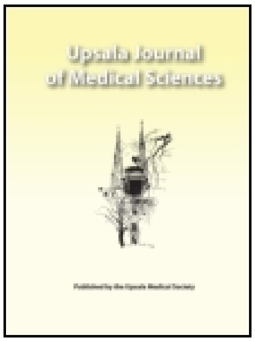

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ORIGINAL ARTICLE

Impedance cardiographic hemodynamic variables and hypertension in elderly Han residents

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Abstract

Objective. We studied the relationship between systolic blood pressure and hemodynamics using impedance cardiography in elderly Han residents in order to evaluate how different hemodynamic variables are altered with normal aging and with hypertension superimposed on aging.

Methods. A total of 670 subjects, aged 60–93 years, were evaluated with impedance cardiography for non-invasive hemodynamic variables. The subjects were categorized as hypertensives or normotensives, and then they were also divided into six subgroups according to actual systolic blood pressure values.

Results. Hypertensive patients had significantly lower values of cardiac output (4.4 ± 1.5 L/min) and cardiac index (2.6 ± 1.0 L/min/m^2) than those in the normotensive group (4.7 ± 1.5 L/min, and 2.8 ± 0.8 L/min/m^2, respectively; $P < 0.05$ for both). Compared to the normotensive group, stroke volume and stroke index values were also lower and systemic vascular resistance and systemic vascular resistance index were higher in the hypertensive group. There were no significant differences in left ventricular stroke work and left ventricular stroke work index between the two groups. When all 670 subjects were stratified to actual blood pressure, cardiac output of group 6 patients (systolic blood pressure ≥180 mmHg) was 19% lower than that of group 1 subjects (SBP <140 mmHg; $P < 0.05$). Similarly, systemic vascular resistance of group 6 patients was 56% higher than that of group 1 subjects ($P < 0.05$).

Conclusion. With aging, arterial systolic blood pressure is elevated as a result of increased arterial stiffness and increased systemic vascular resistance. With hypertension, these values are further elevated. Non-invasive impedance cardiography helps to characterize the hemodynamic mechanisms, which can improve hypertension management.

Key words: *aging superimposed, arterial systolic blood pressure, elderly Han residents, hemodynamics, hypertension*

Introduction

Hypertension is a highly prevalent cardiovascular disease worldwide. Important complications of uncontrolled or poorly treated hypertension include heart attack, congestive heart failure, stroke, kidney failure, peripheral artery disease, and aortic aneurysm (1). Many efforts have been made to control elevated blood pressure in hypertensive patients, and guidelines for hypertension management have established the therapeutic goal for the treated hypertensive patients (2,3). However, most evaluation studies have observed high percentages of uncontrolled hypertensive patients despite current therapeutic options (4,5). Epidemiologic studies report that on average only 25% of hypertensive patients have controlled blood pressure levels (6,7). In the elderly population, blood pressure control is even less successful. Many factors influence the control of blood pressure in hypertensive patients, including drug compliance, the choice of antihypertensive agent, blood vessel elasticity, the availability of medical care, and the presence of co-morbidities. Changes in hemodynamics also have effects on the ability to control blood pressure.

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The primary function of the cardiopulmonary system is to deliver an appropriate amount of oxygen and nutrients to meet the metabolic demands of the body and to remove metabolic waste products. Hemodynamics is defined as the study of the forces affecting the flow of blood throughout the body. In people with cardiovascular and systemic vascular dysfunction, hemodynamic imbalances occur and the body is forced to compensate, often severely. Hypertension affects hemodynamics, both directly and indirectly. Of the hemodynamic variables measured, left ventricular stroke work (LSW) has been most often used to assess patient prognosis. In recent years, left ventricular stroke work index (LSWI) has been used as a simple hemodynamic estimation of the severity of valvular aortic stenosis (8). Systemic vascular resistance (SVR) is defined as the resistance to the flow of blood in the vasculature, also known as afterload. The systemic vascular resistance index (SVRI) is defined as the systemic vascular resistance normalized for body surface area.

