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Arterial Stiffness for the Diagnosis and Prevention of Cardiovascular Risks

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Arterial stiffness measurement by ultrasound scanner

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Abstract

The aim of this study is to introduce for the first time an innovative model allowing us to determine the 3-D arterial stiffness. Arterial stiffness is increasingly recognized as a predictor of cardiovascular events but there is no method suited to calculate the arterial stiffness in 3-D. We measured 6 pairs of diameter, and diameter change of the right and the left common carotid artery of normal tension patients and their systolic and diastolic tensions. Then we calculate the arterial stiffness by introducing an hyper-elastic model in 3-D. Measurement of deformation of the common carotid artery on normal tension patients allows us to determine the average arterial stiffness of 474 kPa compared to 803 kPa recently published “Carotid and Aortic Stiffness : Determinants of Discrepancies ”, Stephane Laurent et als, Hypertension 47; 371-376 (Beaujon Hospital/Pr Leseche July 23, 2009)**.** Our hyper-elastic model takes into account the thickness and the incompressibility of the biological artery wall tissues.

Key Words : Arterial Stiffness, Compliance, Pulse Wave Velocity, Wall Thickness, Elasticity, Incompressibility, Hypertension, Hyper-elasticity, Diabetes, Smoking, Obesity and Overweight, Cholesterol, Aging.

1. Introduction

According to statistics from the World Health Organization (WHO), each year more than 17 million people die from cardiovascular disease (CVD), an estimated 31% of all deaths worldwide !

It is for these reasons that arteries gradually lose their elasticity and become more rigid than normal and that, without regular monitoring, even young people could be victims of CVD. We discovered about 20,000 people in Parisian region for 10 years [1] although the blood pressure (BP) is normal, but the pulse pressure (PP) difference from the systolic pressure (P_s) to diastolic pressure (P_d) is abnormal, for example, 138/68 mmHg (138-68 = 70 mmHg is too wide, while the value P_s = 138 is always less than 140 mm and the value P_d = 68 mm less than 90 mm according to WHO recommendations. However there is no 3-D method to determine AS precisely. We need to consider the value PP above, 6 pairs of diameter and thickness (h) (Fig.1) and 6 pairs of diameter and DC (Fig.2) to calculate AS by a hyper-elastic description [3-4] in a cylindrical coordinate system (Fig.6).

2- Method and equipment

2.1 Equipment

We start by measuring P_s (maximum systolic value), P_d (minimum diastolic value) and heart rate with an electronic blood pressure monitor, then we measure 6 pairs of thickness h = QIMT, diameter D (Fig.1) and the diameter change ΔD = DIST (Fig.2) by an ultrasound scanner Esaote. Then the stiffness of the wall is automatically calculated (Fig.3)

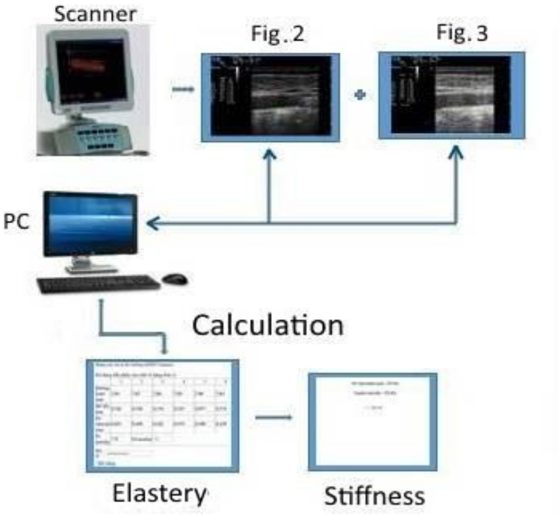
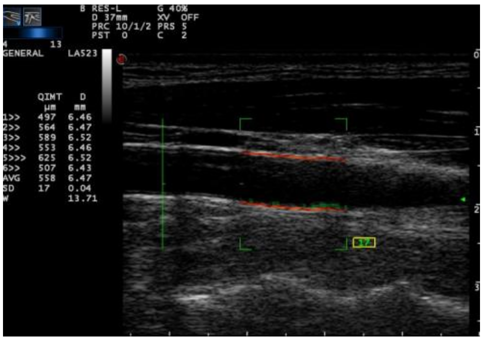


Fig.3. AS calculation by data acquisition from ultrasound scanner

The data saved (Fig.1&2) from the ultrasound scanner Esaote allow us to filling in 6 columns of the Elastery table and the software located in PC will automatically calculate AS coresponding to individual measure.

