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ARTICLE

Multiscale mathematical modeling vs. the generalized transfer function approach for aortic pressure estimation: a comparison with invasive data

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Abstract

We aimed to evaluate the performance of a mathematical model and currently available non-invasive techniques (generalized transfer function (GTF) method and brachial pressure) in the estimation of aortic pressure. We also aimed to investigate error dependence on brachial pressure errors, aorta-to-brachial pressure changes and demographic/clinical conditions. Sixty-two patients referred for invasive hemodynamic evaluation were consecutively recruited. Simultaneously, the registration of the aortic pressure using a fluid-filled catheter, brachial pressure and radial tonometric waveform was recorded. Accordingly, the GTF device and mathematical model were set. Radial invasive pressure was recorded soon after aortic measurement. The average invasive aortic pressure was 141.3 ± 20.2/76 ± 12.2 mm Hg. The simultaneous brachial pressure was 144 ± 17.8/81.5 ± 11.7 mm Hg. The GTF-based and model-based aortic pressure estimates were 133.1 ± 17.3/82.4 ± 12 and 137 ± 21.6/72.2 ± 16.7 mm Hg, respectively. The Bland-Altman plots showed a marked tendency to pressure overestimation for increasing absolute values, with the exclusion of mathematical model diastolic estimations. The systolic pressure was increased from the aortic to radial locations (7.5 ± 19 mm Hg), while the diastolic pressure was decreased (3.8 ± 9.8 mm Hg). The brachial pressure underestimated the systolic and overestimated diastolic intra-arterial radial pressure. GTF errors were independently correlated with the variability in pulse pressure amplification and with the brachial error. Errors of the mathematical model were related to only demographic and clinical conditions. Neither a multiscale mathematical model nor a generalized transfer function device substantially outperformed the oscillometric brachial pressure in the estimation of aortic pressure. Mathematical modeling should be improved by including further patient-specific conditions, while the variability in pulse pressure amplification may hamper the performance of the GTF method in patients at the risk of coronary artery disease.

Keywords Aortic pressure · Hypertension · Generalized transfer function · Mathematical modeling · Pulse pressure amplification

Introduction

Arterial hypertension is the main cardiovascular risk factor among adults [1]. Clinical blood pressure evaluation is based on the measurement of the pressure at the brachial artery. However, blood pressure changes along the arterial tree: systolic value increases from the aorta to the main peripheral arteries, while the diastolic value is modestly reduced [2], exhibiting a phenomenon usually called pulse pressure amplification (PPA).

Several studies have proven that the aortic blood pressure has a higher prognostic value than brachial values [3–5]. Moreover, as several studies have reported drug-specific

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effects on central pressure [6–9], the possibility of specifically targeting the central pressure instead of the brachial pressure was foreseen [9–11].

Most previous studies have adopted non-invasive techniques for aortic pressure estimation. The most used technique is based on the elaboration of radial tonometry waveforms through generalized transfer functions (GTFs). Although concerns were raised about the reliability of this approach and use of brachial systolic/diastolic or diastolic/mean values to set absolute pressure values of tonometry waveform [12, 13], the GTF technique allowed researchers to unveil important relationships between the aortic blood pressure and future cardiovascular events [14], LV hypertrophy [3], and renal disease [4], among others. Nonetheless, validation studies reported a large dispersion of GTF method errors [15], which were proven to be partially dependent on the brachial pressure used for calibration [16].

Another possible approach to estimate the central pressure may come from mathematical modeling. Among other simpler physically based representation based on lumped methods [17, 18], spatially distributed, one-dimensional mathematical modeling, performed well in various conditions [19–27]. Moreover, suitable tailoring of these models to patient-specific conditions resulted in an improvement of the results [20, 22, 25, 27] and satisfactory comparisons with GTF methods [22]. Nonetheless, a comparison with invasive aortic pressure is still missing.

The aim of the present study was twofold: to evaluate the reliability of a subject-specific mathematical model and currently available non-invasive techniques (GTF method and oscillometric brachial pressure) to estimate the aortic pressure and to investigate how errors of the mathematical model and GTF method depend on the oscillometric brachial errors, demographic and clinical conditions. Through the measurement of invasive radial pressure, we further evaluated aorta-to-radial intra-arterial pressure changes.

