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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 808 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 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), which represents 29% of all death !

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 cardiovascular disease. We discovered about 20,000 people in Parisian region for 10 years [6] although the blood pressure is normal, but the pulse pressure PP (difference between the systolic pressure and 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 the artery stiffness precisely. We need to consider the pulse pressure PP above, 6 pairs of diameter and thickness (Fig.1) and 6 pairs of diameter and diameter change (Fig2) to calculate the artery stiffness by an hyper-elastic description [1, 13, 14, 15, 16] in a cylindrical coordinate system (Fig.4).

2- Method and equipment

2.1 Equipment

We start by measuring the blood pressures 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 values h = QIMT, diameter D (Fig.1) and the diameter change ΔD = DIST (Fig.2) with an ultrasound scanner. Then the stiffness of the wall is automatically calculated (Fig.5)

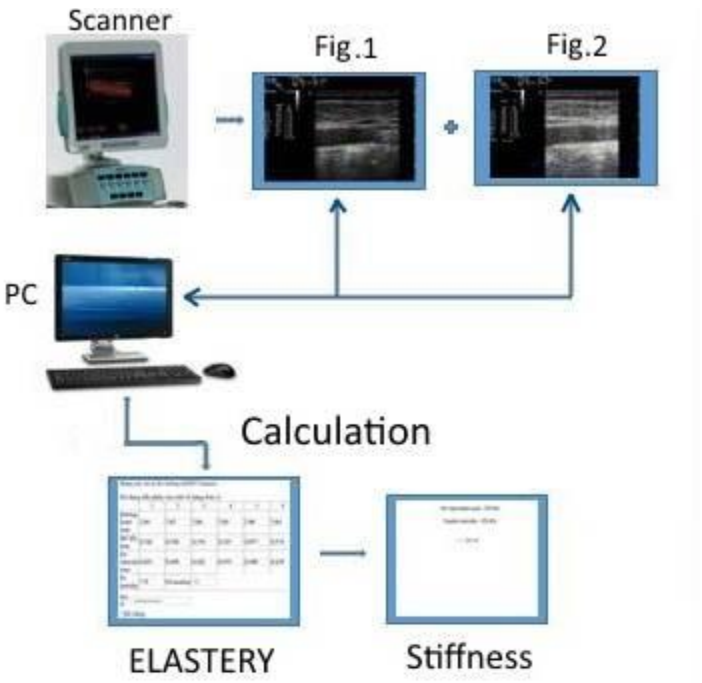

Fig.5. Artery stiffness with data acquisition for calculation

Scanner ⟹ (Diameter, Thickness) + (Diameter, Diameter change)

⇓

Calculation

2.2 Method

We collection 6 pairs (QIMT, D) (Fig.1) and (DIST, D) (Fig.2) of 3 measurements 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 measurement of IMT together with blood pressure P_s, P_d. The stiffness calculation was performed automatically (Fig.5).

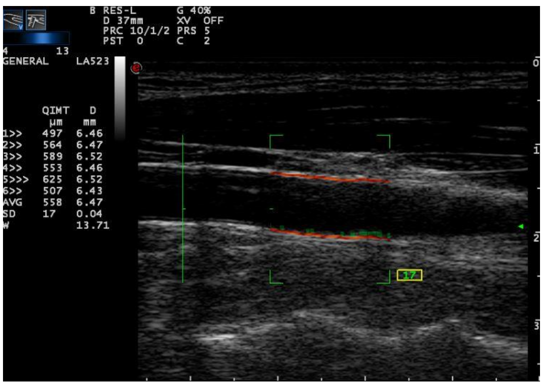

Fig.1. (QIMT, D) measurements of thickness and diameter

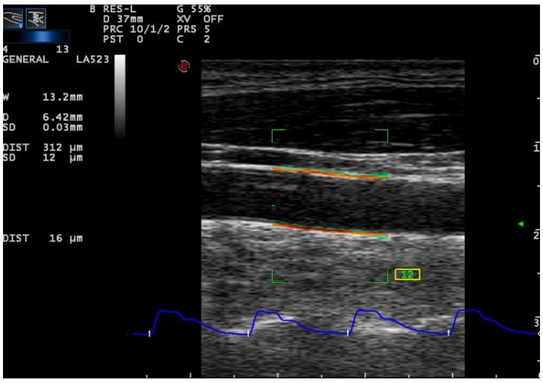

Fig.2. (DIST, D) measurements of diameter and diameter change

3- Results and discussion

3.1 Results

The measurement results are stored (Table 1) allowing us to calculate the arterial stiffness using an hyper-elastic equation of deformation and stress exerted on the wall, in a cylindrical coordinate system (Fig.4), with thickness h (QIMT) and invariable volume (Fig.8). We must determine the stress in the circumferential direction e_θ (Fig.4) of a cross section. The individual measures of normal hypertension patients are averaged summed and used for stiffness calculation of 474 kPa.

