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Influence of Blood Pressure and Heart Rate on PWV Measurement: Assessment Under Real-Time Blood Pressure Monitoring

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Summary

Pulse Wave Velocity (PWV) is widely used to assess arterial elasticity and is an independent risk factor for cardiovascular disease, but it is influenced by multiple factors. Objective is to assess the impact of blood pressure and heart rate on PWV. Twenty healthy young individuals were enlisted as subjects. Real-time blood pressure monitoring was performed by non-invasive continuous blood pressure measuring instrument during the detection of subjects' carotid PWV. During real-time blood pressure monitoring, exercise load caused fluctuations in blood pressure and heart rate, and PWV changes of each subject under different blood pressure and heart rate conditions were recorded simultaneously. Among the 20 subjects, PWV was associated with blood pressure in four subjects and heart rate in one subject. PWV increased with rising blood pressure when the systolic pressure fluctuation range was ≥30mmHg, diastolic pressure fluctuation range was ≥18mmHg, and mean arterial pressure fluctuation range was ≥20mmHg. PWV increased with rising heart rate, when the heart rate fluctuation range was >30 beats/min. Blood pressure and heart rate have some influence on PWV. However, the fluctuation range of blood pressure and heart rate should reach a certain value, the impact is significant.

Keywords

Pulse wave velocity • Blood pressure • Heart rate

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Introduction

Decreased arterial elasticity represents the earliest alteration in the progression of arteriosclerosis, succeeded by modifications in the artery wall structure, ultimately resulting in inner media thickening and plaque formation. To a certain extent, reduced arterial elasticity indicates early arteriosclerosis. Given the importance of early diagnosis and prevention of arteriosclerosis, the investigation of arterial elastic function has become a focal point in current academic research [1-4]. Pulse Wave Velocity (PWV) is considered the gold standard for assessing vascular elasticity [5]. However, numerous influencing factors affect PWV [6-7], with age and blood pressure identified as the primary factors. PWV is higher in hypertensive individuals compared to normal individuals, yet whether this elevation is due to arteriosclerosis resulting from hypertension or the hypertension itself remains unclear. This study aims to elucidate the relationship between blood pressure, heart rate, and PWV, determining whether blood pressure and heart rate impact PWV measurement. The goal is to enhance the evaluation of arterial stiffness in clinical settings.

Methods

Objects

This study recruited 20 healthy young adults, comprising 5 males and 15 females, with ages ranging from 22 to 30 years and an average age of 26±2.14 years.

Inclusion criteria: No history of hypertension, diabetes, dyslipidemia, or smoking. Absence of carotid artery intima-media thickening and luminal plaque formation. No neck trauma or mass.

Exclusion criteria: History of hypertension, diabetes, dyslipidemia, or smoking. Presence of carotid intima-media thickening and luminal plaque formation. History of neck trauma or mass.

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Methods

Instruments and equipment

The VINNO M80 ultrasonic diagnostic instrument was utilized to assess the common carotid artery PWV in the study subjects, employing the X6-16L linear array probe (frequency 6.5 ~ 18MHz). Real-time blood pressure monitoring was conducted using the finometer, a non-invasive continuous blood pressure measuring instrument from Shenzhen Delekai Company.

Data acquisition methods

- *Carotid PWV assessment*

Subjects assumed a supine position on the diagnostic bed with their heads slightly tilted to the left, ensuring neck relaxation. The linear array probe was gently positioned at the right common carotid artery, aligned parallel to the front and back walls of the artery for optimal visualization. The instrument's PWV function was initiated after selecting the straightest position of the common carotid artery for measurement. Upon determining the position, the PWV key on the instrument panel was activated, and the size of the sampling frame, number of sampling lines, and density were adjusted based on the examined position. Pressing the ENTER key displayed the movement track of the common carotid artery wall on each sampling line, represented as expansion waves. Dilatation waves, depicting at least one stable cardiac cycle of the common carotid artery wall motion track, were observed. Four parameters, namely local PWV, compliance coefficient (CC), distensibility coefficient (DC), and elasticity parameter (EP) of the vascular wall, were obtained by positioning the measuring cursor at the "trough to trough" position of one cardiac cycle (Fig. 1).