Methods

Study population

One-hundred patients referred to invasive hemodynamic evaluation for chest pain or suspected coronary artery disease were prospectively and consecutively included in this study. The exclusion criteria comprised BMI > 40 kg/m^2, age < 18 or > 80 years, severe aortic valve stenosis or regurgitation, non-native or bicuspid aortic valve, premature ventricular contraction or atrial fibrillation during invasive measurements, and Marfan and Turner syndrome. Moreover, as suggested by recent recommendation [13], we excluded patients with intravenous infusion of nitrates < 10 min before aortic invasive pressure measurement those with a difference in systolic or diastolic brachial blood pressure between arms > 10 mm Hg before entering the coronary unit. After the exclusion criteria, 62 patients were retained. The study was approved by the local ethics committee (CEI/330), and informed consent was signed by all participants.

Before entering the hemodynamic room, all the patients underwent echocardiographic screening of the left-ventricle. End-diastolic and end-systolic left ventricular volumes were evaluated by two-dimensional echocardiography using the Simpson's disk method. The presence of aortic valve stenosis and regurgitation was screened. The brachial blood pressure was measured following current guidelines [1] by a validated oscillometric device (Omron Matsusaka, Kyoto, Japan) at both arms, and the hypertensive status was defined based on the patient clinical history and administration of antihypertensive therapy. The height and weight were recorded.

Tonometric measurements at the carotid and femoral arteries were performed after the stabilization of brachial pressure values, which were obtained after a suitable resting period. The carotid-femoral pulse wave velocity (cfPWV)—i.e., the gold standard for measuring central arterial stiffness [28]—was performed using a high-fidelity micromanometer (SPC-301; Millar Instruments, Houston, TX, USA) following current guidelines [28]. The distance covered by the waves was assimilated to the distance measured between the two recording sites.

Invasive pressure measurements

All the patients underwent radial artery cannulation. Invasive pressure was measured using a calibrated fluid-filled pressure catheter (SUPERTORQUE® Plus, Cordis) at the level of the proximal ascending aorta. This catheter has a maximum sampling frequency equal to 200 Hz. Fluoroscopic guidance was used to verify the measurement location. Time-resolved pressure waveforms were recorded and analyzed off-line by an experienced physician to define the systolic, diastolic and pulse pressure values. Brachial oscillometric pressure and radial tonometric recordings were performed simultaneously with invasive aortic pressure registration. The invasive radial pressure was recorded soon after the aortic pressure reading, during catheter pull-out. The location of the radial pressure reading was consistently defined as 10 cm proximally to the radial access—i.e., the location where the 10-cm-long radial sheath ends and, thus, pressure measurement can be registered.

The heart rate, QT period and ejection time at the moment of aortic pressure evaluation were recorded. Pulse pressure amplification was computed as $PPA = PP_{peripheral}/PP_{aorta}$, where PP is the pulse pressure, defined as systolic minus diastolic blood pressure levels.

Generalized transfer function method

Radial artery waveforms were obtained using a high-fidelity micromanometer (SPC-301; Millar Instruments, Houston, TX, USA) from the wrist simultaneously with the invasive aortic reading. The corresponding central waveform was generated using a validated transfer function technique (Sphygmocor, AtCor Medical, Sydney, Australia) following recommendations [13]. Calibration of the radial arterial tonometric waveform was carried out with systolic and diastolic blood pressure values recorded non-invasively on the same side using a validated automatic oscillometric device (Omron Matsusaka, Kioto, Japan).

Multiscale mathematical model

The investigated multiscale mathematical model is based on a spatially detailed, physically based description of the arterial tree comprising a network of 48 large arteries and a set of zero-dimensional (lumped) models representing the left-ventricle, aortic valve, and peripheral circulation [20]. Large arteries were modeled as one-dimensional axi-symmetric tapered vessels, which were assembled into a standard bifurcating arterial tree [23] by setting the conservation of the total pressure and mass. The vessel wall mechanical properties were modeled as non-linear viscoelastic. The arterial velocity profile was assumed to be formed by a central flat profile joined to a parabolic boundary layer of fixed minimal thickness. The peripheral circulation regions were described by three-element Windkessel models, while left-ventricle dynamics were based on a time-varying elastance model. The aortic valve was modeled as proposed by Blanco et al. [29]. The mathematical model was tailored on each individual by a subject-specific setting procedure based on non-invasive measurements, which were previously described in detail [22, 24]. The patient's height, weight, cfPWV, brachial pressure, heart rate, ejection time, and left ventricular volumes were used to specify the values of the main parameters of the model, tailoring it on the specific subject considered. This was achieved using several coefficients relating patient data to corresponding reference values, as previously described [20]. Notably, all the listed data are needed for the subject-specific setting.