Table 1: Arterial parameters

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 the arterial stiffness determined by our hyper-elastic equation with that published in a recent publication [4] the Carotid Stiffness (CS) or Pulse Wave Velocity (PWV) = 7.79 m/s (Normal Tension, NT) (Table 2), stiffness 808 kPa (according to the Moens-Korteweig equation $PWV^2 = Eh/D\rho$) which is too high compared to 474 kPa.

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 ($P<0.05$).

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3.3 Histological analysis

1-D models

- **PWV pulse wave velocity**

It is calculated by $PWV = L/\Delta T$, L is the length and ΔT is the duration of the travel time and the stiffness deduced according to the Moens-Korteweig equation above while the 3-D stiffness value will be determined from an hyper-elastic model.

- **DC** (Distensibility Coefficient) and **CC** (Compliance Coefficient) [5] (Fig.6) are often used to determine the arterial stiffness of a 1-D equation, neglecting the thickness of the wall and according to the simple formula of a thin cylinder having negligible thickness compared to the diameter (Fig.3) ($h/D \approx 0$) (Fig.4).

- **Meinders and Hoeks** formula [5] (Fig.6) to calculate the stiffness, with the thickness h negligible ($h/D \approx 0$) compared to the diameter (D), h=QIMT (Fig.1), diameter at the point of measurement (D), cross-section area (A) of an artery segment and the pressure at the measuring point (ΔPL). This formula also comes from the equation $v^2 = (\partial^2P/\partial t^2).(\partial^2P/\partial x^2)$, that is to say approximately equal to $A/\rho \, . \, (\Delta A/\Delta P) \approx Eh / D\rho$ (Moens-Korteweig formula).

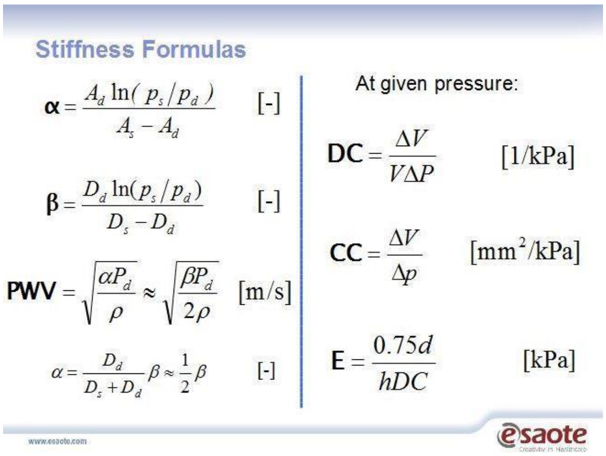

Fig.6. Stiffness formulas

- **Peterson** [9] : Round tube having for radius R (h/R ≈ 0), stress σ = E.ε , ΔP = EP.(ΔD/D) and the stiffness value of Peterson EP will be equal to EP = ΔP.(D / D_d)

- **Young** [3, 6, 7, 9, 10, 11, 12, 17, 18, 19] : Thin cylinder (Fig.3) having radius R, diameter D and negligible thickness h (h/R ≈ 0), the stress in a tangential direction of the surface of a cross section is equal to σ = ΔP.R / h = ΔP.D/2h because by definition σ = E.(ΔR/R) = ΔP.D/2h and YEM (Young Elastic Modulus, Young Stiffness EY) will have as value YEM = ΔP.D^2/2h.ΔD which is an average value in the middle of the cross section thickness, or incremental elastic modulus E_{inc}.

Note The formula EM = 0.75 (D/h.DC) (Fig6) 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 (ΔA/ΔP) ≈ Eh/Dρ 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 σ ≈ 0 in the radial direction (Fig.3). 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.4).