- *Real-time blood pressure monitoring*

During the ultrasound assessment of the elasticity of the right common carotid artery in the study subjects, simultaneous connection of a non-invasive continuous blood pressure meter to the left arm was established. To investigate the impact of varying blood pressure and heart rate on PWV measurement, it was essential to induce a specific fluctuation range in both parameters during real-time blood pressure monitoring and common carotid artery PWV evaluation. Consequently, the PWV value of the right common carotid artery was measured 5-10 times in the subjects' resting state. Subsequently, subjects were instructed to perform 10 sit-ups to induce fluctuations in blood pressure and heart rate (Fig. 2). Following this, the PWV value of the common carotid artery was measured again 5-10 times, and the corresponding images were stored simultaneously.

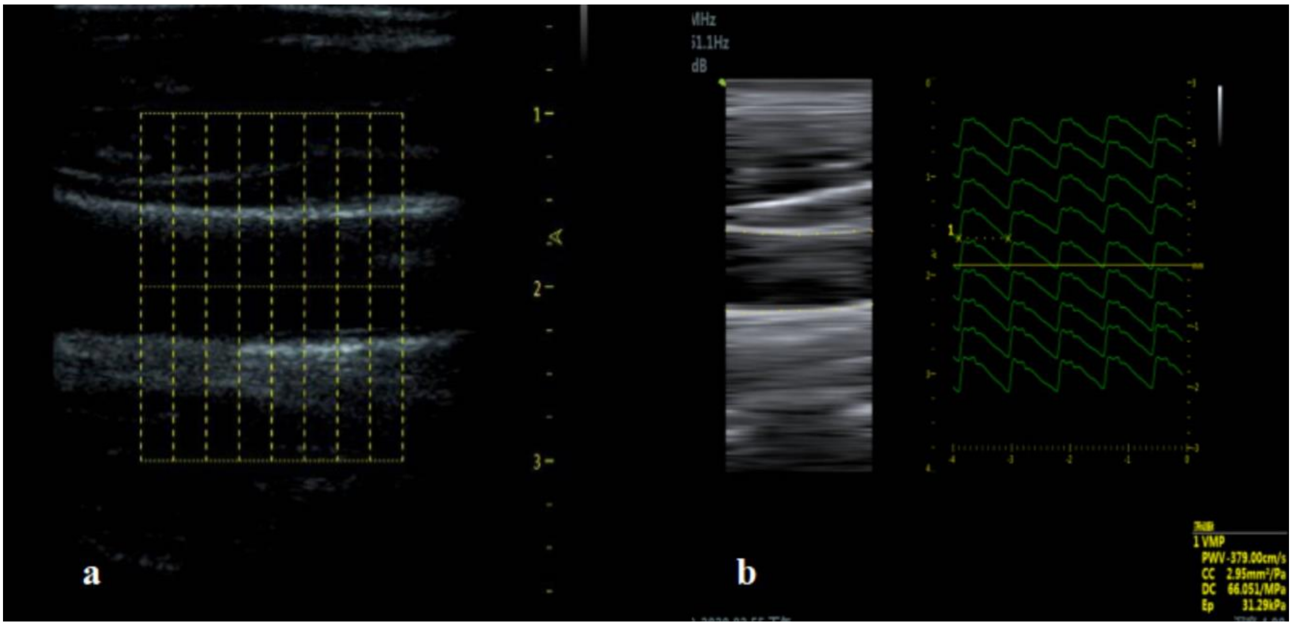

Fig. 1. Common carotid artery elasticity was assessed by ultrasound. (**a**) Represents the number of sampling frames and sampling lines, (**b**) depicts the expansion wave of the artery wall, and the measurement cursor indicates the position for measuring one cardiac cycle trough to trough.

