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Different Methods for Measurements and Estimation of Pulse Wave Velocity are not Interchangeable

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Abstract

Background Carotid-femoral pulse wave velocity (c–f PWV) is a gold standard for the arterial stiffness measurement and important biomarker for the assessment of the cardiovascular (CV) risk. Recent studies have focused on 24-h measurements of arterial stiffness and estimated PWV (ePWV). The aim of this study is to analyze agreement of office c–f PWV measurements (SphygmoCor) with 24-h oscillometric measurements (Mobil-O-Graph and Arteriograph), and with ePWV.

Results This study included 154 patients with primary hypertension (average age 38.75 ± 12.65). Arterial stiffness has been measured in the office with SphygmoCor and 24 h with two oscillometric methods (Mobil-O-Graph and Arteriograph). ePWV was calculated using validated equation. PWV values obtained in office (SphygmoCor) showed higher average values compared to both 24-h oscillometric measurements of PWV and ePWV. The mean values of 24-h PWV measured by Arteriograph were higher compared to values obtained with Mobil-O-Graph. The measurement of PWV over 24 h using the Arteriograph is the most accurate among the methods that were compared with the office PWV measurements (accuracy of 0.989). However, the most precise method was the Mobil-O-Graph (0.631), and the highest degree of agreement also was shown with the Mobil-O-Graph (concordance coefficient correlation (CCC) = 0.447). The smallest deviation (TDI) and the highest probability of overlapping (CP) were observed with ePWV (TDI = 45.524, CP = 0.322, respectively).

Conclusion In our group of young treated mild hypertensive patients with low CV risk, we found weak agreements between cfPWV and 24-h PWV. These methods are not interchangeable.

Keywords Arterial stiffness, Carotid-femoral pulse wave velocity, 24-h measurements, Estimated pulse wave velocity

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1 Background

Arterial stiffness measured directly and non-invasively by carotid-femoral pulse wave velocity (c-f PWV) is an important biomarker of cardiovascular (CV) risk, predicting CV morbidity and mortality independently of traditional risk factors [1–4]. Carotid-femoral PWV is the gold standard for the measurement of arterial stiffness, and has been considered as a surrogate marker for arterial hypertension (AH)-mediated target organ damage (HMOD) [5–7]. Many studies have verified the predictive value of c-f PWV for CV, and c-f PWV was included

in the ESH/ESC guidelines for the management of AH [8]. The measurement of arterial stiffness represented by PWV is an integrator of all the damage done to the arterial wall in response to traditional CV risk factors and to different, poorly identified, non-traditional risk factors such as gestational age, birth weight, genetics and epigenetics factors, etc., which are not included in traditional CV scorings [9–11]. Recent studies have focused on devices for the 24-h measurement of arterial stiffness. Technological advances have allowed the non-invasive assessment of arterial stiffness in ambulatory conditions with portable monitors, mostly based on the oscillometric methods of measurements in the brachial artery. Mobil-O-Graph and Arteriograph are validated oscillometric devices for the 24-h assessment of PWV, central aortic pressure (CAP) and the augmentation index (AiX). Such oscillometric devices have provided an accurate and reproducible estimates of 24-h arterial stiffness [12–14]. The results of a number of recent studies have shown that arterial stiffness estimated over 24 h offers better correlation with preclinical organ damage in comparison to both the standard peripheral blood pressure (BP) measurement and office arterial stiffness measurements [15–17].

The main aim of this study is to explore the concordance, correlation, and overlap between office c-f PWV and 24-h oscillometric PWV measurements using Mobil-O-Graph and Arteriograph, and with the estimated PWV (ePWV) calculated on the basis of validated equation.

2 Methods

2.1 Patients Characteristics

This study included 154 patients, over the age of 18 with a diagnosis of primary AH. The participation rate was 90.2%.

The study flow chart diagram of enrollment of patients is shown in Fig. 1.

The research was conducted at the Department of Nephrology, Arterial Hypertension, Dialysis and Kidney Transplantation of the University Hospital Centre of Zagreb.

The patients were completely evaluated to exclude secondary forms of AH, and after the diagnosis of primary (essential) AH was established, they were included in the study.

The inclusion criteria were: (a) aged over 18 years; (b) diagnosed with primary AH; and (c) having given their signed informed consent. The exclusion criteria were: (a) a diagnosis of resistant AH; (b) any previous myocardial infarction and/or stroke, heart failure; (c) CKD (eGFR (CKD-EPI) < 60 ml/min/1.73 m^2); (d) ACR > 30 m/g; (e) a diagnosis of malignant or inflammatory diseases (e.g., rheumatoid arthritis, systemic lupus, inflammatory bowel diseases); (f) a diagnosis of a terminal illness and life expectancy less than 6 months; (g) pregnancy and lactation; (h) patients with an amputation of one or more limbs, (i) patients with dementia or cognitive dysfunction; and (j) a failure to give signed informed consent.

