ORIGINAL RESEARCH

The Role of Ultrasound Shear Wave Dispersion Imaging in Evaluating Carotid Viscoelasticity: A Preliminary Study

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Received May 15, revision received July 1; accepted July 3.

Objective: To evaluate the carotid viscoelasticity using ultrasound shear wave dispersion imaging (USWD) and determine its feasibility.

Methods: Forty-five volunteers were recruited and divided into the group1 (⩾50 years old) and group 2 (<50 years old). The shear wave elastic modulus (SWE-A_R and SWE-P_R) and shear wave dispersion indexes (SWD-A_R and SWD-P_R), which located at the anterior and posterior walls of the common carotid artery (CCA), were obtained by USWD, and compared with pulse wave velocity (PWV). Pearson correlation analysis was applied to analyze the related factors of viscoelasticity.

Results: Before and after body mass index, systolic blood pressure (SBP) and diastolic blood pressure (DBP) were adjusted, SWE-A_R, SWE-P_R, SWD-A_R and SWD-P_R were all higher in the group 2 than those of group 1 (all $P < 0.05$). In all subjects, SWE was negatively correlated with age, SBP, DBP and PWV, respectively ($r = -0.282, -0.374, -0.321, -0.256$ and all $P < 0.05$). The SWD was negatively correlated with PWV in the group 1, while positively correlated with SBP in the group 2 ($r=-0.393$ and $r=0.366$, all $P < 0.05$).

Conclusion: The viscoelasticity of arterial wall can be assessed by USWD. It provides a new way to describe arterial disease for clinical study.

Key words: Shear wave dispersion; Carotid artery; Pulse wave velocity; Viscoelasticity

Advanced Ultrasound in Diagnosis and Therapy 2019;03:097-102 DOI: 10.37015/AUDT.2019.190816

The carotid artery is a viscoelastic tissue, so it is of elasticity and viscidity [1]. Many studies have focused on the elastic properties of the carotid or aorta, while little has been known about the viscous properties and physiological significance [2]. With the advance of technology, ultrasonic shear wave dispersion (USWD) imaging shows the new hope for non-invasively evaluating the tissue viscosity. Pulsed sound energy can push the soft tissue to vibrate, and generate the shear waves. Shear wave dispersion (SWD), which is the slope of the pulse wave and shear wave velocity, can reflect the tissue viscosity [3]. However, the results of basic experiment had proved the viscosity was positively correlated with shear wave dispersion [4]. However, pulse wave velocity (PWV) is considered as the good indicator for assessment of arterial elasticity in the circular direction. In this study, the viscoelasticity of carotid arteries was evaluated using USWD.

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Materials and Methods

Study population and data collection

Forty-five volunteers were recruited, including 23 males and 22 females. They were divided into two groups according to age, group 1 (≥50 years old) and group 2(<50 years old). The participants had been excluded as following conditions: with the history of cardiovascular, the vascular diseases of extremities, immune diseases, active bleeding, malignant tumors, blood diseases, severe liver, lung and kidney diseases. An electronic questionnaire was used to document the demographic characteristics, such as height and weight. In addition, the blood pressure was measured. This study was performed according to the Declaration of Helsinki. It was approved by the ethics committee of Shanghai General Hospital (2017KY009) and registered with the official website of China Clinical Trial Registration Center (ChiCTR1800016590). The inform consents were signed by all subjects.

Instruments and Methods

The common carotid arteries (CCA) were assessed as the same method in the previous study [5]. The PWV was measured by Mylab Twice ultrasound system (ESAOTE Medical Systems, Genoa, Italy), which equipped with the 4–13 MHz linear array transducer and analysis software (quality arterial stiffness, QAS). During diastole, the anterior and posterior walls of CCA, which were 1.0cm proximal to bifurcation, were optimally presented and tracked by frequency signals. The PWV from left and right CCA were measured respectively and averaged.

The shear wave elastography of CCA had been performed by Aplio 900 ultrasound system (Canon Medical Systems Corporation, Otawara, Japan) with PVI-475BX curved abdominal transducer (frequency range: 1–8-MHz and mid frequency: 5.0 MHz)[6]. Electrocardiography was recorded by synchronization. The arterial viscoelasticity could be evaluated after starting “TCS” button. QuadView provided 4 display maps for the single-shot acquisition, which provide different visual representations of the arterial shear wave profile, including the elastic map (Fig. 1A), propagation map (Fig. 1B), two-dimensional reference map (Fig. 1C) and shear wave dispersion map (Fig. 1D). After recording the motion of vascular wall for 10-20 cardiac cycles, measurements were obtained from a 1.0 cm circular region of interest (ROI) in systolic phase. The ROI was selected in the same area as PWV measurement. Five ROIs were placed selectively on the anterior and posterior walls of the bilateral carotid arteries, respectively (1 to 2 mm apart). Then shear wave elastic modulus (SWE-A_R and SWE-P_R) and shear wave dispersion (SWD_R and SWD-P_R) in electrocardiographic R wave were analyzed and their mean values were calculated for final analysis.