2.2 Method

We collection 6 pairs (QIMT, D) (Fig.1) and (DIST, D) (Fig.2) of 3 measures done at the left and the right common carotid artery with the use of an ultrasound scanner equipped with a 7.5 MHz linear probe (MyLab Twice, Esaote France, HCM City, Vietnam). This setup anables the AS calculation together with blood pressure P_s, P_d will be performed automatically (Fig.3).



```
   B RES-L       G 40%
     D 37mm      XV  OFF
     PRC 10/1/2  PRS 5
     PST  0      C   2
4            13
GENERAL       LA523

        QIMT    D
         µm     mm
1>>     497   6.46
2>>     564   6.47
3>>     589   6.52
4>>     553   6.46
5>>>    625   6.52
6>>     507   6.43
AVG     558   6.47
SD      17    0.04
W             13.71
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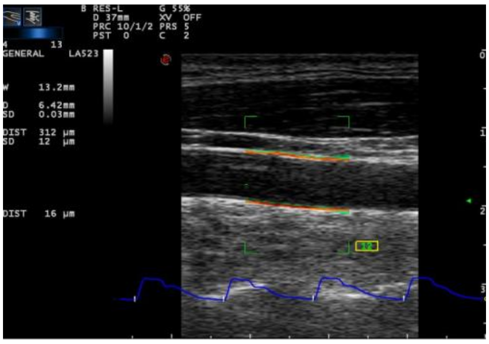
Fig.1. (QIMT, D) measures of thickness and diameter



```
   B RES-L       G 55%
     D 37mm      XV  OFF
     PRC 10/1/2  PRS 5
     PST  0      C   2
4            13
GENERAL       LA523

W       13.2mm

D       6.42mm
SD      0.03mm

DIST    312 µm
SD      12  µm


DIST     16 µm
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Fig.2. (D, DIST) measures of diameter and diameter change ΔD=DIST

3- Results and discussion

3.1 Results

Measures are stored (Table 1) allowing us to calculate the arterial stiffness by a hyper-elastic equation of deformation and stress exerted on the wall, in a cylindrical coordinate system (Fig.6), with thickness h (QIMT) and invariable volume (Fig.8). We must determine the stress in the circumferential direction e_θ (Fig.6) of a cross section. The measures of normal hypertension patients are averaged summed and used for 3-D calculation E_H=474 kPa.

Table 1 : **Arterial measures**

Arterial parameters	Normal Tension N=8
Age	34 ±32
Man / Woman	04/04/08
Weight (kg)	52±16
Size (cm)	162±8
Body index (kg/m2)	19,7±6,2
Systolic pressure Ps (mmHg)	112±15
Diastolic pressure Pd (mmHg)	72±12
Pulse pressure (PP=Ps-Pd)) mmHg	40±13
Diameter (D) mm	6,67±1,2
Thickness h (QIMT)	0,514±0,179
Diamter change (QAS) mm	0,430±0,211
Heart rate	76±25
Arterial stiffness (E_H hyper-elastic) kPa	474

3.2 Discussion

We will compare AS determined by our 3-D hyper-elastic equation (stiffness E_H=474 kPa, Table 1) with that published in a recent publication [2] Carotid Stiffness (CS) or Pulse Wave Velocity (PWV) = 7.79 m/s (Normal Tension, NT) (Table 2), 1-D stiffness E= 803 kPa (according to the Moens-Korteweg equation $PWV^2 = Eh/D\rho$), thickness h, diameter D and blood mass density ρ=1058 kg/m^3. The error committed by this classical equation is 70% in relation to 3-D hyper-elastic model.

