



## OPEN Experimental verification and comparative analysis of peak expiratory flow measuring devices

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This study presents a comprehensive benchmarking of six commercially available peak expiratory flow meters (PFMs), using a precise experimental spirometric test bench. Eight peak expiratory flows (PEF) ranging from 59.40 to 688.80 L/min at three frequencies, were systematically applied to each device. Through a series of controlled tests, the devices' precision, accuracy, linearity, inter-device variability, and dynamic response were meticulously evaluated across their full measurement range. Results reveal distinct performance characteristics among models, with some demonstrating high precision and accuracy in intermediate flow ranges, whereas others exhibited significant deviations at lower or higher flows. Inter-device variability was minimal except for specific models at lower flow rates. Dynamic response at varying frequencies indicated negligible impact on device readings. This benchmarking provides valuable insights for clinicians and researchers selecting appropriate PFMs for respiratory assessments.

**Keywords** Peak expiratory flow meter, PEF, Spirometry, Benchmarking, Respiratory measurement

In the field of pulmonology, one of the inflammatory lung diseases that stands out due to its relevance and impact on both global and national public health is asthma<sup>1</sup>. Asthma affects approximately 11.5% of the global population aged 5 to 69, although this burden varies significantly across regions, largely influenced by differences in the Socio-Demographic Index (SDI)<sup>2</sup>. Between 2018 and 2021, a notable increase in global asthma prevalence was recorded, with the most pronounced rises occurring in high-SDI regions and among children under the age of five<sup>3</sup>. Alarming, in many low- and middle-income countries, an estimated 67% of individuals with asthma remain undiagnosed, while up to 62% of those diagnosed fail to receive adequate or effective treatment<sup>4</sup>.

For a correct diagnosis of asthma, spirometry is positioned as the first-choice diagnostic test, according to the European Respiratory Society guidelines for the diagnosis of asthma<sup>5</sup>. Two types of graphs can be obtained after its performance: the volume/time curve (where the lung air volume is expressed in litres on the y-axis and time in seconds on the x-axis) and the flow/volume curve (where the forced expiratory flow is plotted in litres per second on the y-axis and volume in litres on the x-axis)<sup>6</sup>. Peak expiratory flow (PEF) reflects the maximum speed of expiration and is an important indicator of the severity of airway obstruction, especially in asthmatic patients<sup>7</sup>. It depends on airway resistance, lung elastic recoil, chest wall mechanics, and the strength of the respiratory muscles<sup>8</sup>.

There are a series of devices used for the determination of PEF, known as peak expiratory flow meters (PFM). Most of these devices contain a simple internal spring or piston mechanism that moves with the airflow during a forced expiration manoeuvre, indicating the achieved PEF via a marker. The direct measurement of PEF using PFMs is faster, simpler, and less costly, making them especially suitable for home monitoring<sup>9</sup>. Moreover, the accessibility of these portable meters is greater in primary care consultations or emergency departments, thus making them necessary to confirm the diagnosis of asthma in situations where performing a spirometry test is not possible. PEF measurements fill diagnostic gaps, particularly where spirometry is not easily accessible or practical<sup>10</sup>.

In the case of patients with suspected asthma symptoms, an isolated PEF measurement (best of three attempts) can be used to indicate the likelihood of bronchial obstruction in the absence of confirmatory spirometry, though this approach is constrained by the wider limits of normal. Subsequently, this measurement should be compared to population reference values<sup>8</sup>. Additionally, the use of PEF meters during acute exacerbations in emergency

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services allows for the assessment of the severity of the crisis, helping to determine more objectively whether hospitalization is necessary.

There are reference values available to contrast the peak expiratory flow (PEF) obtained, which depend on height, age, and sex. Ideally, each healthcare setting should have its own theoretical values<sup>11,12</sup>. According to a recent article published by Donahue et al. (2024)<sup>9</sup>, PEF reference values from a peak expiratory flow meter are comparable to those from the gold standard, spirometry, highlighting the instrument's utility as a less expensive and more easily administered option in situations where performing spirometry may be challenging. The most widely used reference tables for adults are those developed by Nunn and Gregg<sup>13</sup>, who employed a standard Wright peak flow meter (Airmed Ltd, Harlow, UK) with an accuracy of  $\pm 5$  L/min, from which the formulas shown in Table 1 are derived (where age is expressed in years and height in centimetres). Additionally, some authors describe approximations of PEF for children and adolescents. Cobos, Reverté and Liñán<sup>14</sup> used two different peak flow meter models, MiniWright and PF-Control, and reported significant deviations of up to 30% in some ranges, discussing their population results separately for each device. They include nomograms for Spanish children and adolescents aged 6 to 16 years. Nojournian<sup>15</sup> offers a simple formula to predict the PEF value through a linear relationship between height (expressed in centimetres) and PEF, also indicated in Table 1.

In order to accurately record the flow resulting from a forced maximal expiration manoeuvre, it is of great importance that the peak expiratory flow (PEF) measuring device meets certain technical requirements regarding dynamic response, linearity, and precision. The article published in 2003 by Miller<sup>16</sup> first highlighted the need to evaluate and improve the accuracy of peak expiratory flow meters (PFMs) in terms of frequency response and waveform shapes. Subsequently, in 2005, the American Thoracic Society (ATS) proposed improvements to the initial standards for testing PFMs<sup>17</sup>. The current international standard that specifies the requirements for peak expiratory flow measuring devices is ISO 23,747<sup>18</sup>.