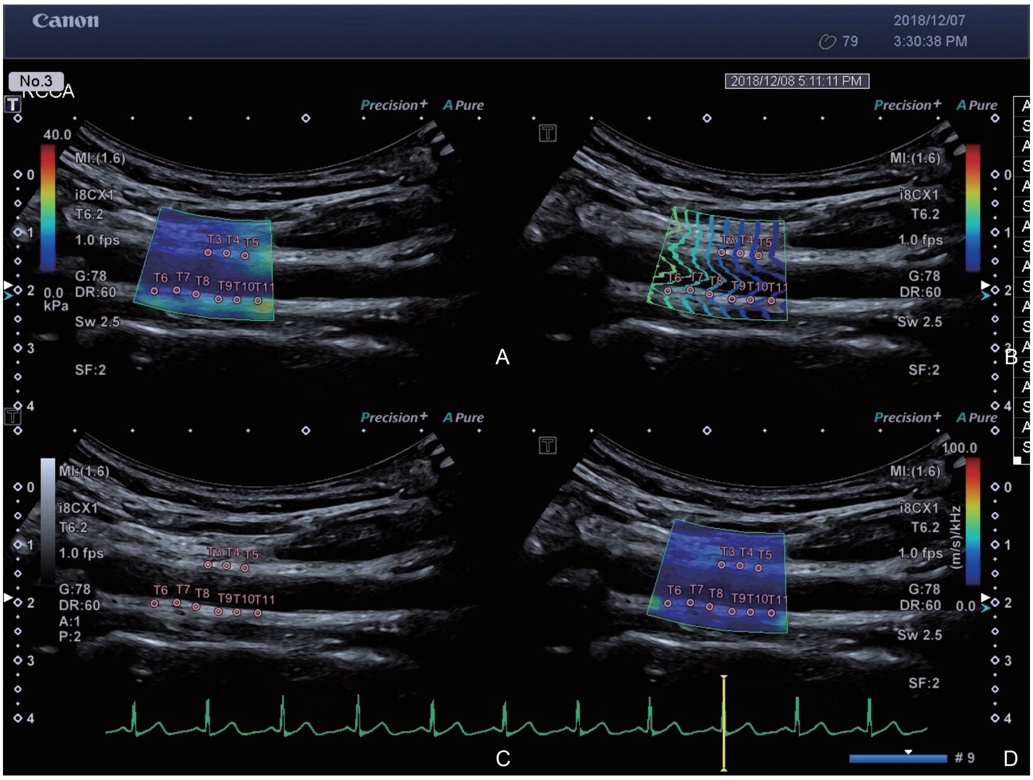

Figure 1 QuadView of shear wave profile. (A) Elastic map. The shear wave speed is coded on a color scale from blue to red, corresponding to ranging the Young modulus between 0.0 and 40.0 kPa; (B) Propagation map. The contour lines represent shear wave arrival times at different points in the tissue; (C) Two-dimensional reference map; (D) Shear wave dispersion map. The shear wave dispersion is also coded on a color scale from blue to red, corresponding to value of dispersion from 0.0 to 100.0 (m/s)/kHz.

Statistical analysis

The continuous data, such as height, weight, BMI, SBP and DBP were expressed as Mean ± SD. Data were compared between two groups using two-sample t-test for continuous data and χ^2 test for categorical data. BMI, SBP and DBP might contribute to carotid viscoelasticity, so data were compared again after standardization. The viscoelastic indicators of anterior and posterior walls were compared by paired *t* test. Correlation analysis was based on Pearson analysis. A value of $P < 0.05$ was considered statistically significant. Data analysis was performed with SPSS 13.0 (SPSS, Chicago, IL, USA).

Results

Participants' characteristics

Table 1 exhibited that in group2, the BSP and DBP were lower, while height was higher than those in group1, respectively. In addition, there was no difference in gender, weight and BMI between two groups.