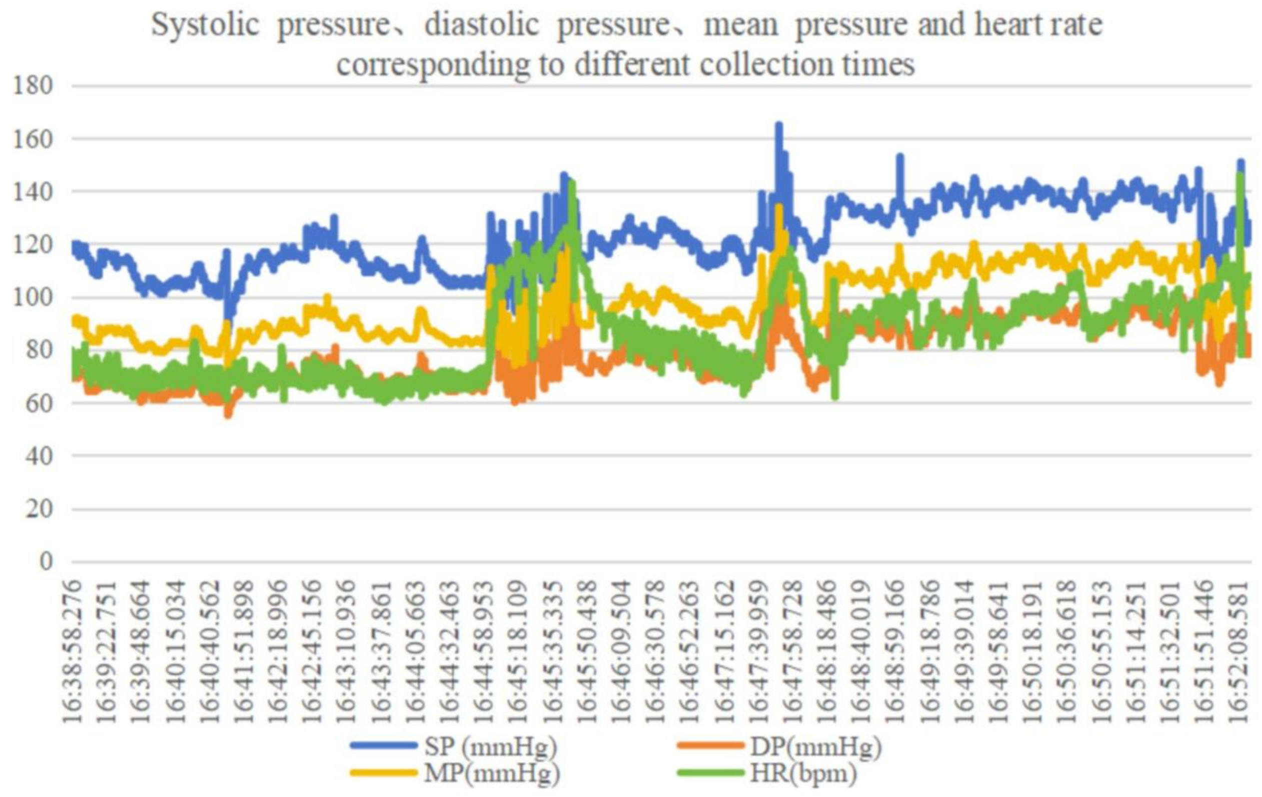

Fig. 2. Fluctuation of blood pressure and heart rate under real-time blood pressure monitoring. SP (systolic blood pressure), DP (diastolic blood pressure), MP (mean blood pressure), HR (heart rate).

Data processing

The data obtained from the real-time blood pressure monitoring device were exported in a text document (.txt) format. This exported data was then converted to an Excel format to facilitate subsequent statistical organization. The mean Systolic Pressure (SP) value, mean Diastolic Pressure (DP) value, mean Mean Pressure (MP) value of blood pressure recorded by the real-time blood pressure monitoring equipment for each minute were calculated. Additionally, the average Heart Rate (HR) value was determined, and the corresponding average PWV value for each minute was recorded. These data were entered into Excel tables, with files named after each research object. Each table documented the SP value, DP value, MP value, HR value, and corresponding PWV value for each research object at different time points.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 26.0 software, employing Pearson correlation analysis. The analysis focused on assessing the correlation between PWV for each research subject at different time points and corresponding systolic blood pressure, diastolic blood pressure, mean blood pressure, and heart rate values. Statistical significance was considered at $P < 0.05$.