Today, several studies evaluate different PFMs with the aim of testing their accuracy by comparing results obtained from devices of different manufacturers<sup>19–23</sup>. The most reliable and widely used method is evaluation using a Pulmonary Waveform Generator (PWG), a device that generates a waveform with a known PEF. Comparative investigations have demonstrated the utility of these experimental benches for assessing the frequency response, linearity, and accuracy of PFMs under controlled conditions, with notable contributions by Hankinson et al.<sup>24–26</sup>. The use of such equipment enables the assessment of regulatory compliance in mechanical and electronic PFMs and provides comprehensive insights into their performance<sup>27</sup>, facilitating the refinement of standard clinical practices and, consequently, enhancing the analysis of results<sup>28</sup>. Nevertheless, the widespread implementation of PWGs remains limited, as their high cost restricts access in most healthcare centres. This limitation directly impacts clinical practice, where detailed knowledge of device performance is essential for ensuring reliable asthma diagnosis and follow-up.

In routine use, PFMs are discarded after a single patient encounter to prevent cross-contamination, which, despite their moderate individual price, results in considerable cumulative costs when applied across large patient populations. Moreover, different commercial models are frequently employed interchangeably in clinical settings, often without adequate awareness of potential systematic discrepancies in their measurements. Such variability poses risks for both the accurate diagnosis and the monitoring of respiratory conditions. These considerations highlight not only the technical relevance of benchmarking PFMs with experimental setups but also the clinical necessity of establishing robust, comparative data that can guide informed device selection and ensure consistency in patient care. In this context, the bench provides a platform for device calibration, research, and methodological studies while supporting clinical decision-making.

The primary objective of this study is to experimentally evaluate and benchmark the technical performance of six commercially available PFMs. This includes the assessment of precision, accuracy, linearity, inter-device variability, and dynamic response, with the purpose of providing clearer insights into their suitability for both clinical and research applications. In addition to this central aim, secondary objectives are to compare the accuracy of these devices in indicating PEF, to analyse their sensitivity across the measurement range, and to address the notable lack of systematic comparative studies reported in the literature. In fulfilling these goals, the study intends to bridge a critical gap and deliver a valuable reference for the field of pulmonology.

## Spirometric test bench and peak expiratory flow meters used

For the present study, a recently developed spirometric test bench was used to replicate various pulmonary conditions and respiratory patterns in a controlled environment. Its precise actuation mechanisms, real-time control, and advanced measurement tools can reproduce the respiratory system, enabling the testing of respiratory devices under various breathing patterns, such as resting breaths, forced breaths, and even cough-induced airflow<sup>29</sup>.

Expression	Range of application	Author
$Ln(PEF) = a \cdot Ln(age) - b \cdot age - \frac{c}{height} + d$ $a = 0.544; b = 0.0151; c = 74.7; d = 5.48$ $a = 0.376; b = 0.0120; c = 58.8; d = 5.63$	Men (15 to 85 years) Women (15 to 85 years)	Nunn and Gregg <sup>13</sup>
$PEF = (height - 80) \cdot 5$	Children and adolescents (6 to 16 years)	Nojournian <sup>15</sup>
PEF(L/min), height (cm); age(years)		

**Table 1.** Compilation of expressions corresponding to the theoretical reference PEFs for each specified application range according to age, sex, and height.

Characteristic	Commercial PWGs	System in this study
Error levels	Low (0.2%–0.5%)	Low (1%–1.5%)
Safety and ease of use	High, extensively validated	High, limited validation
Cost	High	Moderate
Design	Typically single cylinder	Dual-cylinder
Experimental flexibility	Limited	High, multiple configurations
Breathing pattern simulation	Standardized, realistic but limited	Versatile, patient-specific and pathological

**Table 2.** Comparison between commercial PWGs and the experimental test bench.

Code	Commercial name	Measuring range [L/min]	Photograph
 Model-I	AIRZONE® Clement Clarke International	60 - 800	
 Model-II	Mini-Wright® Clement Clarke International	60 - 880	
 Model-III	PINNACLE® Sibelmed	60 - 900	
 Model-IV	DATOSPIR PEAK-10® Sibelmed	60 - 900	
 Model-V	PersonalBest® Philips Respironics	60 - 800	
 Model-VI	ULTECHNOVO® Baluce	60 - 800	

**Fig. 1.** Characteristics of the peak expiratory flow meters utilised.

The operation of the experimental spirometry test bench is based on two distinct data input modes: real spirometry data acquired directly from a patient or externally loaded respiratory curves (spirometric and sinusoidal profiles). Subsequently, the bench enables the controlled replication of the selected input curve as many times as required. Although a single larger cylinder could have been used to reduce complexity, the experimental test bench employs two cylinders to more accurately mimic lung function and provide greater flexibility for additional experimental configurations. This feature is particularly valuable for evaluating peak expiratory flow measuring devices to determine the accuracy and repeatability of their measurements. Finally, the bench enables the recording of the airflows generated by the system<sup>29</sup>.

The spirometry bench demonstrates remarkable precision across all standard spirometry parameters (including FVC, FEV<sub>1</sub>, FEV<sub>1</sub>/FVC (%), PEF, FEF<sub>25%–75%</sub>), replicating input sinusoidal signals with relative errors below 1.5%, and spirometric curves exhibiting relative errors under 1%. The absolute and relative errors are consistently satisfactory, comparing favourably with those of existing commercial Pulmonary Waveform Generators (PWGs) by Piston Medical, which report values of 0.2% for volumetric measurements and 0.5% for flow parameters<sup>30</sup>.