Viscoelasticity analyses

For group 2, the PWV was significantly higher than that of group 1. After adjusting BMI, SBP and DBP, the difference of PWV between the two groups was still significantly (P<0.01). For group 2, the viscoelastic indicators, including SWE-A_R, SWE-P_R, SWD-A_R and SWD-P_R were all higher than those of group 1 (all $P <$ 0.05). Furthermore, after adjusting BMI, SBP and DBP, the viscoelastic indicators were still significant higher for younger group.

The viscoelastic indicators were compared between anterior and posterior walls, and the results were shown in Table 2. The SWE-A_R was higher than SWD-P_R, while there was no significant difference between SWD-A_R and SWD-P_R in both groups.

Table 1 Demographics of participants（Mean± SD)

Characteristics	≥50 years old	<50 years old	t/χ^2 value	P value
N	23	22	/	/
Gender (F/M)	11/12	11/11	0.023	0.879
Age (years)	65.9±9.5	31.1±9.8	13.673	<0.001
Height (cm)	162.9±7.1	167.5±7.9	−2.301	0.025
Weight (kg)	68.3±17.3	66.7±15.6	0.348	0.729
BMI (kg/m^2)	25.8±7.4	23.5±4.1	1.444	0.154
SBP (mmHg)	139.6±11.1	125.7±9.1	5.102	<0.001
DBP (mmHg)	87.9±7.2	79.7±6.1	4.607	<0.001

Table 2 Comparison of carotid structure, elastic modulus and viscoelasticity index between the two groups（Mean± SD)

Item	≥50 years old	<50 years old	P value	Adjusted P value		
				BMI	SBP	DBP
PWV, m/s	8.67±2.13	5.47± 0.70	<0.001	<0.001	<0.001	<0.001
SWE-A_R, kPa	13.82±14.54	25.26±23.74	0.034	0.032	0.022	0.020
SWE-P_R, kPa	6.75±4.60†	9.21±4.39‡	0.045	0.028	0.006	0.007
SWD-A_R, (*m/s*)/kHz	12.45±3.90	14.26±3.04	0.048	0.024	0.002	0.002
SWD-P_R, (*m/s*)/kHz	11.52±3.12	13.68±4.38	0.038	0.022	0.002	0.002

†, Compared with SWE-A_R in group1(≥50 years old) and $P < 0.05$; ‡, Compared with SWE-A_R in group2 (<50 years old) and $P < 0.01$; PWV, Pulse wave velocity; SWE-A_R, Shear wave elastic modulus of anterior wall in systolic phase; SWE-P_R, Shear wave elastic modulus of posterior wall in systolic phase; SWD-A_R, Shear wave dispersion of anterior wall in systolic phase; SWD-P_R, Shear wave dispersion of posterior wall in systolic phase

Correlation analysis

In all participates, the shear elastic modulus (SEM) of the CCA was negatively correlated with age, SBP, DBP and PWV, respectively (r = −0.282, −0.374, −0.321, −0.256 and all $P < 0.05$). In the group 1, the SEM was only negatively correlated with SBP (r = 0.357 and $P <$

0.05). On the other hand, shear wave dispersion (SWD) of CCA was negatively correlated with PWV in the group1, and was positively correlated with SBP in the group 2 ($r = -0.393$ and $r = 0.366$, all $P < 0.05$).

Discussions

Transportion of blood through the cardiovascular system is achieved via two principal mechanisms: conduction, which facilitates transport to the microcirculation, and buffering, which dampens the pulsatility as the pulse wave is propagated from the large to the small vessels. Generally, the larger vessels are more "compliant" and, consequently, they exhibit both elastic and viscoelastic distention, while the smaller vessels are more rigid, and thus for these vessels viscoelastic deformation dominates the response. The latter contributes to preservation of the mechanical integrity of the arterial wall [7]. The "viscoelasticity" of blood vessels might not be completely explained by simple "rigid tube" or "elastic tube" theory, and the non-invasive evaluation of carotid viscoelasticity has been little to report previously. In this study, viscoelasticity of the CCA was assessed firstly using SWD technique. The results showed that the SWE and SWD of arterial wall artery were decreased in elder subjects. In addition, the reduced viscoelastic indicators were closely related to age, blood pressure and PWV. With the age increasing, the viscoelastic characteristics of the arterial wall were weakened, and might contribute to arteriosclerosis.