Since the 1970s, the clinical invasive measurement of cardiac output that utilizes a flow-directed, thermodilution catheter (also known as the Swan–Ganz catheter) has been available. This method represents significant risk to the patient, is costly, and requires a skilled physician in a sterile environment for catheter insertion. Developing a non-invasive protocol to monitor hemodynamics would be extremely valuable clinically because data similar to those achieved by invasive hemodynamic monitoring methods could be obtained with much lower cost and much less risk. There are multiple methods to monitor hemodynamic variables non-invasively, including pulse oximetry, heart rate variability, Doppler and B-mode echocardiography, transthoracic bioimpedance, pressure pulse waveform analysis, and near-infrared spectroscopy. All of these methods have a value in diagnosing and monitoring by hemodynamics. The vital hemodynamic measurements obtained from non-invasive monitoring could be extended to significantly more patients, including out-patients with chronic diseases. This also would make serial assessments more feasible.

Impedance cardiography is a low-cost, non-invasive test that measures systolic time intervals and hemodynamics both at baseline and with changes in electrical impedance during the cardiac cycle. Impedance cardiography proved to be accurate and reproducible in studies comparing impedance cardiography with thermodilution method using a pulmonary artery catheter (9,10). Impedance cardiography has been used to explore age-related changes in hemodynamic variables, and correlations between variables and cardiovascular risk have been made. Use of impedance cardiography improved blood pressure control in resistant hypertension when used by both specialists (11) and general practitioners (12), as it provided a means to diagnose hypertension that was likely to be resistant to first-line therapy options. Using impedance cardiography improves blood pressure control, because it makes it easier accurately to assess baseline hemodynamic status, which is useful for clinicians who develop a therapeutic regimen based on hemodynamic status. Impedance cardiography also measures changes in various hemodynamics in response to therapy. These studies suggest that future risk in patients with hypertension may not be reflected by blood pressure levels alone.

Age is a major risk factor for development of arteriosclerosis and arterial elastic stiffening. In this study, we compared hemodynamic variables between aging normotensive subjects and aging hypertensive patients and studied the relationship between systolic blood pressure and hemodynamics using impedance cardiography in elderly Han residents.

Methods

Participants

The study population consisted of 4,782 permanent residents living in a district in Shanghai, China. The main inclusion criterion was age ≥60 years. Subjects with chronic heart failure, pacemaker implantation, severe hepatic disease, severe renal impairment (GFR <30 mL/(min × 1.73 m^2)), any life-threatening disease, drugs and/or alcohol abuse were excluded. A total of 676 participants were prospectively enrolled between November 2009 and July 2010. None of these participants was under treatment with antihypertensive agents. Of those, 670 patients agreed to undergo the examination and were evaluated for non-invasive hemodynamics. The 670 subjects (372 females and 298 males) were aged 60 to 93 years. The Ethics Committee of Huashan Hospital, China approved the study. All participating persons gave informed consent, and written informed consent to participate in the study was obtained prior to any study procedure.

To analyze the changes of hemodynamics in hypertension, we divided all participants into two subgroups by history of blood pressure. There were 362 subjects with history of hypertension (hypertensives) and 308 subjects with no previous history of hypertension (normotensives).

To study further the association between systolic blood pressure (SBP) and hemodynamics, we divided all 670 participants into six subgroups according to the actual SBP values taken during the

Table I. Clinical characteristics of 670 subjects.

	Total
	n = 670
Age (years)	69 ± 8
Height (cm)	161 ± 8
Weight (kg)	64 ± 11
BMI (kg/m^2)	25 ± 3
Body surface area (m^2)	1.7 ± 0.2
Diagnosis	
Hypertension, n (%)	362 (54)
Diabetes mellitus, n (%)	82 (12)
Hyperlipidemia, n (%)	222 (33)

Impedance Cardiography (ICG) examination. There were 323 subjects constituting group 1 with SBP <140 mmHg, 123 patients in group 2 with SBP ≥140 and <150 mmHg, 89 patients in group 3 with SBP ≥150 and <160 mmHg, 68 patients in group 4 with SBP ≥160 and <170 mmHg, 35 patients in group 5 with SBP ≥170 mmHg and <180 mmHg, and 32 patients in group 6 with SBP ≥180 mmHg.

Participant baseline characteristics

Table I shows the baseline clinical features and exercise information for these participants. SBP and diastolic BP (DBP) were measured twice while the patient was seated and rested for at least 2 min.

Hypertension definition

Hypertension was defined as a DBP ≥90 mmHg and/or a SBP ≥140 mmHg. In patients with diabetes or chronic renal impairment (not regarded as 'severe'; GFR ≥30 mL/(min × 1.73 m^2)), hypertension was defined as a DBP ≥80 mmHg and/or a SBP ≥130 mmHg.