2.2 Procedure

During the study visit, participants provided their signed informed consent, and after that, an interview (structured questionnaire) was conducted, and clinical examination and measurements were performed. The structured questionnaire included data on various demographic, socioeconomic, and clinical parameters.

A sample of 10.5 mL of fasting venous blood was taken from each subject (3 mL tubes with EDTA for complete blood count, 4 mL tubes without additives for biochemistry, and 3.5 mL tubes with citrate anticoagulant). The complete blood count was determined according to the principle of laser light scattering technology (hematology analyzer XN 1000, Sysmex). Serum creatinine (continuous photometry with alkaline picrate; Architect analyzer device, Abbott reagent, standardized according to IDMS) and serum glucose (UV photometry with hexokinase; Architect analyzer device) were measured from centrifuged blood (10 min at 3500 revolutions at room temperature). Triglycerides (photometry with glycerol phosphate oxidase, GPOPAP), total cholesterol (photometry with cholesterol oxidase, CHOD-PAP), HDL-cholesterol (homogeneous enzyme immunoinhibition method), and LDL-cholesterol (homogeneous method with CHE, CHOD—DSBmT) were also measured. On the same platform, that is, on the Architect system, Abbott, USA, with original reagents from the same manufacturer, other biochemical findings were made: alkaline phosphatase (photometric IFCC method), gamma-glutamyl transferase (photometric IFCC method), aspartate aminotransferase (photometric UV method with L-aspartate without pyridoxal phosphate), alanine aminotransferase (photometric UV method with L-alanine without pyridoxal phosphate), lactate dehydrogenase (photometric UV IFCC method), bilirubin (photometric method with diazo-sulfanilic acid), C-reactive protein (immunoturbidimetric method with latex particles), uric acid (photometric method with uricase), serum electrolytes (indirect potentiometric method), calcium in serum (photometric method with arsenazo-III chromogen), serum phosphorus (photometric method with ammonium molybdate), and bicarbonates (indirect potentiometric method). In addition, the following were determined from the blood: insulin and NTpro-BNP (electrochemiluminescent immunoassay ECLIA, measuring instrument Cobas e 411, Roche), renin (immunoradiometric method IRMA, measuring instrument gamma counter), and fibrinogen