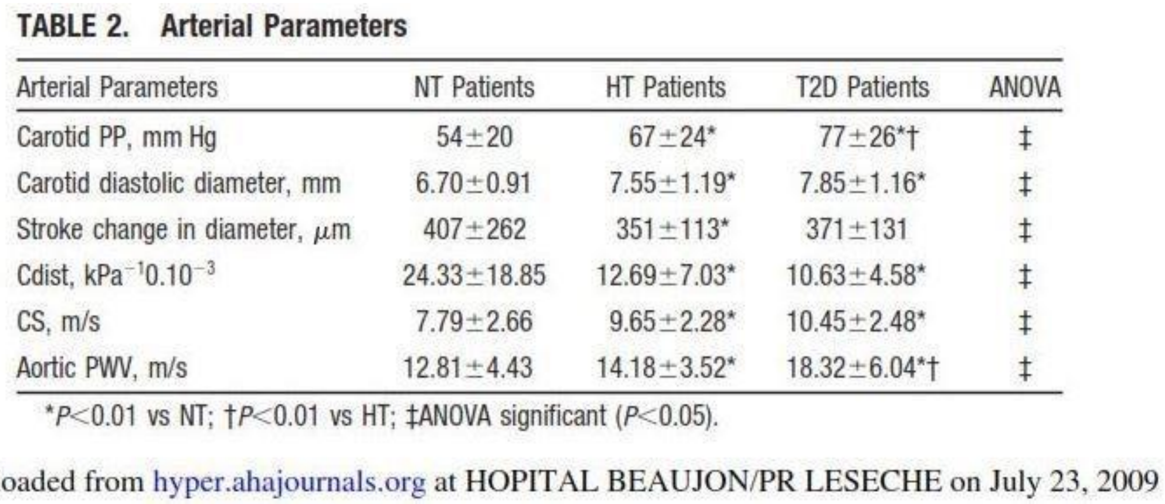


TABLE 2. Arterial Parameters

Arterial Parameters	NT Patients	HT Patients	T2D Patients	ANOVA
Carotid PP, mm Hg	54±20	67±24*	77±26*†	‡
Carotid diastolic diameter, mm	6.70±0.91	7.55±1.19*	7.85±1.16*	‡
Stroke change in diameter, μm	407±262	351±113*	371±131	‡
Cdist, $kPa^{-1}0.10^{-3}$	24.33±18.85	12.69±7.03*	10.63±4.58*	‡
CS, m/s	7.79±2.66	9.65±2.28*	10.45±2.48*	‡
Aortic PWV, m/s	12.81±4.43	14.18±3.52*	18.32±6.04*†	‡

*$P<0.01$ vs NT; †$P<0.01$ vs HT; ‡ANOVA significant ($P<0.05$).

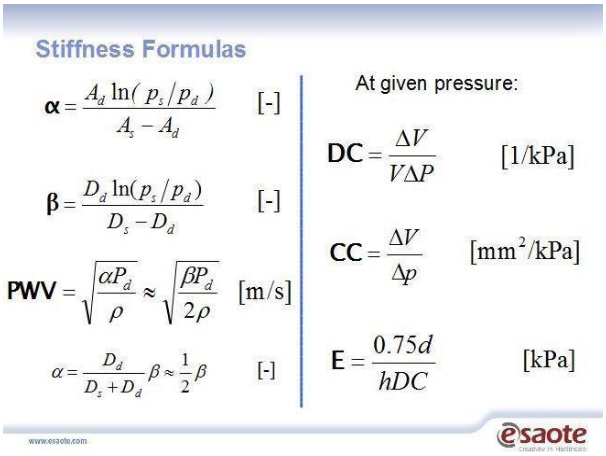
3.3 Histological analysis

1-D models

PWV pulse wave velocity [2]
It is calculated by PWV = L/ΔT, L is the length and ΔT is the duration of the travel time and the stiffness (E, $E_{inc,}$, YEM) deduced according to the Moens-Korteweig equation above while the 3-D stiffness value E_H will be determined from a hyper-elastic model.