Statistical analysis

The Kolmogorov–Smirnov test was used to evaluate distribution normality. Continuous variables were expressed as the means ± standard deviation if they present a normal distribution; otherwise, they were presented as median [1st–3rd] quartiles. Multivariable linear regression analysis with a forward selection procedure was used to identify independent determinants of each dependent variable tested. Variables were entered in the model if $p < 0.15$ in univariate analysis. To avoid multicollinearity, variables were excluded from the multivariable analysis if the tolerance test was < 0.1 or variation inflation factor (VIF) was > 5. A two-tailed p-value < 0.05 was considered statistically significant. SPSS 19.0 software version (IBM SPSS Statistics, Chicago, Illinois, USA) was used for the analysis.

Table 1 Demographic and clinical characteristics of the studied patients

	Mean	Std. deviation
Sex (male)	75%	
Age	66.7	10.7
BMI [kg/m^2]	27.3	3.7
Weight [kg]	78.9	14.7
Height [m]	169.5	8.6
SBP [mm Hg]	144.0	17.8
DBP [mm Hg]	81.5	11.7
EF [%]	54.2	12.7
cfPWV [m/s]	9.4	2.0
Smoking	54%	
Hypertension	80%	
T2 Diabetes	29%	
Dyslipidaemia	63%	
Overweight	75%	
Aortic valve pathology	23%	

Results

Characteristics of the study population

Sixty-two patients fulfilled the design criteria of the study. The mean age of the patients was 66.7 ± 10.7 years, 75% of them were male, and the mean cfPWV was 9.4 ± 2 m/s (see Table 1). The systolic and diastolic pressures were fairly high, with 80% of the studied patients presenting hypertension or being in active antihypertensive therapy. Twenty-nine percent of subjects had type 2 diabetes (29%), and 23% had mild (i.e., non-severe) aortic valve pathologies. Moreover, dyslipidemia and overweight or obesity were highly prevalent (63% and 75%, respectively).

Aortic pressure estimation

The average invasive aortic systolic pressure was 141.3 ± 20.2 mm Hg, while the diastolic value was 76 ± 12.2 mm Hg (see Table 2). The simultaneous systolic and diastolic brachial pressures were 144 ± 17.8 mm Hg and 81.5 ± 11.7 mm Hg, respectively. The GTF-based technique resulted in estimated systolic and diastolic central pressures of 133.1 ± 17.3 and 82.4 ± 12 mm Hg, respectively, while the

Table 2 Aortic pressure as obtained by catheter, brachial oscillometric device, GTF method, and mathematical modeling

				Errors		
		Mean	Std. deviation	Mean	Std. deviation	*R*
Aortic invasive pressure	SBP [mm Hg]	141.3	20.2			
	DBP [mm Hg]	76.0	12.2			
	PP [mm Hg]	65.3	17.8			
Brachial non-invasive pressure	SBP [mm Hg]	144.0	17.8	-2.7	12.0	0.808
	DBP [mm Hg]	81.5	11.7	-5.5	8.6	0.742
	PP [mm Hg]	62.5	13.8	2.8	12.5	0.715
GTF method	SBP [mm Hg]	133.1	17.3	8.2	10.0	0.869
	DBP [mm Hg]	82.4	12.0	-6.4	8.7	0.743
	PP [mm Hg]	50.7	13.2	14.7	10.6	0.807
Mathematical modeling	SBP [mm Hg]	137.0	21.6	4.3	16.7	0.679
	DBP [mm Hg]	72.2	16.7	3.8	10.4	0.784
	PP [mm Hg]	64.8	19.5	-0.5	18.7	0.500

mathematical model provided estimated systolic and diastolic central pressures of 137 ± 21.6 and 72.2 ± 16.7 mm Hg, respectively.

Table 2 reports the means and standard deviation of the errors of the non-invasive techniques tested. The brachial pressure resulted in an overestimation of both systolic and diastolic values. The GTF method underestimated systolic and overestimated diastolic values. Finally, mathematical modeling provided an underestimation of both systolic and diastolic values.

