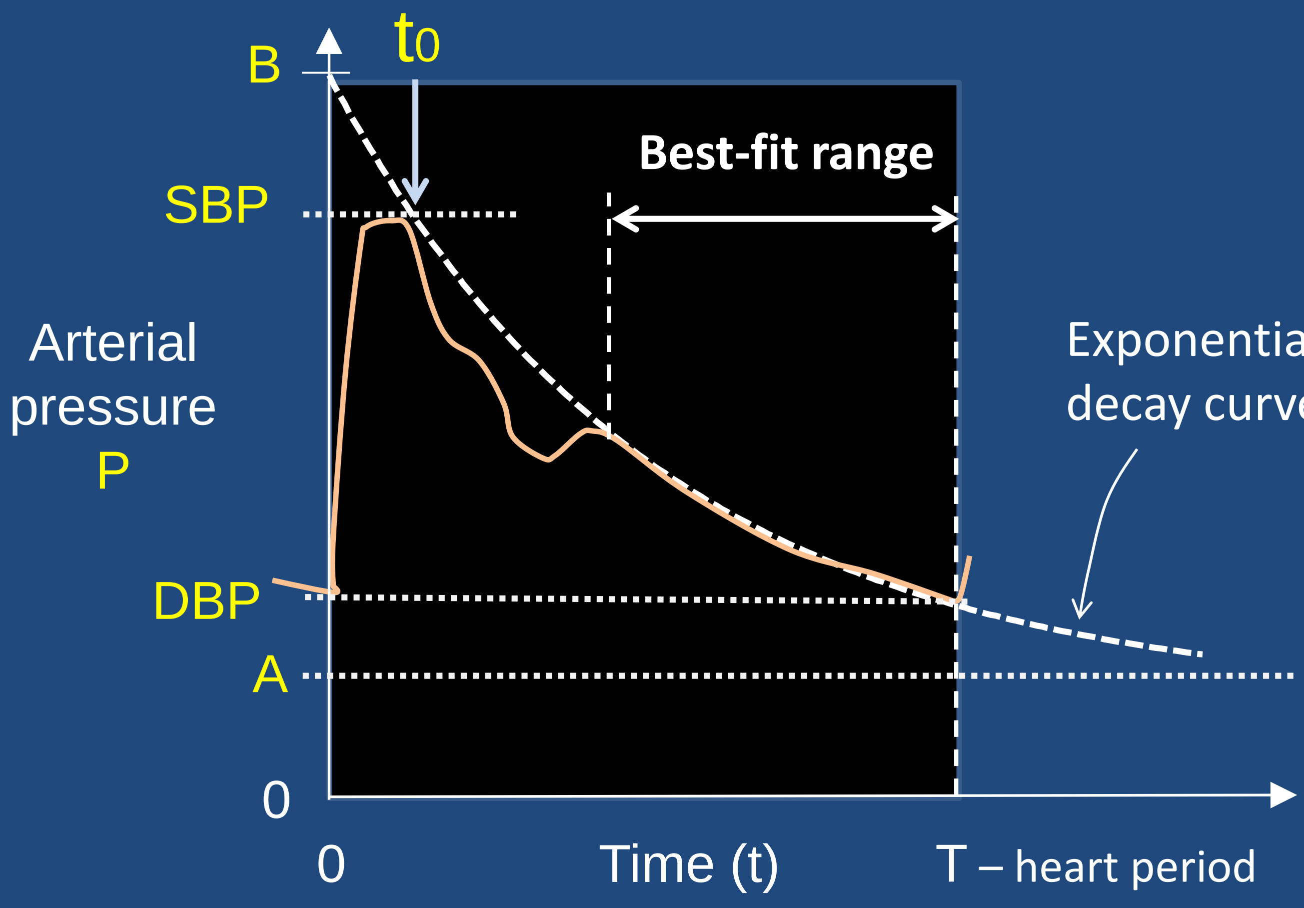
***Derived variables (tau, t0, t0/T, A)*:**

- **Photo-digitization** of Sphygmocor waveforms.
- **Pressure decay modeling -** best-fit curve for P = A + B*exp(-t/tau).
- **Wall-to-lumen ratio -** derived from Bramwwell-Hill (h/r ~ PP/SV * PWV^2)
- **WK Stiffness (tau/SVR) modeling** - multilinear stepwise backward regression for 6 models of “non-colinear” variables.