Impedance cardiography

Bioimpedance equipment (CS Bio Technology, Cheer Sails medical, CSM3000, Shenzhen, China) was used to examine the cardiac function and hemodynamic status of the participants. The electrical bioimpedance monitor used eight disposable single-use spot electrodes. One pair was used to detect the impedance signal at the appendix level, and a second pair detected the signal on the neck. The upper pair of measuring electrodes (U1) was placed symmetrically along the lateral lines of the patient's neck, ~4 cm above the base of the neck. The lower pair of measuring electrodes (U2) was placed at the xiphoid level. This pair consisted of four spot electrodes (contact area of 4 cm^2 each) placed on top of a 25 cm^2 rectangle. The low skin contact electrode configuration is suitable for a wide range of patients.

Hemodynamic variables

Table II lists the actual hemodynamic variables that were measured. The hemodynamic variables CO, CI, SV, SVI, LSW, LSWI, SVR, and SVRI refer to the function of the heart itself. For the pulmonary artery wedge pressure (PAWP), normal adult values range from 6 to 12 mmHg, and the normal range for right atrial pressure (RAP) is 2 to 6 mmHg. The two variables, LSW and LSWI, are used to estimate the severity of valvular aortic stenosis. SVR is the resistance of blood flow in the vasculature. The SVRI is defined as systemic vascular resistance normalized for body surface area. These two variables reflect the afterload of the heart and the amount of arteriosclerosis in the systemic artery or vein. All of the above hemodynamic variables were automatically obtained using impedance cardiography.

Statistical analyses

Continuous variables that show normal distributions, as documented using the Kolmogorov–Smirnov test,

Table II. Calculations of hemodynamic variables in 670 subjects.

Variable	Formula
Cardiac output (CO)	CO = heart rate × stroke volume (L/min)
Cardiac index (CI)	CI = CO/body surface area (L/min/m^2)
Stroke volume (SV)	SV = end diastolic volume – end systolic volume
Stroke volume index (SVI)	SVI = CI/heart rate × 1000 (mL/m^2/beats/min)
Left stroke work (LSW)	LSW = SV × (MAP – pulmonary artery wedge pressure) × 0.0136 (gm-m/beat)
Left stroke work index (LSWI)	LSWI = SVI × (MAP – PAWP) × 0.0136 (gm-m/m^2/beat)
Stroke systemic vascular resistance (SVR)	SVR = 80 × (MAP – RAP)/CO (dyne s/cm^5)
Stroke systemic vascular resistance index (SVRI)	SVRI = 80 × MAP – RAP)/CI (dyne s/cm^5/m^2)

Table III. Comparison of clinical characteristics of 670 subjects divided into a normotensive group and a hypertensive group based on patient history.

	Normotensive group n = 308	Hypertensive group n = 362
Female (%)	161 (52%)	211 (58%)
Age (years)	67 ± 10	71 ± 8
Height (cm)	163 ± 11	159 ± 7
Weight (kg)	63 ± 12	65 ± 12
BMI (kg/m^2)	24 ± 3	26 ± 5
Diabetes mellitus (%)	34 (11%)	48 (13%)
Hyperlipidemia (%)	99 (32%)	123 (34%)
Smoking (%)	21 (7%)	34 (9%)
Alcohol use (%)	37 (12%)	31 (9%)
Exercise history (times/week)	3 ± 1	3 ± 2

No variables were statistically significant between the two groups.

are presented as mean ± SD. The Student's t test was used to compare these continuous characteristics. Independent variables were analyzed by the chi-square test. Comparisons across each group were made using analysis of variance (ANOVA) for continuous variables. Comparisons of hemodynamic variables between hypertensive and normotensive groups were performed by unpaired t test. Relationships between hemodynamic variables and MAP (MAP = (systolic BP + (2 × diastolic BP)/ 3)) were explored using Pearson's correlation analysis, as well as relationships between hemodynamic variables and age. All statistical analyses were performed using SPSS software version 11.0 (SPSS Inc., Chicago IL, USA). Statistical significance was accepted at a value of $P < 0.05$.

Results

Clinical characteristics

Mean values ± SD concerning age and some other characteristics of participants are given in Table I. Table III shows a comparison of clinical data between the normotensive group and the hypertensive group.