Pearson correlation coefficients were higher for the systolic central pressure estimated by the brachial pressure and GTF method, while the mathematical model performed slightly worse (see Table 2 and Fig. 1). On the other hand, the Pearson correlation coefficient corresponding to the diastolic pressure was slightly higher for the mathematical model estimations with respect to the results obtained by the brachial pressure and GTF method.

Bland-Altman plots are reported in the lower charts of Fig. 1. They show a marked tendency for the overestimation of the systolic pressure to increase the absolute values of the central systolic pressure. A similar tendency was also observed for diastolic pressure as estimated by both the GTF method and brachial pressure. By contrast, mathematical model predictions did not show this tendency.

Although the correlation coefficients for the systolic and diastolic pressures were generally quite high, the presence of a large dispersion of the errors underlined the scarce capacity of these non-invasive methods to describe the large intersubject variability of aortic pressure.

Invasive pulse pressure amplification

The central-to-radial pressure changes were measured invasively between the aortic and radial locations. Invasive radial pressure measures were considered unreliable in three patients due to radial artery spasm or the presence of premature ventricular contraction during the radial measurement. Table 3 presents absolute values of the aortic and radial invasive pressure and their differences in the set of 59 patients considered in this subanalysis.

In line with a recently published large meta-analysis [30], systolic pressure undergoes an increase from the aortic to radial locations, resulting in an absolute difference of 7.5 ± 19 mm Hg. By contrast, the diastolic pressure decreased of 3.8 ± 9.8 mm Hg. This resulted in a marked increase in the pulse pressure of 11.4 ± 17.4 mm Hg, giving an average pulse pressure amplification of 25%.

Notably, the large standard deviations reported in Table 3 highlight the large variability of the changes in pressure between the aorta and radial artery.

Non-invasive brachial pressure errors

Table 4 shows the difference between the intra-arterial radial pressure and non-invasive brachial measures of the systolic, diastolic, and pulse pressure. The non-invasive brachial pressure underestimated the intra-arterial radial systolic pressure of 1.9 ± 14.1 mm Hg, while diastolic values were overestimated of 6.9 ± 9.3 mm Hg. Thus, the intra-arterial pulse pressure was underestimated by the non-invasive brachial technique of 8.8 ± 13.4 mm Hg.

The large standard deviation and reduced bias of SBP errors imply that SBP can be either severely underestimated or overestimated, with a substantially similar probability. By contrast, DBP was, in most cases, overestimated, and PP was most often underestimated.

Error analysis

Multivariate regression analysis was performed to investigate the correlation between the errors of the non-invasively