DC (Distension Coefficient) and **CC** (Compliance Coefficient) (Fig.5) are often used to determine AS of a 1-D equation, neglecting the thickness of the wall and according to the simple formula of a thin cylinder having negligible thickness h compared to D ($h/D \approx 0$) (Fig.4)

Meinders and Hoeks formula (Fig.5) to calculate 1-D stiffness E, with the thickness h negligible ($h/D \approx 0$) compared to D, h=QIMT (Fig.1). This formula in relation with PWV written as E=0.75(d/hDC) comes from the equation $v^2 = (\partial^2P/\partial t^2).(\partial^2P/\partial x^2)$, that is to say approximately equal to A/ρ . $(\Delta A/\Delta P) \approx Eh/D\rho$ (Moens-Korteweig formula).



Stiffness Formulas

$$\alpha = \frac{A_d \ln(p_s/p_d)}{A_s - A_d} \quad [-]$$

$$\beta = \frac{D_d \ln(p_s/p_d)}{D_s - D_d} \quad [-]$$

$$\text{PWV} = \sqrt{\frac{\alpha P_d}{\rho}} \approx \sqrt{\frac{\beta P_d}{2\rho}} \quad [\text{m/s}]$$

$$\alpha = \frac{D_d}{D_s + D_d}\beta \approx \frac{1}{2}\beta \quad [-]$$

At given pressure:

$$\text{DC} = \frac{\Delta V}{V\Delta P} \quad [1/\text{kPa}]$$

$$\text{CC} = \frac{\Delta V}{\Delta p} \quad [\text{mm}^2/\text{kPa}]$$

$$\text{E} = \frac{0.75d}{hDC} \quad [\text{kPa}]$$

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Fig.5. Stiffness formulas

Young, Peterson [5]
Round tube having for radius R ($h/R \approx 0$), stress $\sigma = E.\varepsilon$, $\Delta P = EP.(\Delta D/D)$ and the stiffness value of Peterson EP will be equal to $EP = \Delta P.(D / D_d)$

Incremental elastic modulus [6-9]
Thin cylinder (Fig.4) having radius R, diameter D and negligible thickness h ($h/R \approx 0$), the stress in a circumferential direction of the surface of a cross section is equal to $\sigma = \Delta P.R / h = \Delta P.D/2h$ because by definition $\sigma = E.(\Delta R/R) = \Delta P.D/2h$ and YEM (Young Elastic Modulus, Young Stiffness EY) will have as value $YEM = \Delta P.D^2/2h.\Delta D$ which is an average value in the middle of the cross section thickness, or incremental elastic modulus E_{inc}.

Note The formula E = 0.75 (D/h.DC) (Fig.5) is established in an incompressible medium with rigid wall, $v^2 = (\partial^2P/\partial t^2).(\partial^2P/\partial x^2)$, approximately equal to A/ρ $(\Delta A/\Delta P) \approx Eh/D\rho$ and written as D/h.DC (in addition to the coefficient 0.75), assuming the artery as a thin cylinder and negligible thickness compared to the diameter, h << D to solve the problem 1-D equation, σ approximately equal to ΔP.D /2h in the circumferential direction of a cross section, and $\sigma \approx 0$ in the radial direction (Fig.4). In reality we must solve the 3-D problem in a system of cylindrical coordinates (r, θ, z), e_r radial, e_θ circumferential and e_z axial (Fig.6).