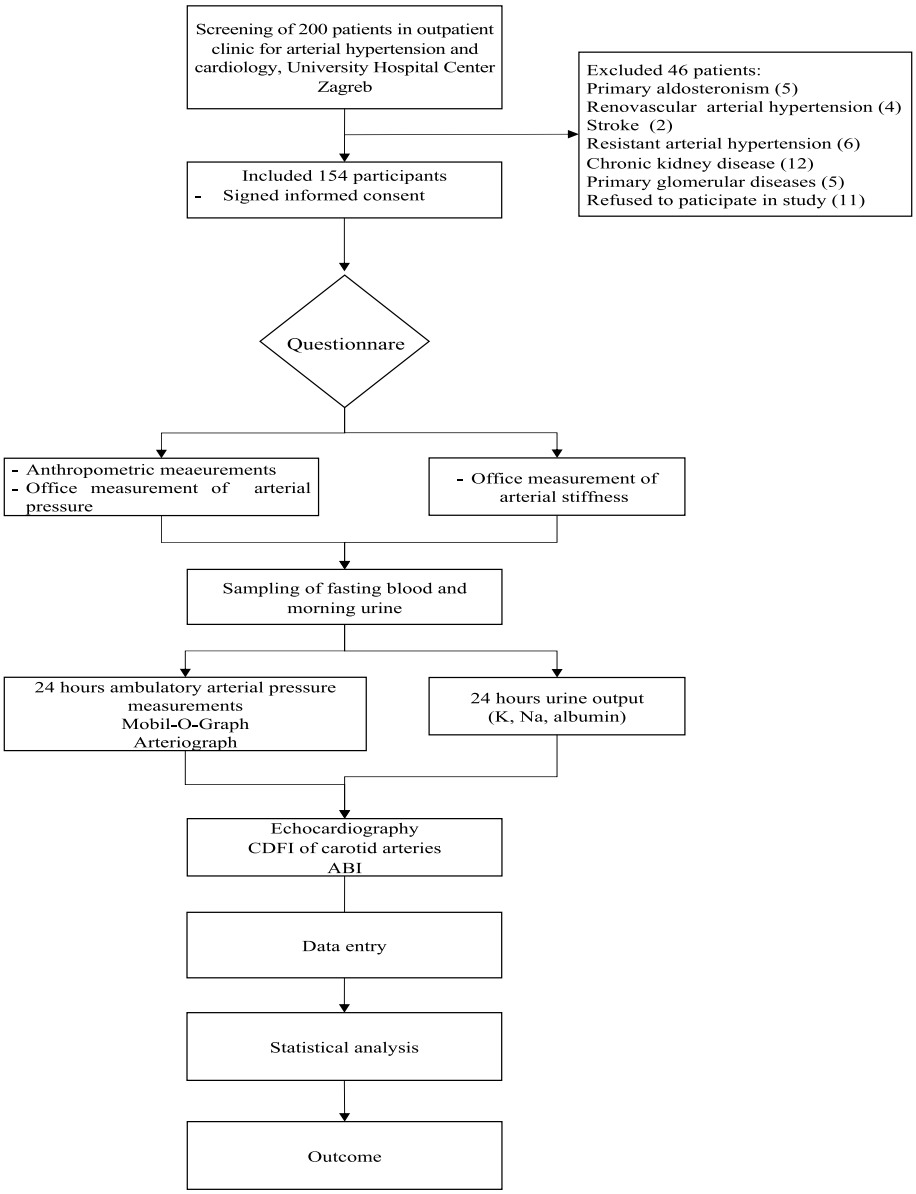

Fig. 1 Flow chart diagram of patient enrollment

(coagulometric method; coagulometric analyzer BCS XP, Siemens).

The estimated daily salt intake from the 24-h natriuretic data was calculated according to Eq. (18): 1. Na (mmol/l) × 0.023 = Na (g); 2. Na (g) × 1.05 × 2.542 = NaCl (g).

Insulin resistance and pancreatic beta cell function were assessed using the HOMA method—HOMA-IR (*Homeostasis Model Assessment for Insulin Resistance*) and i HOMA-β (*Homeostasis Model Assessment of β-Cell Function*), respectively [19]. HOMA (IR) = (FPIxFPG)/22.5;

HOMA β (%β) = HOMA (IR)-(20xFPI)/)FPG-3.5). Explanation of abbreviations: HOMA-IR = HOMA index of insulin resistance (Homeostasis Model Assessment for Insulin Resistance), HOMA-β = HOMA index for assessing the proportion of functional beta-cells of the pancreas (Homeostasis Model Assessment of β-Cell Function, % β); FPI = insulin concentration in fasting blood, mIU/l (fasting plasma insulin); FPG = fasting blood glucose concentration, mmol/l (fasting plasma glucose). Insulin resistance is defined by HOME-IR index values: HOME-IR < 2.5 no insulin resistance; HOME-IR > 2.5 is insulin resistance [20].

Blood pressure (BP) was measured with a validated automatic oscilometric device (Omron M6) in a sitting position, after 5 min of resting, first on both arms in a sitting position and then on the arm with the higher systolic BP. If there was no difference in systolic BP, the BP was measured on the arm with the higher diastolic BP. If there were no differences in either systolic or diastolic BP, a further three measurements were made on the arm that was not dominant. The average value of BP was calculated, which was later used in statistical processing. On the same day, an office measurement of the arterial stiffness was performed using the SphygmoCor device (SphygmoCor®, AtCor Medical Pty LTd, Syndey, Australia) as a standard tonometric procedure. The measurement was made according to the Recommendations of the Society for Vascular Medicine (Artery), after 10 min of rest, on the dominant side of the body [21]. The subjects were instructed not to smoke cigarettes or drink coffee for a total of 4 h prior to the test. The distance between the carotid and femoral arteries was measured by measuring two distances: 1. the distance between the middle of the sternocleidomastoid muscle and the jugular fossa; and 2. the distance between the jugular fossa and the inguinal symphysis. The distances were calculated automatically by entering the data into an appropriate software program, and the distance was calculated based on the difference between those two points. Data on body weight and height were also entered into the data base. At the same time as the measurement of carotid PWV, an electrocardiogram was recorded. The same was repeated when the femoral PWV was measured. Carotid-femoral PWV was calculated according to the equation: PWV = D (m)/Δt(s) (D = distance assimilation from the two recording locations). The ambulatory measurement of BP (ABPM) using Mobil-O-Graph®, I.E.M. GmbH, Stolberg, Germany with a corresponding cuff on the non-dominant arm was also performed. On the same device, the estimated 24-h values of PWV, systolic, and diastolic CAP, AiX were determined, since the device was upgraded with special ARSCSolver software (AIT Austrian Institute of Technology GmbH, Vienna, Austria). Age, BP, body weight, and body height were integrated into the mathematical model, which provided estimated 24-h PWV values. The next day, an Arteriograph was placed on the non-dominant arm. In the Arteriograph technique (Arteriograph; TensioMed, Budapest, Hungary), the cuff was placed on the non-dominant arm; pressure variations in the hand affect the pressure receptors in the cuff and are transmitted via the infrared port to the computer. Arteriograph software version v. 1.9.9.12 was used for the calculations. Estimated pulse wave velocity (ePWV) was calculated for the participants according to Eq. (22): ePWV = 9.587—(0.402 × age) + [4.560 × 0.001 x (age2)]—[2.621 × 0.00001 x (age2) x systolic AT] + (3.176 × 0.001 x age x systolic AT)—(1.832 × 0.01 x systolic AT).