Results

Among the 20 subjects, the PWV values of 4 subjects exhibited an increase with elevated blood pressure, characterized by a systolic blood pressure fluctuation range ≥30mmHg, diastolic blood pressure fluctuation range ≥18mmHg, and mean pressure fluctuation range ≥20mmHg. No significant correlation between PWV and blood pressure was observed in the remaining 16 subjects, where blood pressure fluctuations were below the mentioned values. Additionally, among the 20 subjects, the PWV value of 1 subject increased with elevated heart rate, with a heart rate fluctuation range exceeding 30 beats/min. In 19 subjects, no significant correlation was found between PWV measurements and heart rate changes, and the heart rate fluctuation range was less than 30 beats/min (Table 1, Table 2).

Table 1. Fluctuation Amplitude of Blood Pressure and Heart Rate in 20 Objects During PWV Detection

Object	Sex	Age	Δ SP	Δ DP	Δ MP	Δ HR
1	male	27	12	4	6	5
2	female	30	10	5	9	3
3	female	22	5	9	9	8
4	female	28	10	5	6	5
5	female	25	8	4	3	5
6	female	25	10	8	9	3
7	female	25	16	6	9	9
8	male	30	13	14	14	5
9	male	30	18	7	10	19
10*	female	25	30*	26*	28*	31*
11	female	28	16	11	15	20
12	female	25	18	15	16	23
13	female	25	26	11	14	11
14	female	26	19	8	12	11
15*	male	26	31*	16	18	6
16	female	28	17	8	13	15
17*	female	28	33*	18*	22*	18
18	male	25	16	9	12	13
19*	female	28	32*	18*	20*	11
20	female	25	20	9	11	22

ΔSP: Systolic blood pressure maximum fluctuation range difference value; ΔDP: diastolic blood pressure maximum fluctuation range difference value; ΔMP: mean blood pressure maximum fluctuation range difference value; ΔHR: heart rate maximum fluctuation range difference value; * indicates that PWV measurement difference is statistically significant when the fluctuation range of blood pressure and heart rate reaches a certain degree.

Table 2. Pearson Correlation Analysis Results of Blood Pressure, Heart Rate, and PWV

Object	Comparative factor	Pearson correlation coefficient	P value
1	SP and PWV	0.211	0.586
	DP and PWV	0.037	0.925
	MP and PWV	0.108	0.783
	HR and PWV	0.049	0.901
2	SP and PWV	0.290	0.528
	DP and PWV	0.366	0.419
	MP and PWV	0.326	0.475
	HR and PWV	0.398	0.376
3	SP and PWV	0.070	0.858
	DP and PWV	0.279	0.468
	MP and PWV	0.240	0.534
	HR and PWV	0.168	0.665
4	SP and PWV	0.311	0.476
	DP and PWV	0.037	0.925
	MP and PWV	0.108	0.783
	HR and PWV	0.240	0.534
5	SP and PWV	0.456	0.256
	DP and PWV	0.232	0.580
	MP and PWV	0.361	0.380
	HR and PWV	0.597	0.118

6	SP and PWV	0.488	0.183
	DP and PWV	0.485	0.186
	MP and PWV	0.526	0.146
	HR and PWV	0.281	0.464
7	SP and PWV	0.048	0.881
	DP and PWV	0.134	0.679
	MP and PWV	0.149	0.645
	HR and PWV	0.257	0.421
8	SP and PWV	0.272	0.602
	DP and PWV	0.447	0.374
	MP and PWV	0.284	0.585
	HR and PWV	0.206	0.695
9	SP and PWV	0.318	0.314
	DP and PWV	0.249	0.435
	MP and PWV	0.351	0.263
	HR and PWV	0.289	0.362
10*	SP and PWV	0.897	0.001**
	DP and PWV	0.885	0.002**
	MP and PWV	0.894	0.001**
	HR and PWV	0.922	0.000**
11	SP and PWV	0.122	0.773
	DP and PWV	0.065	0.878
	MP and PWV	0.104	0.806
	HR and PWV	0.613	0.106
12	SP and PWV	0.157	0.644
	DP and PWV	0.016	0.962
	MP and PWV	0.077	0.823
	HR and PWV	0.197	0.561
13	SP and PWV	0.284	0.426
	DP and PWV	0.299	0.402
	MP and PWV	0.296	0.406
	HR and PWV	0.035	0.923
14	SP and PWV	0.671	0.069
	DP and PWV	0.532	0.174
	MP and PWV	0.665	0.072
	HR and PWV	0.344	0.404
15*	SP and PWV	0.710	0.032**
	DP and PWV	0.591	0.094
	MP and PWV	0.596	0.090
	HR and PWV	0.198	0.610
16	SP and PWV	0.064	0.881
	DP and PWV	0.016	0.970
	MP and PWV	0.009	0.984
	HR and PWV	0.030	0.944
17*	SP and PWV	0.627	0.043**
	DP and PWV	0.710	0.014**
	MP and PWV	0.668	0.025**
	HR and PWV	0.553	0.078