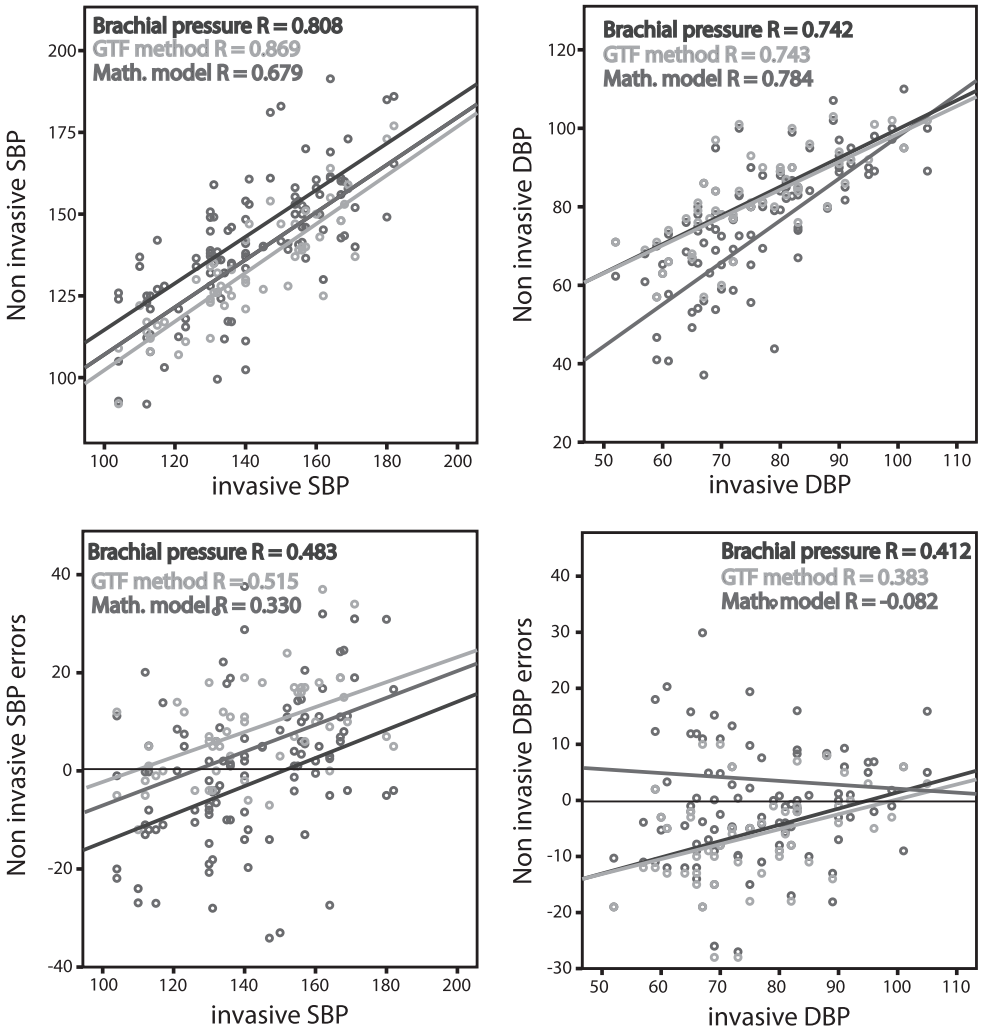

Fig. 1 Scatter (top) and Bland-Altman (bottom) plots for the systolic (left) and diastolic (right) aortic blood pressures, as estimated by the brachial pressure (blue), mathematical model (red), and GTF method (green)

Table 3 Comparison between invasive aortic and invasive radial pressure

				Differences		Pearson correlation coefficient
		Mean	Std. deviation	Mean	Std. deviation	
Aortic invasive pressure	SBP [mm Hg]	143.7	23.2			
	DBP [mm Hg]	77.5	12.8			
	PP [mm Hg]	66.2	20.8			
Radial invasive pressure	SBP [mm Hg]	151.3	23.4	7.5	19.0	0.67
	DBP [mm Hg]	73.7	13.3	-3.8	9.8	0.72
	PP [mm Hg]	77.6	18.9	11.4	17.4	0.62
Aortic-to-radial pulse pressure amplification	1.25	0.42				

estimated aortic pressure and demographic and clinical data, aortic-to- radial pressure changes and differences between the brachial pressure and intra-arterial radial pressure.

The mathematical model errors in systolic pressure estimation were independently related to the BMI ($p = 0.024$) and smoking status ($p = 0.022$), while diastolic errors were independently related to the aortic-to-radial DBP changes ($p < 0.001$), cfPWV ($p < 0.001$), AV regurgitation ($p < 0.001$), and stroke volume ($p < 0.001$) (see Table 5). Moreover, mathematical model pulse pressure errors were independently related to cfPWV ($p = 0.006$) and the stroke volume ($p = 0.012$).

Table 4 Comparison between non-invasive brachial pressure and invasive radial pressure

				Differences with corresponding invasive radial pressure		Pearson correlation coefficient
		Mean	Std. deviation	Mean	Std. deviation	
Brachial non-invasive pressure	SBP [mm Hg]	149.4	20.9	1.9	14.1	0.80
	DBP [mm Hg]	80.6	11.0	-6.9	9.3	0.73
	PP [mm Hg]	68.8	18.1	8.8	13.4	0.74

Table 5 Univariate and multivariable linear analysis for the error of the mathematical model

			Univariate linear analysis *p*-value	Multivariable linear analysis *p*-value
Mathematical model	SBP [mm Hg]	Smoking status (yes/no)	0.071	0.022
		BMI [kg/m^2]	0.076	0.024
	DBP [mm Hg]	Aortic to radial invasive systolic pressure difference [mm Hg]	0.111	< 0.001
		Age [years]	0.001	< 0.001
		cfPWV [m/s]	< 0.001	< 0.001
		Stroke volume [ml]	0.031	< 0.001
		Aortic valve pathology (yes/no)	0.009	< 0.001
	PP [mm Hg]	Age [years]	0.054	-
		cfPWV [m/s]	0.019	0.006
		Smoking status (yes/no)	0.029	-
		Stroke volume [ml]	0.047	0.012