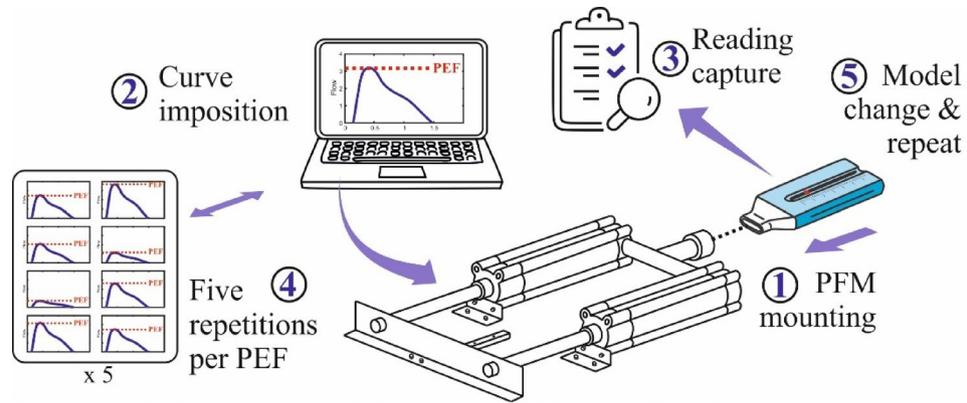
Although its error levels are comparable to those of commercial PWGs, overall, it does not outperform them, and both systems are similarly effective in terms of regulatory capability, safety, and ease of use. Nonetheless, the employed system has a moderate cost, and its primary advantage lies in the versatile and reproducible simulation of patient-specific and pathological breathing patterns, as summarized in Table 2.

Additionally, six peak expiratory flow measuring devices currently available were selected: AIRZONE®, Mini-Wright®, PINNACLE®, DATOSPIR PEAK-10®, PersonalBest® and ULTECHNOVO®. The coding used in this study, the commercial name, as well as the measurement range covered by each device, are shown in Fig. 1. These devices were chosen based on their widespread availability and routine use in the clinical practice of the health area of Vigo, ensuring that the results reflect commonly encountered instruments.

### Methodology and testing conditions

For the verification and comparison of the peak expiratory flow measuring devices (PFMs), the methodology implemented encompassed the following aspects:

- Evaluation of the sensitivity of each PFM through the study of the precision and accuracy with which they can indicate the predefined peak flow administered to each device, across the entire measurement range.



**Fig. 2.** Diagram of the methodology employed.

Peak expiratory flow input (L/min)							
59.40	102.60	203.40	305.40	408.00	495.60	609.00	688.80

**Table 3.** Maximum peak expiratory flows administered to the different meters.

- Analysis of the relationship between the imposed input flow from the test bench and the corresponding output readings obtained from each device, by assessing the linearity of the measurements across the full measurement range.

There is a common process for all tests, based on the imposition of predefined curves on the meters with variable characteristics, depending on what is intended to be studied. For this purpose, each curve is designed beforehand following the guidelines established in the manual of the spirometric bench used<sup>29</sup>. As a preliminary clarification, the parameters denoted as “input” refer to those established in the curve reproduced by the bench, while those denoted as “output” correspond to the readings from the PFMs.

Before extracting the results, eight spirometric curves with variable PEFs are prepared (considering the spirometric bench’s error of 0.25% for PEF values<sup>29</sup>). By establishing different peak flow values, the aim is to cover the entire scale range of the devices, from 59.40 L/min to 688.80 L/min.

The principal stages of the procedure conducted with each peak expiratory flow meter are illustrated in Fig. 2 as follows:

1. The PFM is connected to the spirometric bench mouthpiece.
2. The bench generates a spirometric curve with a predetermined PEF.
3. The PFM reading is recorded, accounting for a sensitivity of 5 L/min.
4. Five repetitions —as specified in ISO 23747:2015<sup>18</sup>— are performed for each PEF value in Table 3, yielding a total of 40 measurements.
5. The procedure is then repeated with the next peak expiratory flow meter (Model).

Thus, 40 readings are obtained for each of the six meters studied. In order to assess the precision with which each meter indicates the peak expiratory flow, the repeatability range ( $r_n$ ) for each input PEF ( $n$ ) is determined using Eq. 1, as indicated in ISO 23,747<sup>18</sup>, where  $q_{max,n}$  is the highest reading of the PFM for input flow  $n$ ; and  $q_{min,n}$  is the lowest reading for input flow  $n$ .

$$r_n = q_{max,n} - q_{min,n} \quad (1)$$

On the other hand, the individual accuracy analysis of the PFMs for each reference maximum flow  $n$  is performed by calculating the measurement error  $e_n$ , expressed by Eq. 2, also described in ISO 23,747<sup>18</sup>, where  $\bar{q}_n$  is the mean of the five PEF values recorded by the PFM for input flow  $n$ ; and  $q_{ref,n}$  is the reference PEF for input flow  $n$ .

$$e_n = \bar{q}_n - q_{ref,n} \quad (2)$$

Finally, to study whether there is a linear relationship between the input flow  $n$  and the reading recorded by the PFM, the difference  $d$  is calculated for each reference PEF  $q_{ref,n}$ , using Eqs. 3 and 4, as described in ISO 23,747<sup>18</sup>, where  $e_n$  is the error of the PFM for input flow  $n$ ;  $e_{n+1}$  is the error of the PFM for the next input

flow increment;  $\bar{q}_n$  is the mean of the five PEF readings for input flow  $n$ ; and  $\bar{q}_{n+1}$  is the mean for the next input flow.

$$\bar{q}_{n+1} \geq \bar{q}_n : \quad d [\%] = \frac{(e_n - e_{n+1}) \cdot 100}{\bar{q}_{n+1}} \quad (3)$$

$$\bar{q}_{n+1} \leq \bar{q}_n : \quad d [\%] = \frac{(e_n - e_{n+1}) \cdot 100}{\bar{q}_n} \quad (4)$$

## Results and discussion

This section presents the results obtained from the experimental evaluation of the peak expiratory flow meters (PFMs), encompassing both individual and comparative analyses. For the PEF measurements reported below, an instrumental uncertainty of  $\pm 5$  L/min was considered, corresponding to half the smallest scale division on the devices. This level of uncertainty was regarded as acceptable, given the adequate spacing of the scale intervals, which allows for consistent and reliable interpretation of the measurements.