2.3 Statistical Analyses

The data of the categorical variables are presented as both number (n) and percentages (%). The data of the continuous variables are presented as the mean and the SD (standard deviation) and as the median and corresponding 25th and 75th percentile for skewed variables. All variables were checked for normality using descriptive statistics, plots, and tests for normality. The comparison of the continuous variables between individual groups was performed using the Student *t* test and the ANOVA test, and the comparison of the categorical variables between individual groups was examined using the Chi-square test. Univariate and multivariate linear regression methods were used. For post hoc comparisons of mean arithmetic value, the LSD test was used. The Bland–Altman method was used for the assessment of the mutual matching of pairs of measures (i.e., the method of measuring a certain parameter), within which 95% confidence intervals were obtained. The results of this analysis are shown on the appropriate, characteristic diagram for this method. Total deviation index (TDI), overlap probability (CP), correlation coefficient (CCC), interval of agreement (loA), and bias were also calculated. Total deviation index (TDI) implies that 90% of the values obtained by measurement deviate in one way ± as much as the TDI value; the higher the TDI, the greater the deviation is. CP—coverage probability, the higher it is, the agreement between the methods should be greater. The concordance correlation coefficient (CCC) represents a measure of the agreement of values obtained, for example, by applying two different methods (one is, for example, the gold standard, and the other, for example, a new method); CCC—measure of the precision and accuracy of a measurement/method.

LoA—interval of agreement (limits of agreement)—has a lower and upper limit value, between which there is 95% of the difference in values obtained by different methods. Bias—arithmetic mean of differences in pairs of values obtained by two different methods.

Linear regression analysis was used to access capacity of systolic and diastolic arterial pressure for prediction of different PWV values.

The statistical calculations were performed by SPSS statistical software (IBM® SPSS®, version 26). We deemed the statistical significance at $\alpha < 0.05$.

3 Results

The study included 154 patients with primary AH with an average age 38.75 ± 12.65, predominantly men (69.5%). The majority of participants were overweight (48.7%).

One quarter (25.5%) of the participants were born preterm. A majority of the study participants had positive heredity on AH (89.6%) and CV diseases (65.4%).

The relevant demographic, clinical, and anthropometric characteristics of the participants are presented in Table 1.

Office measurements of PWV (SphygmoCor) showed higher average values compared to both 24-h, oscillometric measurements of PWV and ePWV. The mean values of 24-h PWV measured by Arteriograph were higher compared to the measurements made by Mobil-O-Graph. The average values of PWV measured in the office and over 24 h are presented in Table 2.

The results of the LSD test (Table 3) showed the statistically significant differences in the PWV values measured in the office with SphygmoCor and the Mobil-O-Graph (over 24 h), in favor of the first method of measurement. The average PWV values measured by Arteriograph (over 24 h) were statistically significantly higher compared to the PWV values measured using the Mobil-O-Graph. On the other hand, there was no statistically significant difference in the PWV values when the office measurement by the SphygmoCor was compared with the average values measured over 24 h with the Arteriograph and with the ePWV.

To examine the concordance of the 24-h measurements and ePWV with the office measurement of PWV using the SphygmoCor, the "gold standard", the following parameters were calculated: accuracy, precision, the correlation concordance coefficients (CCCC), the total

Table 1 Baseline characteristics of the included subjects

	Mean value ± SD; f (N%)	**Median (Min–Max); f (N%)**
Gender (male)	107 (69.5%)	
Age (years)	38.75 ± 12.65	37.5 (20–74)
Body mass index (BMI) (kg/m^2)	28.51 ± 4.22	27.76 (20.01–41.45)
Body mass index (categories)	Underweight (BMI < 18.5)	0 (0%)
	Normal weight (BMI: 18.5–24.9)	31 (20.1%)
	Overweight (BMI: 25–29.9)	75 (48.7%)
	Obesity (BMI > 30)	48 (31.2%)
Body surface area(m^2)	2.11 ± 0.22	2.14 (1.43–2.62)
Waist circumference (cm)	93.14 ± 12.87	94 (56–123)
Systolic blood pressure office (mmHg)	141.15 ± 10.87	140 (119–174)
Diastolic blood pressure office (mmHg)	87.34 ± 7.9	87 (67–110)
Heart rate (bites/min)	79.97 ± 10.39	79 (56–111)
Smoking	Yes	57 (37%)
	Ex-smoker	30 (19.5%)
	Never smoker	67 (43.5%)
Term of birth	Preterm (before the 37th gestational week)	39 (25.5%)
	Term (in the 37th -42nd gestational week)	109 (71.2%)
	Post term (after the 42nd gestational week)	5 (3.3%)
Birth weight (g)	3106.64 ± 683.45	3200 (1450–5000)
Number of days before term of birth	28.08 ± 2.47	28 (23–32)
AH in family (yes)	138 (89.6%)	
CVD in family (yes)	100 (65.4%)	
Cerebrovascular disease in family (yes)	47 (30.7%)	
Kidney diseases -family (Yes)	22 (14.3%)	
Death of CVD family (yes)	52 (33.8%)	
Death of Cerebrovascular disease in family (yes)	25 (16.2%)	
Antihypertensive drugs (yes)	143 (92.8%)	
RAAS inhibitors (yes)	115 (74.7%)	