Comparison of hemodynamic variables between normotensive subjects and hypertensive patients

As shown in Table IV, the patients in the hypertensive group had significantly lower values of CO ($P = 0.01$) and CI ($P = 0.006$) than those in the normotensive group. The values of SV and SVI were also lower in the hypertensive group than in the normotensive group ($P < 0.05$). SVR and SVRI values were significantly higher in hypertensive patients compared to normotensive subjects ($P < 0.001$). There were no significant differences in LSW and LSWI between the two groups ($P = 0.42$ for LSW and $P = 0.15$ for LSWI).

Hemodynamic variables in six SBP subgroups

Generally, there was no difference in the CO value between normotensive subjects (group 1) and hypertensive patients (groups 2–4), but CO values decreased significantly in group 5 and group 6 (both $P < 0.05$). Similarly, CI was significantly lower in group 6 compared to group 1 ($P < 0.05$; Table V).

SVR and SVRI both increased with the increase in SBP. SVR was significantly higher in groups 4, 5, and 6 compared to group 1 (all $P < 0.05$). The value of SVR in group 6 patients was 56% higher than that in

Table IV. Comparison of hemodynamic variables between the normotensive group and the hypertensive group.

	Normotensive group n = 308	Hypertensive group n = 362	P
CO (L/min)	4.7 ± 1.5	4.4 ± 1.5	0.01
CI (L/min/m^2)	2.8 ± 0.8	2.6 ± 1.0	0.006
SV (mL)	68.7 ± 23.3	62.0 ± 22.8	< 0.001
SVI (mL/m^2)	42.5 ± 25.7	36.7 ± 13.1	< 0.001
SVR (dyne s/cm^5)	310.0 ± 263.3	387.5 ± 220.1	< 0.001
SVRI (dyne s/cm^5/m^2)	179.4 ± 81.4	226.2 ± 112.2	< 0.001
LSW (gm-m/beat)	73.8 ± 26.2	72.1 ± 27.0	0.42
LSWI (gm-m/m^2/beat)	44.4 ± 14.4	42.7 ± 15.4	0.15
PP/SV (mmHg/mL)	0.60 ± 0.06	0.87 ± 0.05	< 0.001

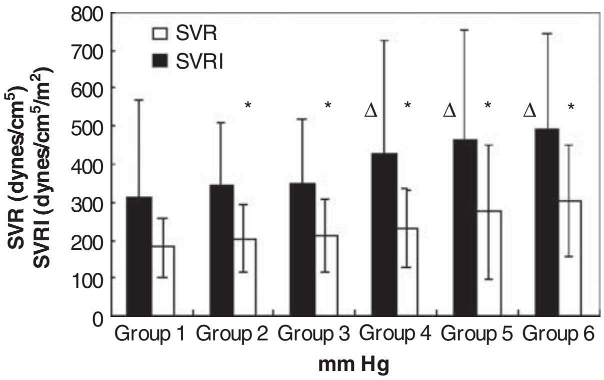

Figure 1. Distribution of SVR (dyne s/cm^5) and SVRI (dyne s/cm^5/m^2) among the six subgroups. Data are mean ± SD. SVR: Δ $P < 0.05$ versus group 1. SVRI: * $P < 0.05$ versus group 1.

group 1 subjects. The SVRI value increased with increasing SBP as well (Figure 1).

There were no significant differences in SV among participants in groups 1–4 (all with SBP <170 mmHg). However, SV was significantly lower in patients of groups 5 and 6 compared to subjects in group 1 ($P < 0.05$). SVI was significantly lower in group 6 compared to group 1 ($P < 0.05$). There were no differences in LSW and LSWI in groups 1–6 (Table V). The ratio of pulse pressure (PP = SBP – DBP) to SV increased with increasing levels of SBP, and this ratio was 80% higher in group 6 than it was in group 1.

Correlations between hemodynamic variables and SBP

Table VI shows correlation coefficients between hemodynamic variables and SBP of the 670 participants. The highest correlations were found between SVR and SBP ($R = 0.20$, $P < 0.0001$), and between SVRI with SBP ($R = 0.30$, $P < 0.0001$). The PP/SV ratio also displayed a strong positive correlation with SBP ($R = 0.49$, $P < 0.0001$).

Table VI. Correlation coefficients (R) between various hemodynamic variables and SBP in 670 subjects.