### Individual evaluation of precision, accuracy, and linearity

After subjecting all six PFMs to the eight spirometric curves with variable PEF (ranging from 59.40 L/min to 688.80 L/min, covering the entire measurement scale range of the devices), the precision, accuracy and linearity of the measurements provided by each device are quantified, as explained in the corresponding section. The values obtained for each PFM are shown in Table 4.

In general, the range values  $r_n$  (calculated using Eq. 1, according to ISO 23747<sup>18</sup>) are observed to fall between 0 and 20 L/min (with 0 being the ideal scenario, indicating no variation across the five measurements). The maximum range value of 20 L/min was reached by the model I device when a PEF of 408 L/min was administered.

Next, the accuracy of the devices for each reference maximum flow is analysed through the calculation of the measurement error  $e_n$  (Eq. 2, according to ISO 23747<sup>18</sup>). The results initially suggest considerable differences between the mean of the five readings and the input PEF, where negative values indicate an underestimation (the input PEF is greater than the average reading), and positive values indicate an overestimation by the device (the average reading exceed the actual input flow).

Regarding the instrumental uncertainty value of 5 L/min, some peak expiratory flow meters show measurement error results below this threshold; however, most of them exceed the established value.

Finally, in order to study linearity, the difference  $d$  (Eqs. 3 and 4, according to ISO 23747<sup>18</sup>) was calculated for each input PEF and expressed as a percentage. Linearity varied across the models. Models II, III, V, and VI showed optimal linearity, particularly at intermediate scale values, with percentage differences close to 0%. Model II, in particular, showed high consistency across most of its range, maintaining deviations around 1% up to an input PEF of 495.60 L/min. In contrast, Models I and IV exhibited less consistent behaviour, with more pronounced deviations across the measurement ranges.

Figure 3 illustrates the distributions of the output readings recorded by each peak expiratory flow meter (PFM) in response to the different PEF input values generated by the spirometry bench. Visual representation using boxplots highlights the variability and central tendency of each device's measurements for every imposed flow level. In general, distributions closer to the reference input value are observed for the intermediate ranges of the devices' scales (from 200 to 500 L/min) whereas more evident deviations are observed at the high and low extremes. This behaviour at low ranges has been observed in other comparative studies<sup>22</sup>. Similarly, these findings are consistent with results from other model comparisons, where devices may underestimate in some cases and overestimate in others, showing significant differences when compared to spirometric values<sup>20</sup>. Such results do not reflect unusually poor accuracy, the reliability of each PEFM for daily comparisons remains intact. However, these variations should be considered when switching devices, as previously noted in studies such as Nazir et al. (2005)<sup>23</sup>, which reported average differences of 20.08 L/min between different PEFMs (95% CI: 17.85–22.29,  $P < 0.0001$ ). Based on all recorded values, 95% confidence intervals were calculated for each flow and model, showing an average range of  $\pm 2.16$  L/min and a maximum of  $\pm 5.88$  L/min, both comparable to the instrumental uncertainty of  $\pm 5$  L/min.

Analysing Fig. 3 from lower to higher flow rates, at input PEF of 59.40 L/min, a substantial increase is observed in the reading obtained by the Model V, as well as a considerable decrease for Model III. For these two devices, no data dispersion is observed, implying high precision but low accuracy for the lowest PEF studied. Conversely, Model VI demonstrates both high precision and accuracy for this specific range.

At an input PEF of 102.6 L/min, greater accuracy and increased dispersion are observed in the readings of the PFMs, except for Model I, whose readings deviate considerably from the reference value. Models II and V stand out for their accuracy at this input PEF, achieving an average reading of  $102 \pm 5$  L/min and a third quartile of  $102.5 \pm 5$  L/min (with a mean and median of  $100 \pm 5$  L/min), respectively.

At 203.4 L/min, results generally show narrower readings distributions across all meters, implying greater overall precision. Similar to the pattern observed at the flow of 102.6 L/min, Model I shows considerably deviated results, with the mean of its readings differing by  $50.59 \pm 5$  L/min. Models II and III stand out for their reliability, with the means readings very close to the reference value ( $200 \pm 5$  and  $205 \pm 5$  L/min, respectively).

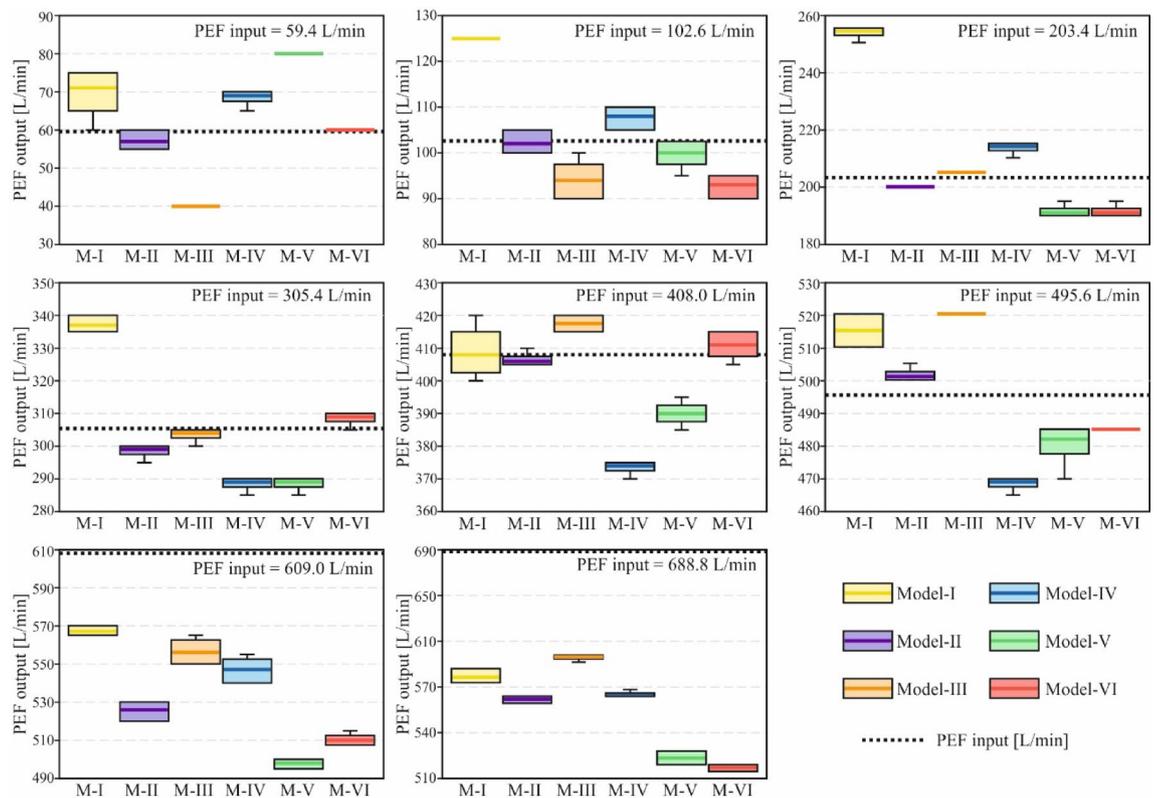
The results at 305.4 L/min are similar to those observed at 203.4 L/min. Once again, Model I demonstrates low reliability, while Models II and III show good agreement between the input PEF and the readings obtained.