CVD cardiovascular diseases, *RAAS* renin-angiotensin-aldosterone system, *AH* arterial hypertension

Table 2 Results of PWV measured in the office (SphygmoCor) and over 24 h (Mobil-O-Graph and Arteriograph) and of estimated PWV

PWV (m/s)	PWV SphygmoCor	PWV Mobil-O-Graph 24 h	PWV Day Mobil-O-Graph	PWV Night Mobil-O-Graph	PWV Arteriograph 24 h	PWV Day Arteriograph	PWV Night Arteriograph	ePWV
Mean ± SD	8.28 ± 2.27	6.64 ± 1.71	6.7 ± 1.71	6.41 ± 1.66	8.59 ± 2.21	8.65 ± 2.17	8.14 ± 1.99	7.75 ± 1.20
Median (Min–Max)	7.8 (4.50–21.80)	6.20 (3.80–18)	6.25 (4–17)	6.0 (3.70–16)	8.6 (4.3–18.4)	8.7 (4.3–18.2)	8.2 (4–18.4)	7.38 (6.23–12.51)

PWV pulse wave velocity, *ePWV* estimated pulse wave velocity, *SD* standard deviation, *Min* minimum value, *Max maximum value*

Table 3 Results of repeated measures analysis of variance (PWV)

Measurement pairs PWV (m/s)	ΔM*	p
SphygmoCor—Arteriograph 24 h	− 0.307	0.091†
SphygmoCor—Mobil-O-Graph 24 h	1.670	0.000†
SphygmoCor- ePWV	1.870	0.089†
Arteriograph 24 h—Mobil-O-Graph 24 h	1.947	0.000†

† LSD test; *PWV* pulse wave velocity, *ePWV* estimated pulse wave velocity

* The difference between the an average values of the first mentioned and the second mentioned PWV measurement method

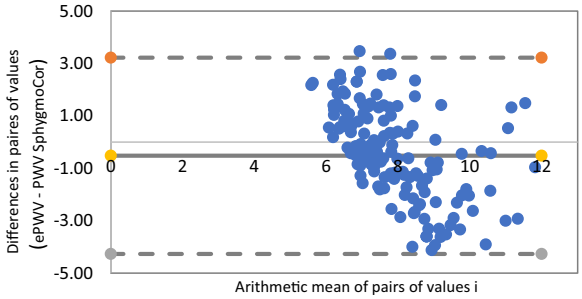

Fig. 2 The Bland–Altman graph—agreement between the ePWV and the PWV measured with the SphygmoCor

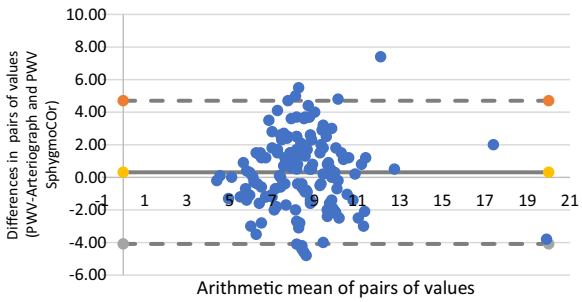

Fig. 3 The Bland–Altman graph—agreement between the PWV measured with the Arteriograph with the PWV measured with the SphygmoCor

deviation index (TDI), and coverage probability (CP). The measurement of PWV over 24 h using the Arteriograph was the most accurate among the methods that were compared with the office PWV measurement (with an accuracy of 0.989). On the other hand, the least accurate method of measuring PWV was the Mobil-O-Graph (0.707). The most precise method was the Mobil-O-Graph (0.631), and the least precise method was the Arteriograph (0.439). The highest degree of agreement with the office PWV measured by the SphygmoCor was shown by the PWV measured with the Mobil-O-Graph (CCC = 0.447), and the lowest by the ePWV calculated using the equation (CCC = 0.392). Regarding the TDI values (which are interpreted such that higher scores indicate more deviation), the deviation of the ePWV from the results obtained by the office measurement of PWV using the SphygmoCor was the smallest (TDI = 45.524). This result was interpreted to mean that 90% of the ePWV values had a magnitude deviation of −45.5% to 45.5% from the PWV values obtained using the SphygmoCor. On the other hand, the largest deviation was verified in the case of the PWV measurement using the Mobil-O-Graph (TDI = 63.430). The probability of overlapping was the highest in the case of the ePWV (CP = 0.322) and the lowest in the case of the PWV measurement using the Mobil-O-Graph (CP = 0.213). It should be noted that the CP values were considered taking into account the present TDI value of 10%, which is the allowable difference between the gold standard and the measures that are compared with this standard.