GTF method systolic errors were independently related to aortic-to-radial SBP changes ($p = 0.001$), the brachial-intra-arterial systolic pressure difference ($p < 0.001$), and LV EF ($p = 0.045$) (see Table 6). Diastolic errors were independently related to aortic-to-radial DBP changes ($p < 0.001$) and the brachial-intra-arterial diastolic pressure difference ($p < 0.001$). GTF method errors in the estimation of the aortic pulse pressure were independently related to aortic-to-radial PP changes ($p = 0.001$), as well as LV EF ($p = 0.029$).

Discussion

In this study, we tested, for the first time, the capacity of a multiscale mathematical model to assess the aortic pressure measured invasively. Moreover, comparisons with available non-invasive techniques were provided, and corresponding in-deep error analyses were performed. To be used in clinical practice, a non-invasive technique for aortic pressure appraisal should provide an unbiased estimation and a limited dispersion of the errors. The tested multiscale mathematical model provided, on average, a similar underestimation of both systolic and diastolic values, resulting in no bias in the pulse pressure estimation. Similar results were obtained analyzing brachial oscillometric data, although both extreme values were overestimated. By contrast, the GTF method resulted in a large overestimation of the aortic pulse pressure, obtained by both the overestimation of systolic and underestimation of diastolic pressure. These characteristics, which were previously reported by two large meta-analyses [15, 30], may have implications on the use of the GTF method in population studies. Thus, concerning aortic pulse pressure estimation, the brachial pressure and mathematical models may be superior to the GTF method.

Irrespective of the average bias of each method, a crucial aspect for the clinical use of these techniques is related to the dispersion of the results. Considering the single-patient scenario, the (reading) error by the physicians is expected to fall within a limited range of value—i.e., to have a reduced dispersion with the AAMI fixing to a standard deviation of

Table 6 Univariate and multivariable linear analysis for the error of the GTF method

			Univariate linear analysis *p*-value	Multivariable linear analysis *p*-value
GTF-method	SBP [mm Hg]	Brachial-invasive radial systolic pressure [mm Hg]	0.059	< 0.001
		Brachial-invasive radial diastolic pressure [mm Hg]	0.053	-
		Aortic to radial systolic pressure difference [mm Hg]	0.137	0.001
		LV EF	0.065	0.045
	DBP [mm Hg]	Aortic to radial diastolic pressure difference [mm Hg]	< 0.001	< 0.001
		Aortic to radial pulse pressure difference [mm Hg]	0.006	0.007
		Brachial-invasive radial systolic pressure [mm Hg]	0.053	-
		Brachial-invasive radial diastolic pressure [mm Hg]	0.126	< 0.001
		Stroke volume [ml]	0.121	-
		Aortic valve pathology (yes/no)	0.090	0.090
	PP [mm Hg]	Aortic to radial diastolic pressure difference [mm Hg]	0.014	0.020
		Aortic to radial pulse pressure difference [mm Hg]	< 0.001	0.001
		LV EF	0.017	0.029
		Overweight (yes/no)	0.055	-
		Stroke volume [ml]	0.030	-

8 mm Hg the limit for the validation of a new device [31]. Translating this recommendation for aortic pressure estimation, neither the mathematical model nor the GTF technique would be suitable for clinical use. Similarly, it could not be stated that the brachial pressure is a reliable approximation of the aortic blood pressure. Indeed, a standard deviation of 10 to 19 mm Hg for the systolic values and approximately 9–10 mm Hg for diastolic values precluded the possibility of reliably using these techniques in a single-patient scenario.

One of the key results obtained in this work concerns the intersubject variability of the changes in the pressure characteristics from the aorta to the radial artery. Indeed, although positive amplification of the pressure pulse was seen in most of the subjects, the value of such amplification varied markedly, with a standard deviation of 17.4 mm Hg. The average values of both the systolic pressure increase and diastolic pressure decrease measured here agree with those reported in previous studies [2, 30, 32].