Model	$\bar{q}_n$ Average PEF (L/min)	$q_{ref,n}$ Ref. PEF (L/min)	$r_n$ Range (L/min)	$e_n$ Error (L/min)	$d$ Linearity (%)
Model I	70.74	59.40	15	11.34	-8.85%
	125.00	102.60	0	22.40	-11.10%
	253.99	203.40	5	50.59	5.64%
	336.99	305.40	5	31.59	7.76%
	407.94	408.00	20	-0.06	-3.77%
	514.98	495.60	10	19.38	10.83%
	566.99	609.00	5	-42.01	10.76%
	583.98	688.80	10	-104.82	-
Model II	56.95	59.40	5	-2.45	-1.79%
	101.97	102.60	5	-0.63	1.39%
	200.00	203.40	0	-3.40	1.01%
	298.99	305.40	5	-6.41	-1.08%
	406.00	408.00	5	-2.00	-1.48%
	501.00	495.60	5	5.40	16.81%
	525.98	609.00	10	-83.02	6.65%
	567.99	688.80	5	-120.81	-
Model III	40.00	59.40	0	-19.40	-11.42%
	93.93	102.60	10	-8.67	-5.01%
	205.00	203.40	0	1.60	0.99%
	303.99	305.40	5	-1.41	-2.63%
	417.59	408.00	5	9.59	-2.85%
	520.00	495.60	0	24.40	13.93%
	555.97	609.00	15	-53.03	6.14%
	599.00	688.80	5	-89.80	-
Model IV	68.97	59.40	5	9.57	3.89%
	107.97	102.60	5	5.37	-2.44%
	213.99	203.40	5	10.59	9.34%
	288.99	305.40	5	-16.41	4.71%
	373.99	408.00	5	-34.01	-1.58%
	469.00	495.60	5	-26.60	6.48%
	546.97	609.00	15	-62.03	9.77%
	571.00	688.80	5	-117.80	-
Model V	80.00	59.40	0	20.60	23.26%
	99.95	102.60	10	-2.65	5.11%
	190.99	203.40	5	-12.41	1.38%
	288.99	305.40	5	-16.41	0.41%
	389.99	408.00	10	-18.01	-0.91%
	481.96	495.60	15	-13.64	19.55%
	497.99	609.00	5	-111.01	10.06%
	524.98	688.80	10	-163.82	-
Model VI	60.00	59.40	0	0.60	11.01%
	92.97	102.60	5	-9.63	1.45%
	190.99	203.40	5	-12.41	-5.18%
	308.99	305.40	5	3.59	0.15%
	410.98	408.00	10	2.98	2.80%
	485.00	495.60	0	-10.60	17.34%
	509.99	609.00	10	-99.01	13.86%
	517.99	688.80	5	-170.81	-

**Table 4.** Range, measurement error, and difference across the five measurements for each PEF of the peak expiratory flow meters evaluated.

Additionally, greater precision is observed in Model VI, with its mean differing only  $3.59 \pm 5$  L/min from the reference value.

At 408.0 L/min, readings closer to the input PEF are observed for Model I, contrary to expectations. Nevertheless, the data distribution is highly asymmetrical, with maximum values reaching  $420 \pm 5$  L/min. On



**Fig. 3.** Boxplots of the readings obtained by the PEF meters for each administered peak flow.

the other hand, precision decreases across all meters, except for Models II and VI, which continue to provide reliable results since the first studied input peak flows.

In the boxplots of the three highest flows (495.6, 609.0, and 688.8 L/min), a generalized decline in precision is observed for all models as the administrated input PEF increases. At 495.6 L/min, the most acceptable readings are those provided by Models II and VI, with mean values of  $501 \pm 5$  L/min and  $485 \pm 5$  L/min, respectively. For the input flows of 609.00 and 688.80 L/min, all readings deviate considerably from the reference value, with minimum differences between the mean readings of  $42.01 \pm 5$  L/min (Model I) and  $89.80 \pm 5$  L/min (Model III), and maximum differences of  $111.01 \pm 5$  L/min (Model V) and  $170.81 \pm 5$  L/min (Model VI).

To further evaluate and compare the precision of each peak expiratory flow meter (PEF), Fig. 4 shows the distribution of the Flow Coefficient (*FC*) obtained from the 40 readings recorded for each model. The *FC* corresponding to each PFM model was calculated using Eq. 5, for each administered input flow *n*. Here,  $q_n$  represents the PEF recorded for the input flow *n*.