18	SP and PWV	0.142	0.762
	DP and PWV	0.014	0.976
	MP and PWV	0.158	0.735
	HR and PWV	0.571	0.180
19*	SP and PWV	0.676	0.032**
	DP and PWV	0.751	0.012**
	MP and PWV	0.749	0.013**
	HR and PWV	0.631	0.050
20	SP and PWV	0.277	0.507
	DP and PWV	0.198	0.638
	MP and PWV	0.178	0.673
	HR and PWV	0.048	0.910

SP:systolic blood pressure, DP: diastolic blood pressure, MP: mean arterial pressure, HR: heart rate, PWV: pulse wave velocity, r value: Pearson correlation coefficient; * indicates objects in which blood pressure, heart rate and PWV are correlated, ** indicates that $P < 0.05$ is statistically significant.

Discussion

Pulse wave velocity

The pulse wave is generated by the rhythmic contraction and relaxation of the heart, propelling blood into the aorta, and subsequently propagating along the arterial vascular system to peripheral vessels. This systematic, rhythmic oscillation of blood within the arterial vascular system constitutes the pulse wave. Pulse Wave Velocity (PWV) measures the speed at which the pulse wave travels along the arterial system and serves as a mechanical parameter directly associated with arterial stiffness. In the course of arteriosclerosis development, a reduction in blood vessel elasticity accelerates the propagation speed of the pulse wave in the arterial system. PWV serves as a diagnostic indicator for early detection of arteriosclerosis and is an independent predictor of cardiovascular events and all-cause mortality. It is considered the gold standard for evaluating arterial stiffness [5]. As vessel wall stiffness increases, compliance diminishes, and the function of the elastic reservoir of major arteries weakens, leading to an increase in PWV, signifying elevated arterial stiffness. The two-point method determines PWV by measuring the conduction time of the pressure waveform along two ends of a blood vessel, expressed as $PWV = L/\Delta t$, where L is the length of the blood vessel segment, and Δt is the conduction time of the pulse wave, i.e., the time difference between the two pulse waveforms. Currently, two widely adopted methods in medical practice for PWV evaluation are carotid-femoral PWV (cfPWV) [8], brachial-ankle PWV (baPWV) [9], also known as brachial-ankle PWV, and carotid-radial PWV (crPWV) [10], cardio-aortic PWV (aPWV) [11]. This study employs a local method, measuring the PWV of a specific blood vessel point without assessing the length of the blood vessel or the conduction time of the pulse wave. The local PWV measurement methods include ultrafast pulse wave velocity (UFPWV) [12] and Echo-tracking (ET) technology [13].

Pulse wave velocity and blood pressure

Arterial stiffness and blood pressure are intricately connected, exhibiting a complementary relationship. Elevated blood pressure induces mechanical stress on the blood vessel wall, leading to the breakdown of elastic fibers, vascular endothelial dysfunction, and contraction of vascular smooth muscles, resulting in increased vascular stiffness. Moreover, hypertension activates the renin-angiotensin-aldosterone system, promoting the proliferation of collagen fibers in the vascular wall and further contributing to increased vascular stiffness. As arterial stiffness rises, arterial compliance diminishes, and arterial wall baroreflexes decrease, ultimately causing a subsequent increase in blood pressure. PWV has been widely adopted to assess arterial stiffness, showing a rapid increase with escalating arterial stiffness [14]. Studies, such as that conducted by Yin ji Ma *et al.* [15] have demonstrated the association between blood pressure and PWV. The hyperelastic characteristics of blood vessels result in an increase in PWV as blood pressure rises. This study, through theoretical derivation and modeling, verified the linear relationship between blood pressure and PWV, suggesting the potential use of PWV for non-invasive blood pressure monitoring. Additionally, Teemu Koivistoinen *et al.* [16]