Another important aspect for the estimation of aortic pressure is the need for non-invasive brachial pressure as the input parameter, either for the estimation of mathematical model parameters or calibration of the tonometric waveform based on the GTF method. Our results, which were consistent with the literature data [30], showed a markedly variable undervaluation of the intra-arterial radial pulse pressure by the oscillometric technique. Concerning the systolic value, the limited bias and large dispersion resulted in a similarly high likelihood of the underestimation or overestimation of the intra-arterial value. By contrast, both the diastolic and pulse pressure values presented a higher probability of overestimation and underestimation, respectively. This large variability has a strong effect on the clinical classification of hypertension, with a recent meta-analysis showing that approximately half of patients with less than stage 2 hypertension (< 160/100 mmHg) would be reclassified using intra-arterial radial values [30].

Thus, we evaluated the impact of these characteristics on the capacity to non-invasively estimate the aortic blood pressure. Mathematical model errors were found to be dependent on several demographic and clinical conditions, such as age, BMI, cfPWV, stroke volume, aortic valve pathology and the smoking status. This result highlights the need to improve the physically based description of these characteristics when already accounted for or to include new, properly designed submodels (e.g., the pathological behavior of the aortic valve) in the existing mathematical framework. Notably, the model errors were independent of the brachial to intra-arterial pressure difference. Although further studies are needed to provide conclusive evidence on this aspect, this result may be seen as a case where complex dynamic interactions, such as those described by the multiscale mathematical model, dampen input errors. This is a desired aspect of a dynamic model, and further investigations about input/output error propagation and interaction are required.

By contrast, the error provided by the GTF method was statistically (and independently) related to both aortic-to-radial intersubject pressure variability and the inability of non-invasive brachial pressure values to reflect the intra-arterial radial pressure. The first dependence, which, in the authors' knowledge, was never reported previously, reflects a key characteristic of the GTF method: the transfer

function applied to the radial waveform is indeed general—i.e., it does not change according to the patients' characteristics. Considering the large variability in the pulse pressure amplification reported here and elsewhere [30, 32], this aspect may be seen as an intrinsic limitation of the GTF technique. The development of individualized transfer function, as proposed by Fazeli et al. [33]., may result in the improvement of the estimates and should be pursued. Moreover, the need for calibration of the radial waveform using non-invasive brachial pressure entails a direct dependence of the resulting error from the inability of non-invasive brachial pressure values to reflect the intra-arterial radial pressure. This characteristic, which was evidenced here by multivariate linear regression analysis, was already shown in a previous study [16].

Limitations

Consecutive patient selection resulted in a predominance of males, many comorbidities and an average age of 68 years. These characteristics, which reflect the population affected by chest pain or suspected coronary disease, may limit the applicability of our results to subjects with other characteristics. Moreover, the effect of comorbidities could not be discerned due to the limited data available.

Invasive radial pressure was quantified 10 cm proximally to the radial artery access. This distance was conserved among individuals to avoid a possible bias due to regional pressure dynamics. Nevertheless, the location does not perfectly match either the position where brachial pressure is normally measured or location where arterial tonometry is performed.

Fluid-filled catheters are known to have technical limitations, and the measured quantities are thus subject to error. Nonetheless, as the fluid-filled catheter is the gold standard in clinical practice, we considered it as a ground truth for comparison. We further underlined that the catheter used in the present investigation has a high frequency response and low damping; thus, errors are expected to be limited. A minor inaccuracy in the catheter used cannot be excluded. However, because prior tests performed in a similar setting resulted in a limited damping coefficient of approximately 0.7 and an overall natural frequency of approximately 40 Hz, it is unlikely that catheter errors may bias our results.

The relatively high number of input parameters for the setting of the mathematical model may be a limitation for the application of this technique in clinical practice.

Due to the cross-sectional nature of the study design, no information on the prognostic value of these techniques can be inferred from these data. Longitudinal studies are needed to unveil the eventual difference in the prognostic value of these techniques.

Conclusions

In 62 subjects, we tested the capacity of a multiscale mathematical model and a GTF method to estimate the invasive aortic pressure. The mathematical model resulted in a slightly larger dispersion of the estimations than the GTF method but provided better estimation of the aortic pulse pressure. The GTF method's large dispersions were related to the large intersubject variability of aorta-to-radial pulse pressure amplification and to the inability of the non-invasive brachial pressure values to reflect the intra-arterial radial pressure. As mathematical model errors were related to only demographic and clinical conditions, further model improvement may result in increased precision of the estimations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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