Comparison (n = 670)	Correlation coefficient (R)	P
CO (L/min)	–0.10	< 0.05
CI (L/min/m^2)	–0.09	< 0.05
SV (mL)	–0.14	< 0.001
SVI (mL/m^2)	–0.15	< 0.001
SVR (dyne s/cm^5)	0.20	< 0.0001
SVRI (dyne s/cm^5/m^2)	0.30	< 0.0001
LSW (gm-m/beat)	0.07	0.08
LSWI (gm-m/m^2/beat)	0.04	0.25
PP/SV (mmHg/mL)	0.49	< 0.0001

Correlations between hemodynamic variables and MAP

Pearson's correlation analysis revealed that CO and CI correlated inversely with MAP (R = –0.08, $P < 0.05$; R = –0.09, $P < 0.05$, respectively). SVR and SVRI correlated positively with MAP ($R = 0.35$, $P < 0.001$; $R = 0.47$, $P < 0.001$, respectively). LSW, too, correlated positively with MAP ($R = 0.17$, $P < 0.001$) as well as LSWI ($R = 0.14$, $P < 0.001$).

Discussion

Hypertension remains the most common risk factor for cardiovascular morbidity and mortality. The incidence of hypertension is rising in China and the rest of the world, in part due to an increased incidence of risk factors such as dietary sodium, obesity, physical inactivity, excessive alcohol intake, psychological stress,

Table V. Hemodynamic variables in groups 1–6 stratified to systolic blood pressure levels.

	Group 1 n = 323	Group 2 n = 123	Group 3 n = 89	Group 4 n = 68	Group 5 n = 35	Group 6 n = 32
SBP (mmHg)	<140	≥140–<150	≥150–<160	≥160–<170	≥170–<180	≥180
CO (L/min)	4.6 ± 1.5	4.5 ± 1.5	4.7 ± 1.6	4.5 ± 1.7	4.0 ± 1.3[a]	3.7 ± 1.6[a]
CI (L/min/m^2)	2.8 ± 0.8	2.7 ± 0.9	2.8 ± 0.9	2.6 ± 0.9	2.7 ± 1.8	2.2 ± 0.9[a]
SV (mL)	67.2 ± 22.7	65.6 ± 23.7	66.1 ± 23.8	62.9 ± 25.4	57.6 ± 19.4[a]	50.3 ± 19.1[a]
SVI (mL/m^2)	41.5 ± 25.2	39.3 ± 14.0	39.3 ± 13.3	36.3 ± 12.4	34.0 ± 11.3	30.5 ± 10.5[a]
SVR (dyne s/cm^5)	314.1 ± 256.5	343.6 ± 168.6	350.9 ± 167.3	427.7 ± 295.4[a]	464.1 ± 289.2[a]	492.4 ± 252.4[a]
SVRI (dyne s/cm^5/m^2)	181.2 ± 77.5	203.5 ± 91.4[a]	211.2 ± 98.9[a]	231.2 ± 103.4[a]	273.09 ± 176.1[a]	302.3 ± 148.3[a]
LSW (gm-m/beat)	70.5 ± 25.1	75.0 ± 27.2	77.9 ± 28.1	78.2 ± 33.7	73.4 ± 26.2	65.0 ± 26.1
LSWI (gm-m/m^2/beat)	43.6 ± 14.3	45.5 ± 16.1	46.2 ± 16.0	45.6 ± 16.2	42.7 ± 16.9	40.0 ± 14.4
PP/SV (mmHg/mL)	0.62 ± 0.05	0.72 ± 0.04[a]	0.74 ± 0.04[a]	0.78 ± 0.03[a]	0.94 ± 0.05[a]	1.12 ± 0.05[a]

[a]$P < 0.05$ versus Group 1.

and increased survival of our aging population. The clinical burden of hypertension is predicted to increase between now and 2025 due to the increasing number of people with hypertension in China (13).

This study is the first to present hemodynamic variables for the Han elderly population and to provide details how hemodynamic variables change with age in hypertensive subjects. Hypertension represents an imbalance of hemodynamic forces within the circulation. It is usually characterized by elevated SVR and abnormal hemodynamics, which play a central role in the development and perpetuation of high blood pressure. In this study, we used impedance cardiography to measure hemodynamic variables in elderly subjects.

The small difference in age between the hypertensive patients and normotensive subjects was not statistically significant. We found significant changes in multiple hemodynamic variables (CO, CI, SV, SVI, SVR, and SVRI) in Han patients with hypertension. The hypertensive patients showed impaired cardiac function and increased SVR. CO and CI were both lower in these patients. Stratifying our data to SBP revealed that CO and CI levels did not differ proportionally to SBP but were abruptly decreased in patients with SBP >170 mmHg. The same trend was also seen for SV and SVI.