Arterial viscoelasticity

The arterial wall is mainly composed of elastic fibers fibrillar, collagens, contractile smooth muscle and proteoglycans/glycosaminoglycans, and the mechanics mainly are of elasticity and viscosity [8]. The relationship between stress and stain is of importance to understanding the mechanism behind the CCA viscoelasticity. The elastic modulus is defined as the slope of stress-strain curve, and a stiffer material will have a higher elastic modulus. On the other hand, the viscosity exhibits a non-linear behavior and documents as stress-relaxation and creep, according to the relationship between stain and time. Stress-relaxation is a decrease in stress under constant strain. In vivo, the arterial wall exhibits a decrease in tension under constant expansion. On the other hand, creep is an increase in strain under constant stress. In vivo, the artery presents that under constant blood pressure (constant tension) an increase in expansion and extension of arterial wall with stain increasing [10]. Therefore, arterial viscoelasticity contributes to the reserve and remodeling of the arteries. In this study, the elder group showed a decrease in viscoelastic indicators of CCA, meaning the arterial reserve function was weakened [11]. DH Xu [12] respectively reseted CCA from the young and elder cadaver and preformed the stress relaxation and creep tests. The results revealed that the stress relaxation and creep in the elder were all significantly lower than those of young. Scanning electron microscope revealed that the collagen fibers, elastin fibers and smooth muscle cells arranged in disorder with age increasing, as well as the degeneration, rupture, disintegration, abundant plaques and inflammatory cells, which characterized as atherosclerosis [13]. Thus, the arterial viscoelasticity is closely related to the arteriosclerosis.

Shear wave dispersion and viscoelasticity

SWE is an exciting and rapidly evolving US technique that allows quantification of mechanical and elastic tissue properties, which uses the pulses to generate the shear waves [14]. In elastic tissue, the shear wave speeds are not dependent on the frequency. However, viscoelastic tissue results in dispersion and attenuation [15], and shear waves exhibit changes with the frequency of the excitation pulses, which is named shear wave dispersion (SWD) (Fig. 2A). In rat models, increasing accumulations of microsteatosis and macrosteatosis will increase the lossy viscoelastic properties of shear waves in a medium. The study also confirms a potential of scoring system for steatosis based on SWD [16, 17]. Based on the existing SWE, the SWD technique develops easily and shows new highlight, including supersonic shear imaging [18], slow shear wave imaging [19] and MR elastography [20]. In this study, ultrasonic excitation waves in different frequencies triggered tissue vibration and cause shear waves, then the velocities of shear waves were detected by pulse echo technique. Subsequently, the elastic and viscosity coefficient of the tissue were analyzed according to the Voigt model [19] (Fig. 2B). In this study, the results showed that the elastic modulus of the anterior wall was higher than that of the posterior wall in all participants, while there was no significant difference in the indicators of SWD. However, SWE technique was pressure dependent and the anterior wall of CCA was more affected by the probe pressure than posterior wall [21].

Most of commercial scanners tend to report a single shear wave speed (or elastic modulus) to the end user under the assumptions that tissue is elastic [22,23]. In elastic tissue, with propagation distance increasing, the amplitude of the shear wave decreases, while the waveform does not change (Fig. 2C). In viscoelastic structures, with the propagation distance increasing, the waveform and amplitude of the shear wave all change (Fig. 2C). Human tissues, however, are known to be viscoelastic, resulting in dispersion and attenuation. There was a certain bias in evaluating viscoelastic structures using SWE. The Voigt model consists of a Newtonian damper and Hookean elastic spring connected in parallel, and is used to explain the viscoelastic behavior [19]. Kumar et al. [24] explored the role of viscoelastic parameters in suspicious breast masses using SWD. Voigt model based shear elasticity showed a significantly higher median value for the malignant masses compared to benign masses and suggested that SWD can be used to differentiate between malignant and benign breast masses. It was noted that this study also found that the SWD was good for assessing the carotid viscoelasticity. Therefore, the SWD technique might be a clinically valuable diagnostic tool for non-invasive evaluation of tissue viscoelasticity.