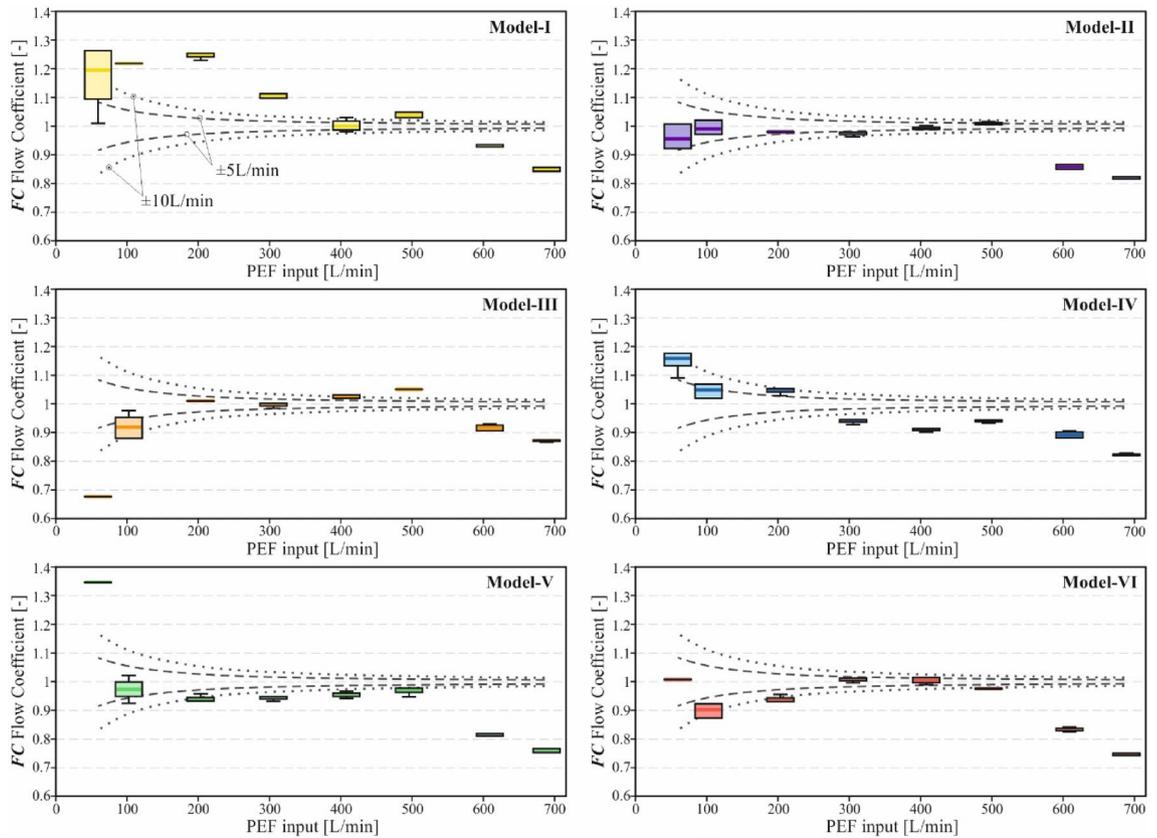
$$FC = \frac{q_n}{q_{ref,n}} \tag{5}$$

In Fig. 4, it can be observed that the peak expiratory flow meter, Model I, tends to overestimate the PEF when operating at low flows and to underestimate it at high flows, with the flow coefficient being greater than 1 in the former case and less than 1 in the latter. As the input PEF increases up to 609 L/min, the flow coefficient approaches 1, possibly indicating improved precision in the intermediate ranges of its scale. The variability of the readings provided by this PFM is highest at the lowest input PEF of 59.50 L/min, becoming more consistent as the input flow increases.

In general, Model II places its flow coefficients very close to 1 at most input PEFs, indicating high precision across almost the entire scale. For the highest flows of 609 and 688.80 L/min, the flow coefficient is slightly below 1, meaning a slight underestimation of 14% and 18%, respectively. Greater variability is observed at the lowest flows of 59.40 and 102.60 L/min, although it is not particularly substantial. Overall, the variability is small across the device’s entire scale, demonstrating high consistency in its measurements.

Model III achieves flow coefficients very close to the ideal value for the intermediate ranges of the scale. For the lowest input PEF of 59.40 L/min, a consistent underestimation of 33% in its readings is observed, although this underestimation is less pronounced at higher flows, where it is still present. In general, the device demonstrates high accuracy in flow measurement, as indicated by the narrow boxplot ranges. Moderate variability stands out particularly at the input PEF of 102.60 L/min compared to the other flows.

For Model IV (Fig. 4), it is observed that at low flows, the flow coefficient is greater than 1, indicating a tendency of the meter to overestimate the actual flow. As the input PEF increases, the coefficient decreases,



**Fig. 4.** Variability of the flow coefficient (FC) across the full range of flow rates for each model evaluated.

	Source	Sum of Squares	Degrees of Freedom	Mean Square	F-statistic	p-value	F-Critical
One way	Between groups	0.5641	5	0.1128	8.1109	4.5·10 <sup>-7</sup>	2.25262
	Within groups	3.2547	234	0.0139			
	Total	3.8188	239				
Two way	Flow levels	0.6168	14	0.0441	6.7133	2.1·10 <sup>-8</sup>	1.83568
	Models	0.2630	5	0.0526	8.0158	5.1·10 <sup>-6</sup>	2.34558
	Error	0.4594	70	0.0066			
	Total	1.3393	89				

**Table 5.** Summary of the main results from one-way and two-way ANOVA.

approaching 1 and thereby improving the precision of its readings. With higher input flows (from 609 L/min onward), the meter slightly underestimates the actual PEF value. Except for the lowest flows of 59.40 and 102.60 L/min (where greater variability is observed), there is high consistency across all measurements.