Hypertension may influence the heart's ability to pump blood, even in patients with higher SBP, and higher SBP was shown to significantly impair cardiac contractile function. Lund-Johansen found a significant and progressive decrease in CO with borderline hypertension at 10 and 17 years of follow-up, although there were no differences in CO or CI in patients with borderline hypertension (14). In addition to impaired heart pump function, SVR was also increased. Increases in SVR and SVRI were accompanied by increased SBP as well. Considering body surface area, SVR became impaired when SBP exceeded 140 mmHg. In aged people, elevated arterial BP is the result of increased arterial stiffness and increased SVR, and this increase in SVR has been reported by others (14). SVR and SVRI are important markers in the treatment and control of hypertension.

Arterial compliance is another important determinant of hypertension and is a complex variable determined by PP and SV. Studies have shown that arterial compliance can be reliably estimated as the ratio of PP to SV. In this study, SV and SVI were significantly lower in hypertensive patients. The ratio of PP to SV (the reciprocal of arterial compliance) is higher in hypertensive patients compared to normotensive subjects. PP-to-SV ratios increased with SBP, which may provide a useful functional index to evaluate heart pump function in hypertensive patients. The ratio of PP to SV is independently associated with cardiovascular events or death (15). By stratifying the aged participants by SBP, a key finding of our present study was that SVR and SVRI increased with SBP.

CO and CI were not changed proportionally to SBP but were significantly lower at SBP ≥170 mmHg. In aged patients, hypertension is more commonly associated with elevated SVR. The fact that CO and CI decreased with increased SBP may be an effect of aging that is caused by decreased aortic and vascular compliance, decreased myocardial contractility, decreased intravascular volume, and increased systemic vascular resistance. There were no significant differences in SV and SVI. When we evaluated the ratio of PP to SV, however, significant differences were seen among the groups. A higher SBP was associated with higher SVRI, and decreased arterial compliance was often associated with increased SVR, which is consistent with the known pathophysiology of hypertension. Slotwiner et al. found that the ratio of PP to SV increased with age, whereas CO and SVR levels did not vary significantly with age (16). In our study, participants were all over 60 years old, and we found that the ratio of PP to SV increased with SBP. This may be another hemodynamic mechanism that is a key to the pathophysiology of hypertensive cardiovascular disease in elderly people. No differences were observed in LSW and LSWI when SBP increased.

MAP correlated with CO, CI, SVR, and SVRI. MAP is the product of CO and SVR, and elevation of BP can result from the elevation of either or both. In our study, we found that CO and CI correlated inversely with MAP and that SVR and SVRI correlated positively with MAP.

We also found that the significant differences in hemodynamic variables versus the different SBP levels reflect the progression of changes in hemodynamic characteristics with the severity of hypertension. In the clinic, there is a limited ability to determine vascular resistance using measurement of BP alone. The accuracy of predicting the hemodynamics by clinical evaluation is low (17). Hypertension management is even less successful in an elderly population. Our findings provide some additional insight into the mechanism of hypertension in an elderly population (18). In aged people, elevated arterial BP is the result of increased arterial stiffness and increased SVR. The findings of this study may provide support for future studies linking the use of impedance cardiography-guided therapy to improvement in BP control. From a hemodynamic point of view, the ideal treatment regimen for hypertension should lower BP while normalizing CO and SVR. Studies support the view that when medications appropriately target the underlying hemodynamic abnormalities in patients with hypertension, BP is more effectively controlled (19). Resnick and Lester found that despite similar changes in SBP, DBP, and PP during treatment, there were improvements in arterial compliance with angiotensin-converting-enzyme inhibitor (ACEI), angiotensin receptor blocker (ARB), and calcium channel blockers (CCB) but not with β-blockers (20). Taler et al. randomized 104 patients with hypertension uncontrolled by two or more drugs in a 3-month trial of impedance cardiography-guided therapy or standard therapy directed by a hypertension specialist (11). In this study, BP control was achieved 70% more often in the impedance cardiography-guided group. Use of impedance cardiography resulted in greater reductions in SVR.

Conclusion

Hypertension is characterized by significant alterations in multiple hemodynamic variables that vary with the different SBP levels. In aged people, elevated arterial SBP is the result of increased arterial stiffness and increased SVR. Non-invasive impedance cardiography can help characterize hemodynamic values and may improve hypertension management.

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Declaration of interest: We declare that we have no conflicts of interest. The producer of the CSM 3000 did not sponsor this study. Authors alone are responsible for the content and writing of the paper.

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