The overlap between the PWV measured by the SphygmoCor and the PWV estimated using the other methods (ePWV, Arteriograph and Mobil-O-Graph) was also tested using the Bland–Altman method, which is shown in Figs. 2, 3, and 4. Results on the ePWV and office values (SphygmoCor) were examined as shown in Fig. 2. It was found that the average of the differences between the pairs of values of these two methods of measurement (bias) was -0.52 (in Graph A shown as a solid line), and the standard deviation of the bias was 1.91. It should be noted that the 95% interval of agreement, i.e., the limits of agreement—LoA (bias ± 1.96SD) was from − 3.22 to 4.27 (dashed line sin the graph—upper and lower). The relationship between the PWV measured by the

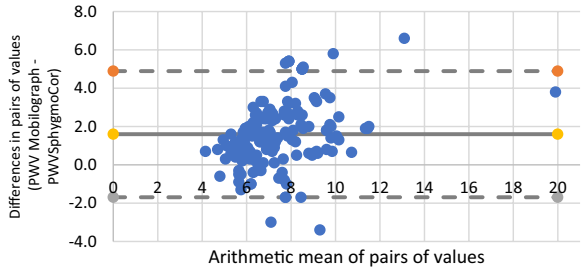

Fig. 4 The Bland–Altman graph—agreement between the PWV measured with the Mobil-O-Graph and the PWV measured with the SphygmoCor

Arteriograph and the SphygmoCor was also examined as shown in Fig. 3. In this case, the bias was 0.31, with a standard deviation of 2.24. In addition, the 95% interval of agreement (LoA) was −4.08 to 4.70. In the case of the PWV measured with the Mobil-O-Graph, compared to the SphygmoCor measurement, the bias was 1.60, and the standard deviation was 1.68 (Fig. 4). The 95% interval of agreement (LoA) had a lower limit of -1.69 and an upper limit of 4.89.

The highest degree of overlap (or agreement) with the office PWV values was estimated with the ePWV equation, then with Arteriograph, while the smallest degree of overlap was found with the PWV measured using the Mobil-O-Graph (Table 4).

The weak association between office AP values with PWV measured with SphygmoCor, intermediate association with PWV measured during 24 h with Mobil-O-Graph, and the highest association with ePWV were observed (Table 5).

Increased systolic arterial pressure for 1SD leads to increase of PWV measured with Mobil-O-Graph and 47.5% variance of the dependent variable (PWV measured during 24 h with Mobil-O-Graph) can be explained with systolic arterial pressure.

Increased systolic arterial pressure for 1SD leads to increase in PWV measured with SphygmoCor for 0.185 SD and 3.4% variance of the dependent variable (PWV-SphygmoCor) can be explained with systolic arterial pressure (Table 6).

Increased diastolic arterial pressure for 1SD leads to increase in ePWV for 0.173 SD and 3.0% variance of the dependent variable (ePWV) can be explained with diastolic arterial pressure.

Increased diastolic arterial pressure for 1SD leads to increase in 24 h Mob-O-PWV for 0.438 SD and 19.2%

Table 4 Accuracy, precision, concordance correlation coefficient (CCC), total deviation index (TDI), and coverage probability (CP)

Accuracy	Precision	CCC	TDI	CP	LoA 95% coverage interval	Bias
PWV-SphygmoCor vs. ePWV						
0.830	0.471	0.392	45.524	0.322	− 3.22 to 4.27	− 0.52
PWV-SphygmoCor vs. PWV Arteriograph						
0.989	0.439	0.434	56.417	0.279	− 4.08 to 4.70	0.31
PWV-SphygmoCor vs. PWV Mobil-O-Graph						
0.707	0.631	0.447	63.430	0.213	− 1.69 to 4.89	1.60

CCC concordance correlation coefficient, *TDI* total deviation index, *CP* coverage probability

Table 5 Correlation between arterial pressure and PWV measured in the office and during 24 h

		Systolic AP (office)	Diastolic AP (office)				
PWV (SphygmoCor)		0.111	0.115				
ePWV		0.280*	0.443*				
Continues 24 h measurement of arterial pressure							
PWV (Mobil-O-Graph)		24 h		Day		Night	
		Systolic AP	Diastolic AP	Systolic AP	Diastolic AP	Systolic AP	Diastolic AP
	24 h	0.186*	0.176*	0.169*	0.117	0.208**	0.312***
	Day	0.184*	0.176*	0.172*	0.134	0.191*	0.309***
	Night	0.155	0.172*	0.13	0.099	0.232**	0.369***

PWV pulse wave velocity, *AP* arterial pressure

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 6 Systolic arterial pressure as predictor of different PWV—linear regression

Variable	Unstandardized coefficient B	Std. Error	Standardized coefficient B	*t*	95% CI		*p*
					Lower bound	Upper bound	
PWV-SphygmoCor	0.027	0.012	0.185	2.314	0.004	0.050	**0.022**
ePWV	0.000	0.006	0.005	0.059	0.012	0.012	0.953
24 h Mob-O-PWV	0.4	0.034	0.689	11.735	0.467	0.332	**< 0.001**

* $p < 0.05$; **$p < 0.01$; ***$p < 0.001$

variance of the dependent variable (24 h Mob-O-PWV) can be explained with diastolic arterial pressure (Table 7).