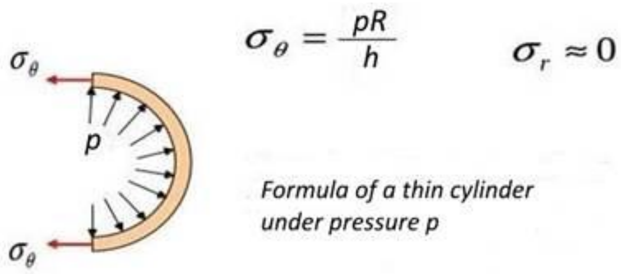
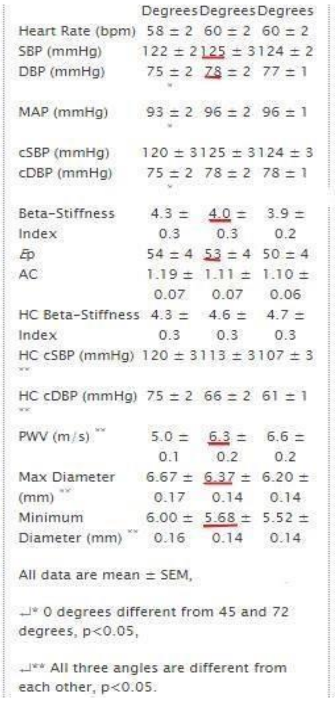


Fig.4. Thin cylinder under pressure

Since the 1980s, we have been content to measure the thickness of the arterial wall, but this parameter, if it has a relationship with pathologies [9], has no relation with artery stiffness.

More recently the measure of the **Cadio-ankle vascular index CAVI** [10] (Fig.7) whose formulation depend on PWV. For example Beta-Stiffness = 4.0 (Fig.7) (Ep = 53 kPa, PWV = 6.3 m/s), the wall stiffness was equal to E=442 kPa, in one hand according to the Moens-Korteweg equation, and the other hand 53 kPa as published (Ep = 53 kPa) (Fig.7). And also from these measurements published (SBP = 125 mmHg, DBP = 78 mmHg, Max diameter = 6.37 mm, Min diameter = 5.68 mm), we can deduce : PP (SBP - DBP) = 47 mmHg, diameter change (6.37 - 5.68 = 0.69 mm), thickness (0.45 mm) the stiffness should be equal to E_H= 300 kPa according to our proposed hyper-elastic 3-D equation to be compared to E=442 kPa 1-D Moens-Korteweg formula.



	Degrees	Degrees	Degrees
Heart Rate (bpm)	58 ± 2	60 ± 2	60 ± 2
SBP (mmHg)	122 ± 2	125 ± 3	124 ± 2
DBP (mmHg)	75 ± 2 *	78 ± 2	77 ± 1
MAP (mmHg)	93 ± 2 *	96 ± 2	96 ± 1
cSBP (mmHg)	120 ± 3	125 ± 3	124 ± 3
cDBP (mmHg)	75 ± 2 *	78 ± 2	78 ± 1
Beta-Stiffness Index	4.3 ± 0.3	4.0 ± 0.3	3.9 ± 0.2
Ep	54 ± 4	53 ± 4	50 ± 4
AC	1.19 ± 0.07	1.11 ± 0.07	1.10 ± 0.06
HC Beta-Stiffness Index	4.3 ± 0.3	4.6 ± 0.3	4.7 ± 0.3
HC cSBP (mmHg) **	120 ± 3	113 ± 3	107 ± 3
HC cDBP (mmHg) **	75 ± 2	66 ± 2	61 ± 1
PWV (m/s) **	5.0 ± 0.1	6.3 ± 0.2	6.6 ± 0.2
Max Diameter (mm) **	6.67 ± 0.17	6.37 ± 0.14	6.20 ± 0.14
Minimum Diameter (mm) **	6.00 ± 0.16	5.68 ± 0.14	5.52 ± 0.14

All data are mean ± SEM,

↵* 0 degrees different from 45 and 72 degrees, p<0.05,

↵** All three angles are different from each other, p<0.05.

Fig.7. Cardio-ankle vascular index CAVI, Beta-Stiffness (Faseb Journal)

3-D Hyper-elastic description [3-4,11,12, 20]

The cross section (x, y) of an artery segment in absolute coordinate system (x, y, z) and relative coordinate system (e_θ, e_r, e_z) (Fig.6). The circumferential stress σ_θ is variable with the radius of the carotid artery R_M according to the position of the point M ($R_1 < R_M < R_2$) and the value varies if the point located on the internal or external wall (Fig.6), which is not the case of a thin cylinder (Fig.3). The circumferential stress σ_θ on the internal wall is solved using a cylindrical coordinate system (Fig.6), considering the Poisson coefficient v = 0.5 (incompressible medium and invariable volume, Fig.8). Therefor σ_θ is precise and different from that calculated approximately (Fig.4) where v < 0.5 (compressible medium and variable volume, Fig.4).