The behaviour of Model V shows three clearly differentiated zones: for the lowest input flow (59.40 L/min), a consistent overestimation of 35% relative to the actual input flow is observed; this overestimation decreases toward values close to 1 (with a slight underestimation) throughout the intermediate range of the device’s scale. Finally, the underestimation increases notably starting from 609 L/min. The variability in measurements is moderate across the entire scale and is not particularly substantial.

Finally, analysing Model VI, a tendency to underestimate the reference flows imposed is observed, reaching values close to 1 in the intermediate range of the scale. This underestimation becomes more evident at higher flows (609 and 688.80 L/min), reaching values of 16% and 25%, respectively. The variability with which Model VI expresses peak flows is relatively low, with a slight increase when an input flow of 102.60 L/min is administered.

To quantitatively assess these observations, one-way and two-way analysis of variance (ANOVA) tests were performed, with post-hoc Tukey Honestly Significant Difference (HSD) tests to identify specific differences. The one-way ANOVA revealed significant differences among the mean errors of the six models (see Table 5), with Model I differing significantly from all others, while no significant differences were observed among the remaining models. Incorporating volumetric flow as a second factor in a two-way ANOVA confirmed significant effects for both factors: ‘Models’ (F = 8.02, p ≈ 5.1·10<sup>-6</sup>) and ‘Flow levels’ (F = 6.71, p ≈ 2.1·10<sup>-8</sup>) on measurement

error. Post-hoc analysis further showed that High flow rates differed significantly from Low and Medium flow rates, highlighting a clear flow-dependent pattern in model accuracy.

In order to better understand the accuracy with which the peak expiratory flow meters indicate each input PEF, the relative measurement error with respect to the input PEF  $n$  is plotted for each device (Eq. 6), across their entire measurement range. These graphs are shown in Fig. 5. Here,  $e_n$  represents the measurement error for the reference maximum flow  $n$ ; and  $q_{ref,n}$  is the reference PEF for the input flow  $n$ .

$$e_{rel,n} [\%] = \frac{|e_n|}{q_{ref,n}} \quad (6)$$

Except for the Model I peak expiratory flow meter, similar trends in measurement accuracy are observed, achieving minimal relative differences between the input PEF and the average of the measurements in the intermediate ranges of the scale. The minimum values reached in this intermediate range are 0.79% and 0.46% for input PEFs of 203.40 and 305.40 L/min, respectively, in Model III, and 0.49% for an input PEF of 408 L/min in Model II.

Model I achieves the lowest relative error among all peak expiratory flow meters (0.01% for the input PEF of 408 L/min), but its heterogeneous progression throughout the entire scale is not consistent enough to be positively evaluated.

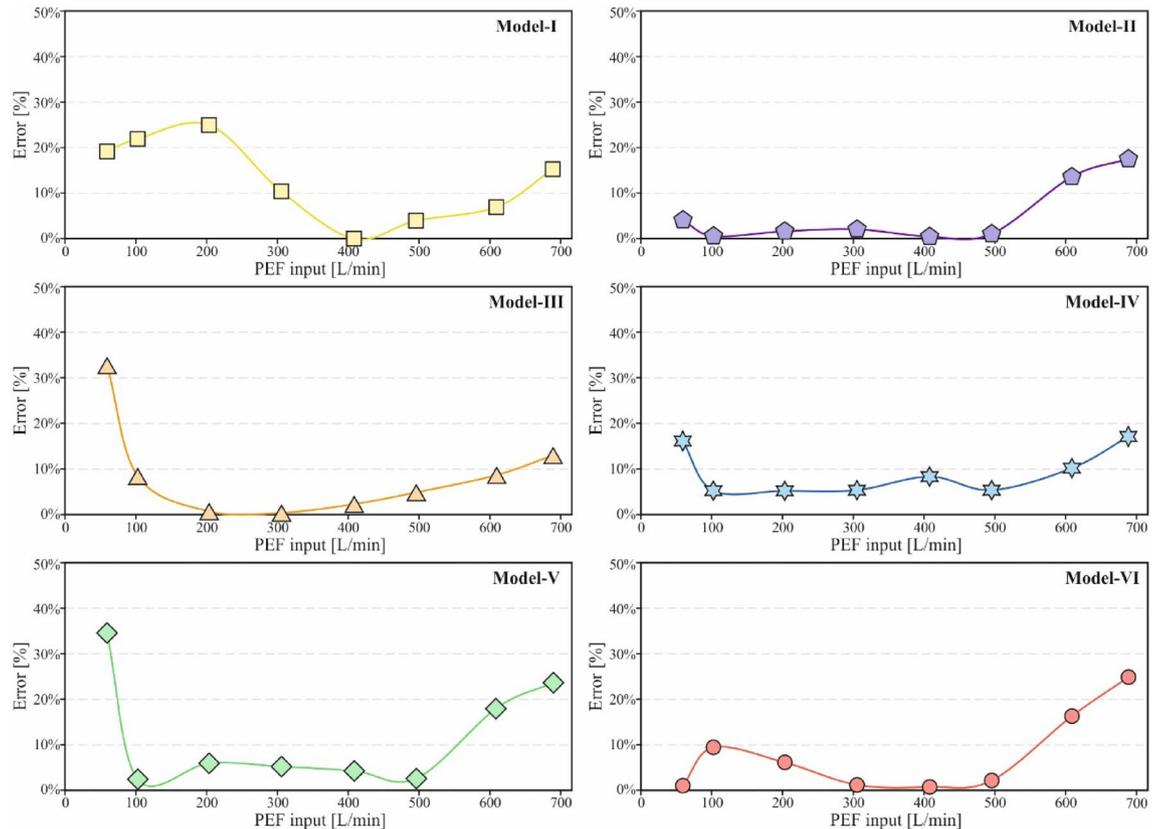
For Models III, IV, and V, a high error is observed for the first input PEF (59.40 L/min), which immediately decreases, leading to a consistent error progression across the intermediate ranges of the scale.