4 Discussion

The comparison of PWV values measured in the office with SphygmoCor and those measured over 24 h (Mobil-O-Graph and Arteriograph) and ePWV was our main goal. We found a statistically significant difference between office and 24-h average values when Mobil-O-Graph was used. On the other hand, no statistically significant difference in the PWV value was verified when comparing the office PWV measurements with the 24-h PWV measurements by the Arteriograph. The PWV values obtained by the Arteriograph were statistically significantly higher than the PWV values obtained by the Mobil-O-Graph. Our results are in disagreement with two other studies. Del Giorno et al. in a study which included 1162 participants, in general population, older than 18 years, failed to find significant differences between the office or the 24-h PWV measurements (using tonometric and oscillometric measurements) [23]. On the contrary, the results of the study by Berukstasis et al., which included 82 participants with high and very high CV risk, showed that the values of the 24-h PWV measurement (Mobil-O-Graph) were significantly lower than the office values (SphygmoCor) [24]. Based on our results, it can be concluded that the greatest degree of overlap (i.e., agreement) of office PWV (SphygmoCor) is with the PWV values measured by the Mobil-O-Graph (49% variance), followed with the Arteriograph, while the smallest degree of overlap was observed with the ePWV values. Other studies have shown similar results. Del Giorno et al. showed that there is an adequate level of connection between the methods for assessing PWV comparing the office measurements using the SphygmoCor and the 24-h oscillometric measurements using the Mobil-O-Graph [23]. Bland–Altman analysis showed a moderate association between 24-h oscillometric PWV and c-f PWV (95% CI 4.23–6.22). According to the results of our research, the 95% agreement interval of these methods had a lower limit of −1.69 and an upper limit of 4.89. The study by Grillo et al. compared the short-term reproducibility of aortic PWV measured with six different devices in elderly patients with high CV risk [25]. They showed that all devices offer good reproducibility for PWV estimation. Reproducibility levels are higher for devices that are oscillometric (e.g., the BPLab or the Mobil-O-Graph) compared to devices that measure c-f PWV tonometrically (i.e., the SphygmoCor, the Complior, or the Pulse Pen).

The differences in the PWV values measured in the office using the SphygmoCor and the Mobil-O-Graph can also be explained by the differences in method, one of which is tonometric, while the other is oscillometric. This may partly explain the differences in the values of arterial stiffness parameters. The measurement of c-f PWV (SphygmoCor) is tonometric, and the analysis of PWV between the carotid and femoral arteries is conducted. This procedure includes the measurement of two distances: the sternal–femoral distance and the sternal–carotid distance, and as such body height and to a degree body mass have an influence on the outcome of the measurement. On the other hand, the oscillometric method of measuring PWV using the Mobil-O-Graph

Table 7 Diastolic arterial pressure as predictor of different PWV—linear regression

Variable	Unstandardized coefficients B	Std. Error	Standardized coefficients B	*t*	95% CI		*p*
					Lower bound	Upper bound	
PWV SphygmoCor	0.002	0.021	0.008	0.095	− 0.039	0.043	0.925
ePWV	0,023	0.011	0.173	2.159	0.044	0.002	**0.032**
24 h Mob-O-PWV	0.452	0.075	0.438	6.010	0.303	0.600	**< 0.001**

is based on the determination of the change in pulsatile pressure in the brachial artery and the subsequent analysis of pulse waves, through the ARSCSolver algorithm, which is integrated into the Mobil-O-Graph software system. Possible differences in the values of the arterial stiffness parameters measured using these two methods may also arise as a consequence of the difference in the wall structure of different parts of the arterial tree, especially with regard to those structures that are responsible for the elasticity of the arterial wall. Measurement using the tonometric method is performed in the carotid and femoral arteries, which are rich in elastin, while the oscillometric measurement is performed in the brachial artery, which is rich in smooth muscle cells [26, 27]. In addition to the difference in the technical modalities of the methods and the structure of the blood vessels, the emotional component, i.e., the predominance of activation of the sympathetic nervous system when it comes to the office measurement compared to the 24-h measurement, which is actually a 24-h objectification and gives the value of the estimated PWV, is also important [28]. Both Arteriograph and Mobil-O-Graph are oscillometric methods for PWV measurement/determination, and observed differences between these two devices could be explained: 1. the assessment of the return of the reflected wave (the time difference between the early systolic peak); 2. the ways in which the calibration of PWV according to age and systolic and diastolic BP is done for other oscillometric devices; 3 the nature of the equation for the generalized transfer function used to calculate PWV from brachial AP. As such, different calibration models can have an impact on the different results, in situations where this is importance for determining PWV. Age and BP were included in the algorithm for the estimation of PWV measured during 24 h with Mobil-O-Graph and Arteriograph, but also into the equation for ePWV. Since the age is same, the possible difference between the values of 24 h of PWV with both oscillometric methods and ePWV can be explained by the variability in BP.