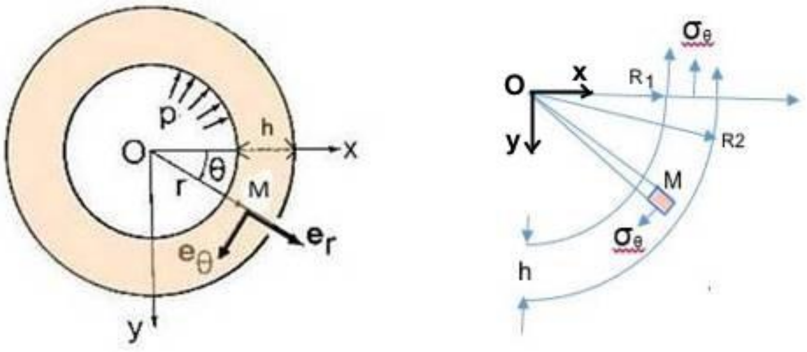


Fig.6. Cylindrical coordinate for a cross section

The Poisson coefficient was not taken into account in the 1-D model, the thickness (h/D ≈ 0) is neglected and the volume is compressible (Poisson coefficient ν<0.5). Or the wall artery tissue volume must be unchanged under load F, Poisson coefficient ν=0.5 (Fig.8). Initial volume (under diastolic pressure) equal to final volume (under systolic pressure) and remained unchanged during heartbeat (incompressibility, ν=0.5).

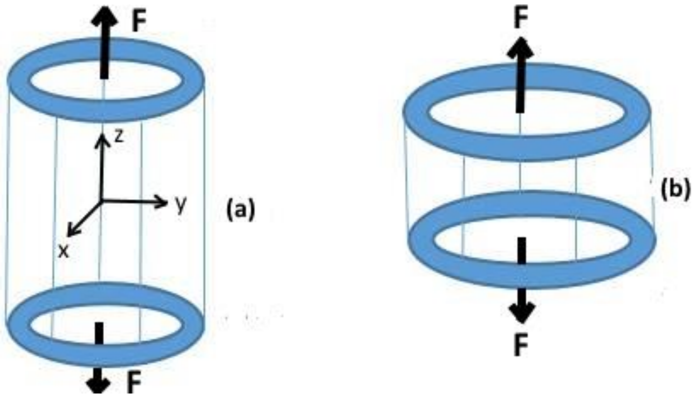


Fig.8. Arterial wall volume unchanged under load F : (a) before and (b) after load

4- Conclusion

We propose a 3-D hyper-elastic description taking into account thickness and incompressibility of the artery wall with a nonlinear stress-strain relation derived from a strain energy density function [3, 4]. The comparison with classical 1-D linear stress-strain behavior described by pulse wave velocity (PWV) [13-17], incremental elastic modulus (E_{inc}), Young elastic modulus (YEM), compliance coefficient (CC), distension coefficient (DC) and beta-stiffness (CAVI) recently published [10] have shown us that the error compared to a nonlinear model was 64% in relation with our 3-D hyper-elastic model [11, 12, 20].

5- Perspectives

When the carotid arterial stiffness will be calculated for normal hypertension subjects we shall be able to perform others studies as hypertension, diabetes, smoking, overweight, cholesterol origin of arterial stiffness increased. Arterial stiffness is as great as the risk of cardiovascular disease is important and finally we can draw a survival curve for lifetime estimated. Others applications to promote physical exercise [18] diet how to be healthy [19] and regularly control the artery stiffness. To do so we must confirm our result of normal hypertension subjects (E_H=474 kPa) with more eligible individuals aged from 20 to 80 years.

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