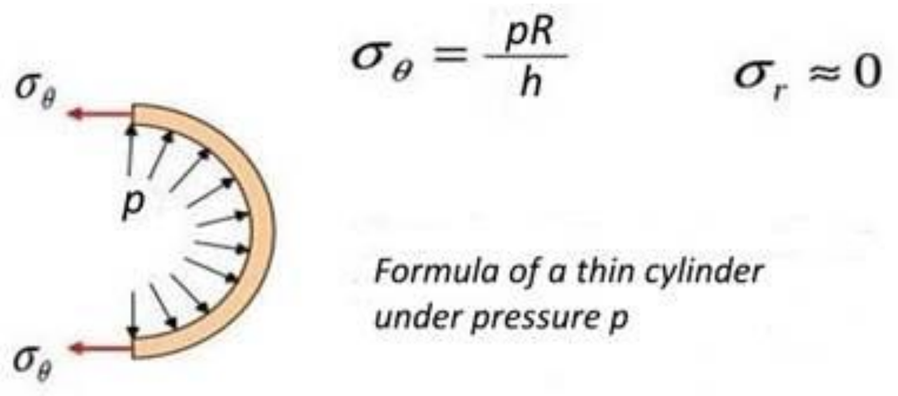

Fig.3. Thin cylinder under pressure

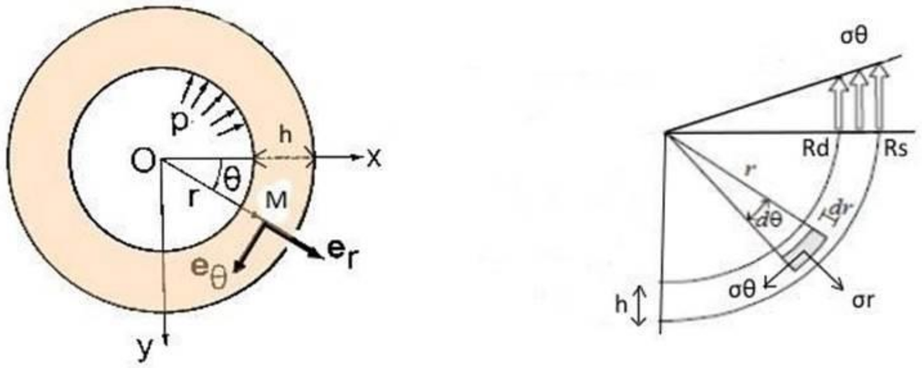

Fig.4. Cylindrical coordinate for a cross section

▪ 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 [17], has no relation with artery stiffness.

▪ More recently the measure of the Cadio-ankle index CAVI [18] (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 520 kPa, in one hand according to the Moens-Korteweig 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 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 300 kPa according to our proposed hyper-elastic 3-D equation to be compared to 520 kPa above.

	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 index, Beta-Stiffness (Faseb Journal)

3-D Hyper-elastic description

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.4). The circumferential stress σ_θ is variable with the radius of the carotid artery RM according to the position of the point M (Rd <RM <Rs) and the value varies if the point located on the internal or external wall (Fig.4), 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.4), considering the Poisson coefficient $\nu = 0.5$ (incompressible medium and invariable volume, Fig.8). Therefor σ_θ is precise and different from that calculated approximately (Fig.3) where $\nu < 0.5$ (compressible medium and variable volume, Fig.3).

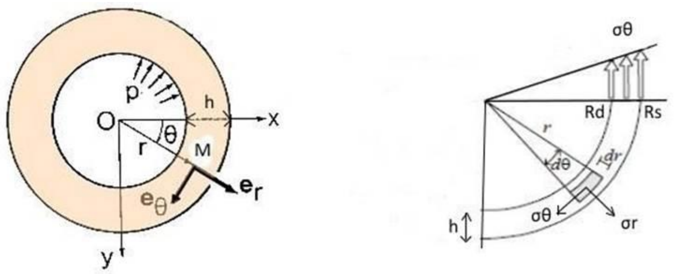

Fig.4. Cylindrical coordinate for a cross section

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

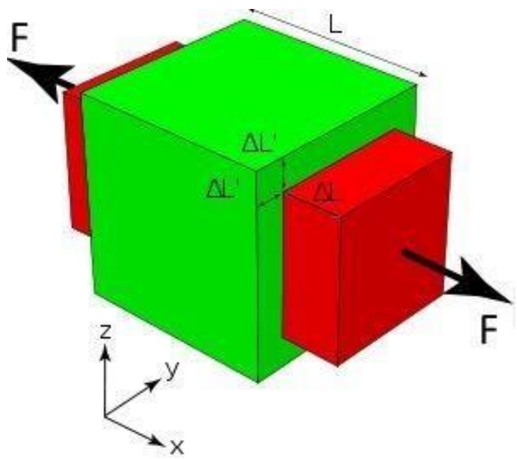

Fig.8. Volume incompressible under load F

4- Conclusion

We propose a 3-D hyper-elastic description taking into account the thickness and the incompressibility of artery wall with a nonlinear stress-strain relation derived from a strain energy density function [13, 14]. The comparison with classical 1-D linear stress-strain behavior described by pulse wave velocity (PWV), incremental elastic modulus (E_{inc}), Young elastic modulus (YEM), compliance coefficient (CC), distension coefficient (DC), indice β (CAVI) have shown us that the error compared to a nonlinear model was at least 64% compared to our 3-D hyper-elastic relation with the recent measurement usable published in the Faseb Journal [18].

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. Because they are origin of arterial stiffness increased compared to normal value. Arterial stiffness is as great as the risk of cardiovascular event is important and finally we can plot a survival curve. Others applications to promote physical exercise and diet how to be healthy and regularly control the artery stiffness. To do so we must confirm our result of 474 kPa with more eligible individuals aged from 20 to 70 years with normal hypertension subjects.

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7- Notes

$PP=P_s-P_d$: Pulse Pressure)

P_s : Systolic Pressure

P_d : Diastolic Pressure

h=QIMT : Thickness (h) (Quality Intima Media Thickness)

D : Diameter

D_d : Diastolic diameter

DIST : Diameter change

IMT : Intima Media Thickness

QIMT : Quality Intima Media Thickness

CC : Compliance Coefficient

DC : Distensibility Coefficient

CS : Carotid Stiffness

PWV : Pulse Wave Velocity

ρ : Blood mass density

σ : Stress

ε : Strain

ν : Poisson coefficient

E_{inc} : Incremental elastic modulus

YEM : Young elastic modulus

CAVI, Beta-Stiffness : Cardio-ankle vascular index