Original Article

Estimation of Carotid Artery Pulse Wave Velocity by Doppler Ultrasonography

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Abstract

Background: *Pulse wave velocity (PWV) is widely used for estimating the stiffness of an artery. Various invasive and non-invasive methods have been developed to determine PWV over the years. In the present research, the non-invasive estimation of the PWV of large arteries was used as an index for arterial stiffness.*

Methods: *A dynamic model based on the Navier-Stokes equations coupled to elasticity equations was introduced for the PWV in arteries with elastic walls. This system of equations was completed by clinical information obtained from the Doppler ultrasound images of the carotid artery of 40 healthy male volunteers. For this purpose, the Doppler ultrasound images were recorded and saved in a computer; and subsequently center-line blood velocity, arterial wall thickness, and arterial radius were measured by offline processing.*

Results: *The results from the analytic solution of the completed equations showed that the mean value of PWV for the group of healthy volunteers was 2.35 m/s when the mean arterial radius was used as the neutral radius and 5.00 m/s when the end-diastole radius was used as the neutral radius. It is noteworthy that the latter value closely complies with that reported by other researchers.*

Conclusion: *By applying this method, a non-invasive clinical and local evaluation of the common carotid artery stiffness via a Doppler ultrasound measurement will be possible.*

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Introduction

It has long been recognized that a high percentage of all cardiovascular diseases is associated with a stiffening of the arteries.[1-3] It is now apparent that a wide pulse pressure and systolic hypertension are the important indicators of morbidity and that systolic hypertension is the predominant risk factor for adverse outcomes in older hypertensive patients. Increased pulse pressure and systolic hypertension represent a later stage in the development of atherosclerosis and are, therefore, less sensitive than arterial elasticity.[4] Changes in elasticity occur very early in the development of atherosclerosis.[5]

There are many factors that can be used as the indices of arterial stiffness such as compliance, distensibility, arterial stiffness index, augmentation index, and elastic modulus. Various invasive and non-invasive methods have been developed to determine those indices.[6,7]

Pulse wave velocity (PWV) is widely used for estimating the stiffness of an artery.[3] PWV (m/s) is defined as the distance a pulse wave travels over a given time period.[1] Various methods have been used, both invasive and non-invasive, and can be applied to either flow or pressure waves.[6] PWV can be measured non-invasively by applanation tonometry,

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ultrasound, and more recently by Cardiovascular Magnetic Resonance (CMR).[8] Also, it is usually measured using the "foot-to-foot" method.[2] The two systems in common use, the SphygmoCor (AtCor) and Complior (Artech) differ with respect to their sensor technology and the algorithm used for calculating the pulse propagation time.[9] Be that as it may, there can be some difficulty in estimating the actual arterial distance between recording sites using only surface measurements. PWV becomes less accurate if the recording points are very close together; and the technique is, therefore, limited to use on larger arteries.[6] Also, PWV is an average indicator of artery stiffness between the two measuring points and, consequently, does not identify local stiffness variations.[2]

PWV provides information on the distensibility of the local vessel being studied rather than on systemic arterial stiffness, with distensibility being inversely related to stiffness. The Moens Korteweg equation6 can be employed to calculate PWV:

$$PWV = \sqrt{\frac{Eh}{2\rho a}}$$

Where E, h, ρ, and a are Young's elastic modulus, arterial wall thickness, blood density, and radial inside radius, respectively. This formula was first derived by Thomas Young in 1808 and is for inviscid fluid and membrane wall.[10] A more useful version of this equation is the Bramwell and Hill equation,[6] which relates PWV to distensibility:

$$PWV = \sqrt{\frac{\Delta PV}{\Delta V\,\rho}} = \sqrt{\frac{1}{\rho D}}$$

Where $\Delta PV/\Delta V$ and D are the relative volume elasticity of the arterial segment and distensibility, respectively. Since there is no direct and non-invasive method to measure the blood pressure of central arteries, the measurements of the pulse pressure made in the periphery, for example in the upper arm, do not always accurately reflect the actual central pulse pressure.[11]

In our research, the estimation of the PWV of large arteries was used as an index for arterial stiffness. A dynamic model based on the Navier-Stokes equations coupled to elasticity equations was introduced for the pulsatile blood flow in arteries with elastic walls. This system of equations was completed by clinical information obtained from ultrasound images of the carotid artery. The final equations were then solved using an analytic approach to determine the PWV in the right common carotid artery.

Methods

A Newtonian, incompressible fluid is assumed and the viscosity (μ) is constant. The flow is assumed to be laminar and axisymmetric. Under these conditions, the Navier-Stokes equations and the equation of continuity[12] simplify to:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}\right)+\frac{\partial P}{\partial x}= \mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}\right)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial r}\right)+\frac{\partial P}{\partial r}= \mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial r^2}+\frac{1}{r}\frac{\partial v}{\partial r}-\frac{v}{r^2}\right)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}+\frac{v}{r}=0$$

In these Equations, u, v, and μ are axial velocity, radial velocity, and viscosity of the blood, respectively.