Estimation of tau

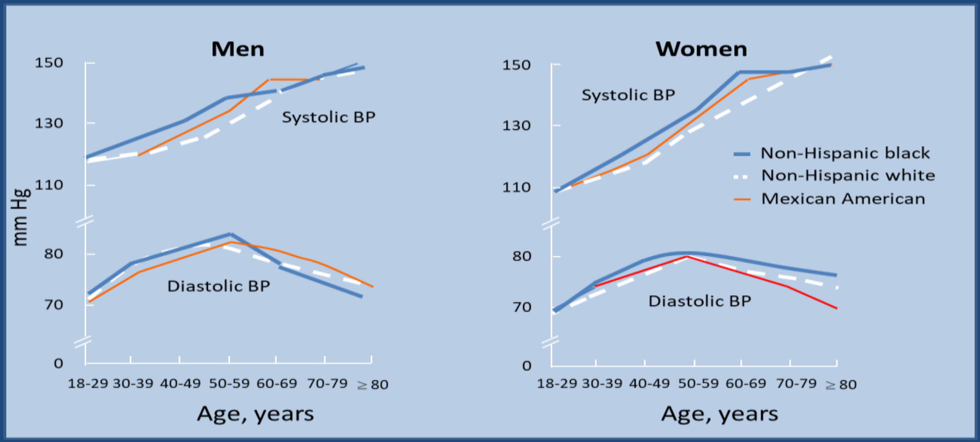
Best-fitted model → $P = A + B*exp(-t/tau)$ → P = SBP at t=t0

t_0 is the hypothetical start of the exponential decay phase.

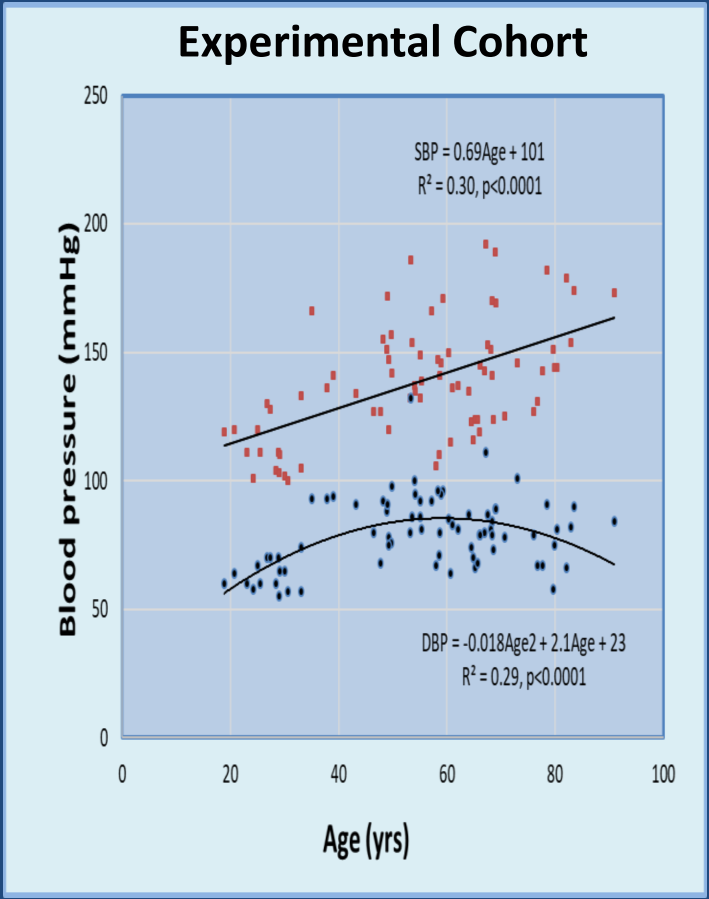


Age and BP in the Experimental Cohort

NHANES III: Age and BP



Burt VL, Whelton PJ, et al. *Hypertension*. 1995;25:305-313.