Regarding the practical usefulness of direct office measurement of PWV and 24-h measurements of arterial stiffness, measurement with SphygmoCor is a gold standard and our study showed that it cannot be used interchangeable as we observed the week agreement between the methods.

On the other side, 24-h methods for the arterial stiffness measurements are objective, operator independent, so those methods can be used as complementary methods. ePWV incorporates risk information other than office-measured c-f PWV, so it could be used as a replacement of c-f PWV measurements when the latter is unavailable in clinical work. A parallel of ePWV with estimated glomerular filtration rate (eGFR) can be made. Estimated GFR is not the same and not equally precise as measured GFR (mGFR), but it is difficult to measure GFR in clinical work or large epidemiological surveys and even in regular everyday clinical work. So, ePWV could help in better risk classification.

Our study has several limitations. The most important limitation of this study is that the devices for 24-h oscillometric measurement of arterial stiffness (Mobil-O-Graph and Arteriograph) were not placed simultaneously the same day on the participants, which was technically challenging and almost impossible to perform. This could contribute to observed differences in the values of the 24-h estimated (Mobil-O-Graph) and the 24-h direct measurement of arterial stiffness (Arteriograph) with two different oscillometric devices.

In addition, we observed the weak association between office AP values with PWV measured with SphygmoCor, intermediate association with PWV measured during 24 h with Mobil-O-Graph, and the highest association with ePWV. Those differences can contribute to different results in PWV values obtained with different methods.

Systolic and diastolic arterial pressure are direct predictors of PWV values measured with SphygmoCor, Mobil-O-Graph measured during 24 h and ePWV, regarding results of linear regression analysis.

The second limitation of this study is the relatively small number of participants involved. Our study has several important strengths. This is the first study which included and assessed comprehensive analysis of arterial stiffness in homogenous group of younger hypertensive patients with low and moderate risk, while other studies included general population or high-risk patients. We analyzed coherence of two different methods for estimation of 24-h PWV with the golden standard for the PWV measurement (SphygmoCor).

5 Conclusion

In the group of young treated hypertensive patients with low-to-mild CV risk, we found only weak agreement between the c-f PWV and the 24 h PWV data. Better concordance was found between the c-f PWV and the Mobil-O-Graph than with the Arteriograph. We concluded that c-f PWV and 24-h PWV are not interchangeable, but those methods can be used complementary for comprehensive assessment of total CV risk. Estimated PWV (ePWV) could be used for initial scoring of CV risk, and for follow-up of individual patient. More results are needed to answer the question of whether 24-h PWV, as well as ePWV, have the same clinical value as c-f PWV.

Abbreviations

C-f PWV	Carotid-femoral pulse wave velocity
CV	Cardiovascular
ePWV	Estimated pulse wave velocity

CCC	Concordance coefficient correlation
TDI	Total deviation index
CP	Coverage probability
ACR	Albumin creatinine ratio
CKD	Chronic kidney disease
eGFR	Estimated glomerular filtration rate
NT pro-BNP	N terminal pro-b-type natriuretic peptide
HOME-IR	Homeostasis Model Assessment for Insulin Resistance, %
HDL	High-density lipoprotein
LDL	Low-density lipoprotein
CKD-EPI eGFR	Chronic kidney disease epidemiology collaboration estimated glomerular filtration rate
AST	Aspartate aminotransferase
ALT	Alanine aminotransferase
BSA	Body surface area

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44200-024-00049-5.

Below is the link to the electronic supplementary material.Supplementary file1 (DOCX 17 KB)

Author Contributions

AJ—participate in investigation, conception, and methodology of the research. KG—performed SphygmoCor measurements for all patients. DB—analyzing and interpreting data regarding Arteriograph measurements. BJ—create design of the work, participate in methodology, statistical analysis, and review research. DR—participate in collecting and interpreting laboratory data. MD—participate in formal statistical analysis. MDD—participate in analyzing results of Mobil-O-Graph and Arteriograph measurements. JJ—participate in writing of the article and in the review process. All authors read and approved final version of manuscript.

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Data Availability

All data generated or analyzed during this study are included in this article. Future enquiries can be directed to the corresponding author.

Declarations

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Conflict of Interest

All authors declare that they have no competing interests.

Ethics Approval and Consent to Participate

This study has been performed with the approval of an appropriate ethics committee and with appropriate participants' informed consent in compliance with the Helsinki Declaration. This study protocol was reviewed and approved by Ethics Committee of University Hospital Center Zagreb and School of Medicine, University of Zagreb. All participations signed informed consent approved by Ethics Committee of University Hospital Center Zagreb.

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