In an elastic tube, pressure changes cause local movements of the fluid and tube wall, which then propagate downstream in the form of a wave. Axial and radial blood velocities depend on locations (x, r) and time (t), and the radial velocity (v) is not zero.

Because the arterial wall is in motion, zero velocities at the arterial wall are no longer valid as the boundary conditions. As a reasonable approximation, the boundary condition is applied at a radius a, which is taken to be the neutral position of the arterial wall; consequently, the required boundary conditions are zero velocities at this radius (a) and finite velocity at the center of the artery.

The final forms of the equations are obtained by matching the equations of the pulsatile flow and arterial wall with clinical information.[11-13] Non-invasive investigations by processing the sequential frames of color Doppler images were performed on 40 healthy male volunteers (average age of 59±12 years) with no history of cardiovascular and/or cerebrovascular disease, hypertension, diabetes, and smoking.[14] This study was performed from June 2004 to January 2006 and was approved by the Ethics Committees of Tarbiat Modarres University. We received informed consent from all the volunteers. The ultrasonic examination of the right common carotid artery was performed after at least 30 minutes of rest in the supine position when the heart rate and blood pressure had reached a steady state. A complete examination, including common, external, and internal carotids, was performed for every subject. The ultrasonic examination of the right common carotid artery at a point approximately 2 cm proximal to the bifurcation was done.[15,16] This point was selected near enough to the bifurcation, for its physiologic importance, and far enough to maintain the validity of axisymmetric geometry. In some studies,[17] this distance is considered 1.5 cm proximal to the bifurcation. High-resolution B-mode ultrasound and color Doppler images from the right common carotid artery were obtained with a 7.5 MHz linear array transducer attached to the ultrasound machine (GE-logic-500 MD version 4, USA, ±0.1 mm and ±0.1 cm/s). A data acquisition system consisting of a personal computer and multimedia board (Video-blaster Snazzi*1, VCD Master HQ, Singapore) was used for monitoring and recording the center-line blood velocity, arterial wall thickness, and the radius of the right common carotid artery (30 frame/s). For each ultrasound examination, matching longitudinal views of the common carotid artery were located; and the frames, representing a minimum of two cardiac cycles, were recorded. Each recorded sequence was saved, frame by frame, on the scanner's hard disk. Pixel-based methodologies allow motion estimation by studying the displacement amongst the frames at the pixel level. During the recording of the images, the center-line blood velocity, arterial wall thickness, and arterial radius were measured by the calipers of GE logic 500MD to obtain the scales of the images for off-line processing. After saving the images, the recorded sequence of the carotid artery was reviewed by Virtual Dub 1.5.9 software (Copyright © 1998-2003 by Avery Lee), and the images were thereafter taken from each frame by Capture Express 1.3.0.1 software (© 1989-1999 Adobe Systems Incorporated) to measure the center-line blood velocity, arterial wall thickness, and arterial radius. The measurements were made at a constant temperature room (26°C). Below equations make a set of seven equations and seven unknown parameters (A, B, C, D, E, PWV, and z), which can be solved by the following analytic method[17]:

$$A = \frac{PWV}{aJ_0(\Lambda)}\left[\frac{2 + z(2\sigma - 1)}{g + \sigma . z(g - 1)}\right]D$$

$$B = \frac{\rho . PWV}{a}\left[\frac{z(g - 2\sigma)}{g + \sigma . z(g - 1)}\right]D$$

$$C = \frac{i.PWV}{\omega . a}\left[\frac{z(1 - g) - 2}{g + \sigma . z(g - 1)}\right]D$$

$$\eta(x,t) = De^{i\omega\left(t - \frac{x}{PWV}\right)}$$

$$\left[(g - 1)(\sigma^2 - 1)\right]z^2 + \left[\frac{\rho_w h}{\rho a}(g - 1) + \left(2\sigma - \frac{1}{2}\right)g - 2\right]z + \frac{2\rho_w h}{\rho a} + g = 0$$

$$z = \frac{Eh}{(1 - \sigma^2)\rho a . PWV^2}$$

$$U(0) = A + \frac{B}{\rho . PWV}$$

Where A, B, C, and D are arbitrary constants; $J_i(\Lambda)$ is Bessel function; and ρ, ρ_ω, σ, and a are blood density, arterial wall density, Poisson's ratio, and arterial neutral radius, respectively. In addition, ω is the frequency of oscillation. U(0) and η express the maximum blood velocity in the center-line of the artery with an acceptable approximation and the radial displacement of the artery, respectively. In these equations, Ω, Λ, and g are defined as:[17]

$$\Omega = \sqrt{\frac{\rho\omega}{\mu}}a$$

$$\Lambda = \left(\frac{i - 1}{\sqrt{2}}\right)\Omega$$

$$g = \frac{2J_1(\Lambda)}{\Lambda J_0(\Lambda)}$$

The constants used to solve this set of equations[18-20] are as follows:

Blood density and arterial wall density	$\rho = \rho_w = 1060\, kg.m^{-3}$
Viscosity of blood	$\mu = 0.003465 \quad pa.s$
Poisson's ratio	$\sigma = 0.45$

In Table 1, we have introduced Nomenclature of these formulas.