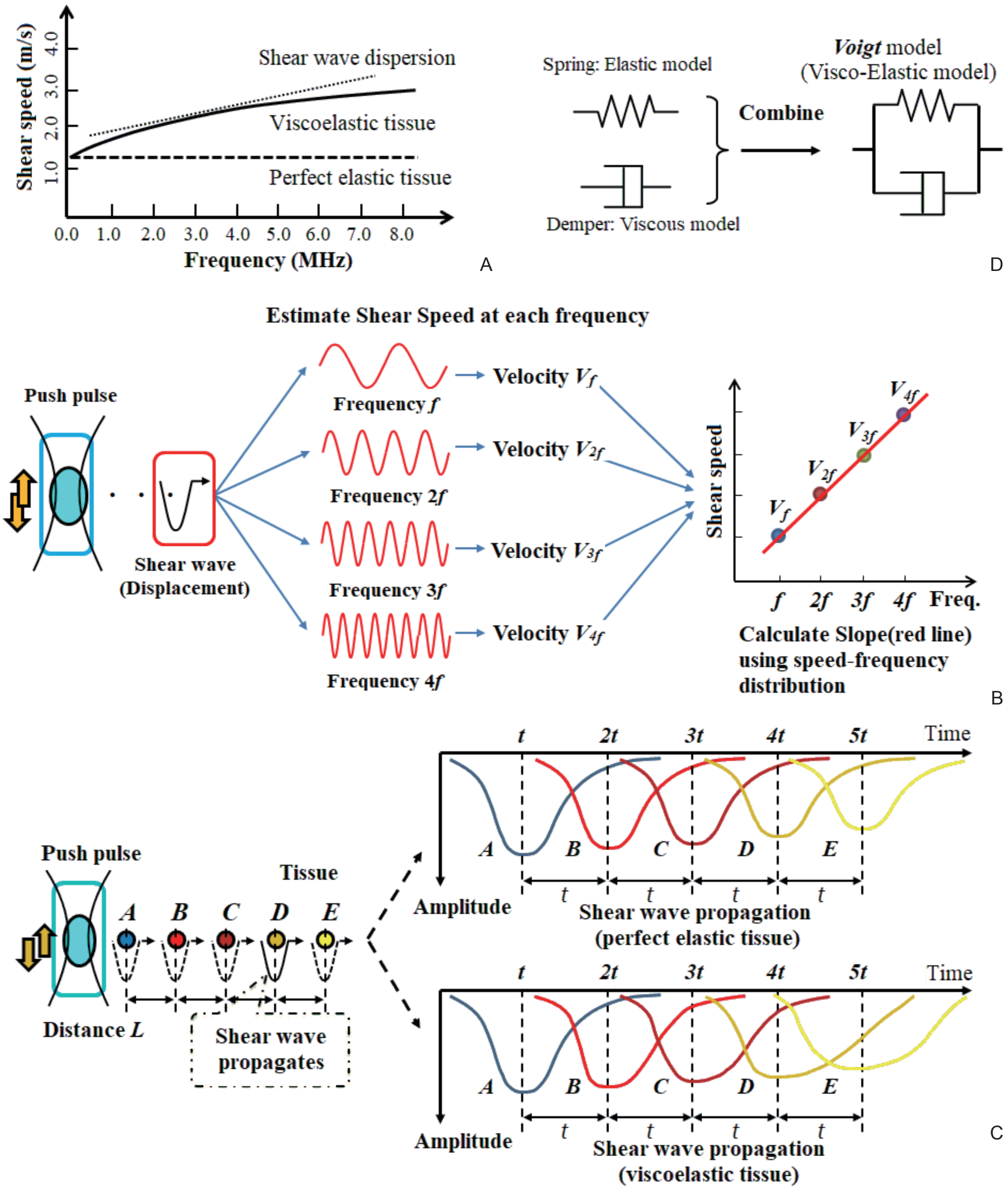

Figure 2 Properties of shear wave dispersion: Basics and applications. (A) Voigt's shear wave viscoelastic model; (B) The relationship between pulse wave frequency and tissue shear wave; (C) The assessment of shear wave elastic modulus; (D) Shear wave dispersion.

There were still some limitations in this study. First, the sample size was relatively small, and the age span was large between the subgroups. Second, curved abdominal transducer was used to evaluate the carotid viscoelasticity, while transducer of linear array could provide better images and measurements. Finally, the arterial viscoelasticity in the patients with cardiovascular or cerebrovascular diseases merited further investigation.

Conclusions

In summary, carotid viscoelastic properties in different age groups were presented. The different behavior of carotid viscoelasticity was related to the age, blood pressure and PWV, and might be a atherosclerotic evidence. The clinical implication of the noninvasive measurement of arterial wall viscosity could be highly relevant to identify high-risk populations with atherosclerosis.

Acknowledgments

This work was supported by research grants from the Three-year Plan for Clinical Skills and Innovation in Municipal Hospitals (Grant No.16CR3105B), Interdisciplinary Program of Shanghai Jiaotong University (Grant No.YG2015MS28), Shanghai Health and Family Planning Commission Fund (Grant No.201640043), Shanghai Science and Technology Committee Fund (Grant No.16411969300) and Shanghai Songjiang District Science and Technology Project (Grant No.18sjkjgg72 and 18sjkjgg53).

Thank Ms. Li Hongqin from the Ultrasonic Research Department of Canon Medical Systems (China) Co., Ltd. for her technical support.

Conflict of Interest

The authors declare that they have no competing interests.

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