reported that pulse wave velocity can predict the onset and progression of hypertension in young individuals. In summary, PWV accelerates in hypertensive individuals, but whether this acceleration is due to hypertension-induced arteriosclerosis or the elevated blood pressure itself requires further clarification. The aim of this study is to assess the impact of blood pressure on PWV under real-time blood pressure monitoring. The study concludes that when the systolic blood pressure fluctuation range is ≥30mmHg, the diastolic blood pressure fluctuation range is ≥18mmHg, and the mean arterial blood pressure fluctuation range is ≥20mmHg, there is a significant increase in PWV measurement values. Correcting for the influence of blood pressure is crucial for accurately evaluating vascular sclerosis using PWV. Blood pressure emerges as a key factor affecting PWV, with systolic blood pressure, mean arterial pressure, and diastolic blood pressure potentially influencing PWV. Short-term fluctuations in individual blood pressure can also induce changes in PWV.

Pulse wave velocity and heart rate

While age and blood pressure are recognized as the primary determinants of PWV, the impact of heart rate on PWV measurement remains a subject of contention. Many studies exploring the effect of heart rate on PWV have yielded inconclusive results, often confounded by simultaneous changes in blood pressure. Despite researchers attributing heart-rate-related changes in arterial stiffness to the viscoelasticity of the arterial wall, the mechanisms underlying variations in heart rate affecting PWV remain incompletely understood [17]. Given that an elevated heart rate is an independent prognostic factor for cardiovascular disease and hypertension [18], understanding the interaction between heart rate and PWV remains crucial for assessing cardiovascular risk. Some studies suggest that a rapid increase in heart rate leads to an elevation in PWV [19-21]. Researchers speculate that the influence of heart rate is manifested through the frequency dependence and viscoelasticity of the artery wall. An elevated resting heart rate corresponds to increased stroke output, augmented intra-aortic blood flow velocity, and shortened tube wall retraction time, resulting in intensified pulsation and mechanical tension of the artery wall. This, in turn, increases shear stress, impacting the tube wall and leading to vascular oxidative stress, endothelial damage, changes in tube wall structure, and subsequent reactions such as smooth muscle cell migration and proliferation. These processes reduce blood vessel compliance and elevate artery wall stiffness. An increased resting heart rate is indicative of heightened sympathetic nerve excitation. Sympathetic nervous system activation accelerates metabolism, releasing carbon monoxide and other free radicals from the vascular endothelium. This contributes to increased permeability and impaired function of the vascular endothelium, heightened peripheral vascular resistance, and facilitates the formation and development of atherosclerosis. Furthermore, sympathetic nervous system activation stimulates heart rate and blood pressure, increasing hemodynamic fluctuations and further promoting arteriosclerosis. In this study, heart rate was found to impact PWV measurements, aligning with previous research. However, normal small-range heart rate fluctuations did not significantly affect pulse wave conduction velocity. The influence on PWV became substantial only when the heart rate fluctuation amplitude exceeded 30 beats/hour.

Blood pressure and heart rate exert a certain influence on PWV measurement, emphasizing the need to consider their impact when utilizing PWV for assessing arterial stiffness. This study uniquely employs real-time blood pressure monitoring to evaluate vascular elasticity using PWV, and it sheds light on the previously unexplored influence of blood pressure and heart rate on PWV measurement. The findings indicate that when systolic blood pressure fluctuates by ≥30mmHg, diastolic blood pressure fluctuates by ≥18mmHg, mean pressure fluctuates by ≥20mmHg, and heart rate exceeds 30 beats/min, PWV demonstrates an increase in response to elevated blood pressure and heart rate. In instances where PWV surpasses the normal reference value, it is essential to account for the influence of blood pressure and heart rate. Fluctuations in blood pressure and heart rate emerge as contributing factors to changes in PWV.

Conflict of Interest

There is no conflict of interest.

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Authors' contributions: JL and LQ carried out the studies, participated in collecting data, drafted the manuscript, performed the statistical analysis and participated in its design. BA and BS participated in acquisition, analysis, or

interpretation of data. XL participated in collecting data. All authors read and approved the final manuscript, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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