Table 1. Nomenclature of formulas

	Nomenclature
u	Axial velocity
v	Radial velocity
x	Axial variable
r	Radial variable
t	Time
ρ	Density of blood
μ	Viscosity of blood
P	Pressure
$U(r)$	Maximum domain of axial velocity
ω	Frequency of oscillation
PWV	Wave speed (Pulse wave velocity)
a	Neutral radius
Ω	Parameter introduced in Eq.13
Λ	Parameter introduced in Eq. 14
g	Parameter defined by Eq. 15
A,B	Arbitrary constants
C,D	Arbitrary constants
E	Elastic modulus
σ	Poisson's ratio
z	Parameter defined by Eq. 11
$Ji(\Lambda)$	Bessel function
J_0	Bessel function of order 0
J_1	Bessel function of order 1
T	Period of oscillation
ρ_ω	Density of arterial wall
τ_ω	Sheer stress on arterial wall
ξ	Axial displacement
η	Radial displacement
P_ω	Blood pressure on arterial wall
h	Arterial wall thickness

All the observations were performed under the same standard conditions. The results from the individual subjects were averaged and shown as Mean±Standard Deviation with 95% Confidence Interval.

Results

It was assumed that the frequency of oscillation is constant (72 beats/min) for the healthy volunteers. After a set of seven equations and seven unknown parameters had been solved, the mean arterial radius was used as the neutral radius. Table 2 summarizes the characteristics of the right common carotid artery [Mean±Standard Deviation (SD) with Confidence Interval (95%)] in the 40 healthy men.

Table 2. Characteristics of the right common carotid artery in 40 healthy men

Parameters	Mean±SD	(95% CI)
a: Arterial neutral radius (mm)*	4.05±0.60	3.86-4.25
h: Arterial wall thickness (mm)	1.32±0.32	1.22-1.43
D: Maximum change of arterial radius (mm)	0.19±0.07	0.17-0.22
U(0): Maximum velocity of blood in center-line of artery (cm/s)	59.01±10.91	55.52-62.50
Pulse wave velocity (m/s)**	5.00±1.13	4.63-5.36

*The neutral radius is the average of the maximum and minimum radii of the artery throughout two cardiac cycles
**Resulting from solving seven equations

The neutral radius was the average of the maximum and minimum radii of the artery throughout two cardiac cycles. The end-diastole radius was subsequently used as the neutral radius.

Table 3 depicts the characteristics of the right common carotid artery [Mean±Standard Deviation (SD) with CI (95%)] in the 40 healthy men. The arterial neutral radius was the end- diastolic radius of the artery throughout two cardiac cycles. A comparison of these two values of PWV with those in other studies shows that the results of Table 2 are more comparable.

Table 3. The end diastolic radius of the right common carotid artery and their pulse wave velocity in the 40 healthy men throughout two cardiac cycles

Parameters	Mean±SD	(95% CI)
a: Radial neutral radius of artery (mm)*	3.86±0.57	3.68-4.04
Pulse wave velocity (m/s)**	2.35±0.58	2.17-2.54

*The neutral radius is the average of the maximum and minimum radii of the artery throughout two cardiac cycles
**Resulting from solving seven equations

Discussion

The estimation of PWV as an index of arterial stiffness can be an independent predictor of cardiovascular risk.[21] In health sciences, non-invasive methods are preferred to invasive ones. In this research, a non-invasive method was introduced to estimate PWV by modeling the blood flow in arteries according to the Navier-Stokes equations and modeling arterial wall according to elasticity equations and matching these two sets of equations with the resultant equations from clinical information. Clinical information was obtained via color Doppler ultrasound, which is a valid, accurate, and standard method.[22] In this study, we proposed a mathematical method for the estimation of PWV. There are many different factors, for example arterial elasticity, age, diseases, and method of estimation, which affect PWV. Age is an important factor in the elasticity and distensibility of the arteries, and our subjects had a mean age of 59±12 years. Typical values range from 3 m/s in central arteries in healthy young people to 15 m/s in peripheral arteries amongst old and sick people.[8-10,23] For instance in a study via CMR on the carotid artery of 7 healthy volunteers (3 women, 4 men; age range: 28-35 years), the mean value of PWV was measured at 5.1 m/s.[8]

Our research presents a new approach to estimate arterial stiffness without blood pressure measurements. Measurements of blood pressure for the estimation of the arterial stiffness index, compliance, distensibility, and Peterson's elastic modulus are necessary and are extracted through invasive techniques.[24] Several methods have been introduced to estimate arterial stiffness based on changes in the brachial blood pressure, but due to the error that results from substituting the brachial blood pressure for central arteries such as the carotid,[6] it is of great importance to present arterial stiffness based on mechanical models without any emphasis on the brachial blood pressure. Moreover, it is not necessary to know the blood velocity and arterial radius each time.

Conclusion

The application of the method introduced in the present study can make a non-invasive and clinical evaluation of PWV via a Doppler ultrasound measurement of the common carotid artery possible, obviating the need for a further measurement of the local blood pressure. The authors of this paper would suggest this dynamic model for an evaluation of the effects of age and various diseases such as atherosclerosis on PWV.

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