Subject Characteristics

(a typical adult population; also similar to NHANES III)

Demographic	
n	75
Age, y	54 (18)
% male/female	56/44
Body surface area, m^2	1.97 (0.22)
Weight, kg	83.9 (16.7)
Height, cm	167 (9.6)
Hemodynamic	
Brachial SBP, mmHg	137 (23)
Brachial DBP, mmHg	79 (14)
Brachial MAP, mmHg	105 (19)
Brachial PP, mmHg	59 (16)
Heart-femoral PWV (corr), m/sec	9.40 (3.19)
Femoral-ankle PWV (corr), m/sec	11.0 (2.34)
Heart rate, beats/min	67 (12)
Cardiac Output, L/min	5.0 (1.2)
Stroke Volume, ml	74.5 (17.3)
SVR, dyne.sec/cm^5	1610 (415)
Wall/Lumen ratio, units	1.6 (0.9)
Model-derived	
Tau, msec	216 (86)
t0, msec	260 (61)
t0/T	0.29 (0.08)
A, mmHg	76 (14)
B, mmHg	451 (510)
WK Capacitance, units	354 (199)
WK Stiffness, units	8.8 (4.8)

Mean (SD); corr, distance-corrected.

Correlations with stiffness indicators

Factor	WK Stiffness (SVR/tau)	Regional arterial stiffness	
		Aorta ($hfPWV^2$)	Leg ($faPWV^2$)
tau	--	**-0.05**	**-0.1**
t0	**0.48****	-0.18	-0.21
t0/T	**0.50****	**-0.23***	**-0.26***
Age	**-0.06**	**0.65****	**0.53****
SBP	**-0.01**	**0.65****	**0.54****
MAP	**0.06**	**0.53****	**0.42***
PP	**-0.07**	**0.61****	**0.52****
W/L	**0.20**	**0.75****	**0.69****

Pearson correlation coefficients;* p<0.05, ** p<0.001.

Multilinear regression models

Model number						
Factor	1	2	3	4	5	6
1	AGE	AGE	AGE	AGE	AGE	AGE
2	HEIGHT	HEIGHT	HEIGHT	HEIGHT	HEIGHT	HEIGHT
3	SV	SV	SV	SV	SV	SV
4	BMI	BMI	BMI	BMI	BMI	BMI
5	HR	HR	HR	HR	HR	HR
6	SEX	SEX	SEX	SEX	SEX	SEX
7	W/L	W/L	W/L	W/L	W/L	W/L
8	DBP	DBP	MAP	DBP	SBP	PP
9	T0	T0	T0	T0	T0	T0
10	hfPWV2	faPWV2				
11	SVR	SVR	SVR	SVR	SVR	SVR
Model correlation coefficients and statistical significance						
	r=0.81 $p<10^{-6}$	r=0.81 $p<10^{-6}$	r=0.81 $p<10^{-6}$	r=0.81 $p<10^{-6}$	r=0.81 $p<10^{-6}$	r=0.82 $p<10^{-6}$

Factors contributing independently to WK stiffness (all models included):

SVR	$p < 10^{-6}$
t0	$p < 10^{-6}$
Constant	$p < 10^{-6}$
HR	$p < 10^{-5}$
W/L	$p = 0.013$

Conclusions

- A high fidelity arterial pressure decay constant (tau) can be derived from radial tonometry
- WK stiffness (calculated from radial arterial tau and SVR) is strongly associated with systemic vascular resistance and heart rate but is not related to any blood pressure indicator or to central or peripheral arterial stiffness (PWV^2).
- Further work will be required to fully interpret these findings.