On the other hand, an increase in relative error is observed in all devices at the higher ranges of their scales, reaching a maximum value of 24.80% for an input PEF of 688.80 L/min in Model VI, and a minimum value of 13.04% for the same input PEF in Model III.

The results obtained, which exhibit relatively high errors, are not novel. Of the six models analysed in this study, three (Models I, II, and V) were evaluated in a previous comparative study<sup>21</sup>, with only Model I meeting the accuracy criteria set forth by ISO 23747:2015.

### Inter-device variability and dynamic response

Additional tests were conducted to evaluate the inter-device variability and the frequency response analysis. Four pairs of identical devices—corresponding to Models I, II, III, and VI—were selected from the six available models. For each pair, the two units were consistently designated as devices A and B. After being subjected again to the eight peak expiratory flows (ranging from 59.40 L/min to 688.80 L/min), the relative difference between



**Fig. 5.** Plots of measurement error relative to the input PEF across the full scale of each peak expiratory flow meter.

paired devices was calculated using Eq. 7, where  $\bar{q}_{n,A}$  is the mean of the five PEF readings recorded by PFM-A for the input flow  $n$ ; and  $\bar{q}_{n,B}$  is the mean of the five PEF readings recorded by PFM-B for the input flow  $n$ .

$$\text{Variability} [\%] = \frac{|\bar{q}_{n,A} - \bar{q}_{n,B}|}{\bar{q}_{n,A}} \cdot 100 \quad (7)$$

The results, plotted in Fig. 6, show a generalized minimal variability. Model II and VI presented low variability (<10%) across the entire range of their scales, while Models I and III exhibited higher variability (>20%) at low flow rates (below 203 L/min), particularly evident at the lowest PEF (59.40 L/min). It should be noted that the inter-device variability analysis included only a limited number of units per model. No systematic testing of intra-batch or inter-batch variability was performed, which may limit the generalizability of the findings. Future studies should incorporate multiple units from different production batches to more comprehensively evaluate variability across devices.

To assess dynamic response, three different waveform profiles (low, medium, and high frequency) were defined, based on mean respiratory frequencies during mild physical activity ( $f_L = 0.46 \text{ Hz}$ ,  $f_M = 0.67 \text{ Hz}$ , and  $f_H = 0.93 \text{ Hz}$ )<sup>31</sup>. For each frequency, each model was tested at three PEF levels, corresponding approximately to 25%, 50%, and 75% of the maximum flow value administered (688.80 L/min). Considering the error of the spirometry bench used to reproduce the curves (1.39%)<sup>29</sup>, the resulting target flows were 174.6, 349.2, and 524.4 L/min.

The evolution of the average of the readings acquired after the imposition of the three input peak flows is plotted in Fig. 7.

In general terms, heterogeneous fluctuations are observed in PEF readings across the three indicated frequencies, showing no consistent correlation with frequency changes.

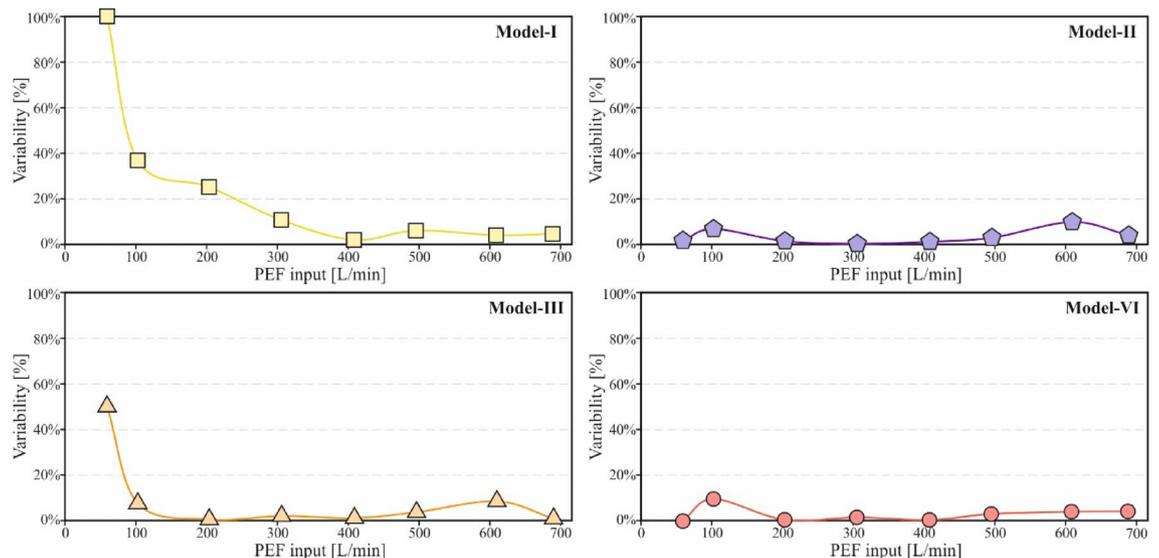
Additionally, for each model, the difference between the average output PEF recorded by the device after administering the waveform corresponding to high-frequency profile (H) and that of low-frequency profile (L), as defined by Eq. 8, is shown in Fig. 8. Where,  $\bar{q}_{L,n}$  represents the average of the five PEF readings recorded by the PFM for input flow  $n$  using low-frequency profile; and  $\bar{q}_{H,n}$  represents the average of the five PEF readings recorded by the PFM for input flow  $n$  using high-frequency profile.

$$\text{difference} [\%] = \frac{|\bar{q}_{L,n} - \bar{q}_{H,n}|}{\bar{q}_{L,n}} \cdot 100 \quad (8)$$

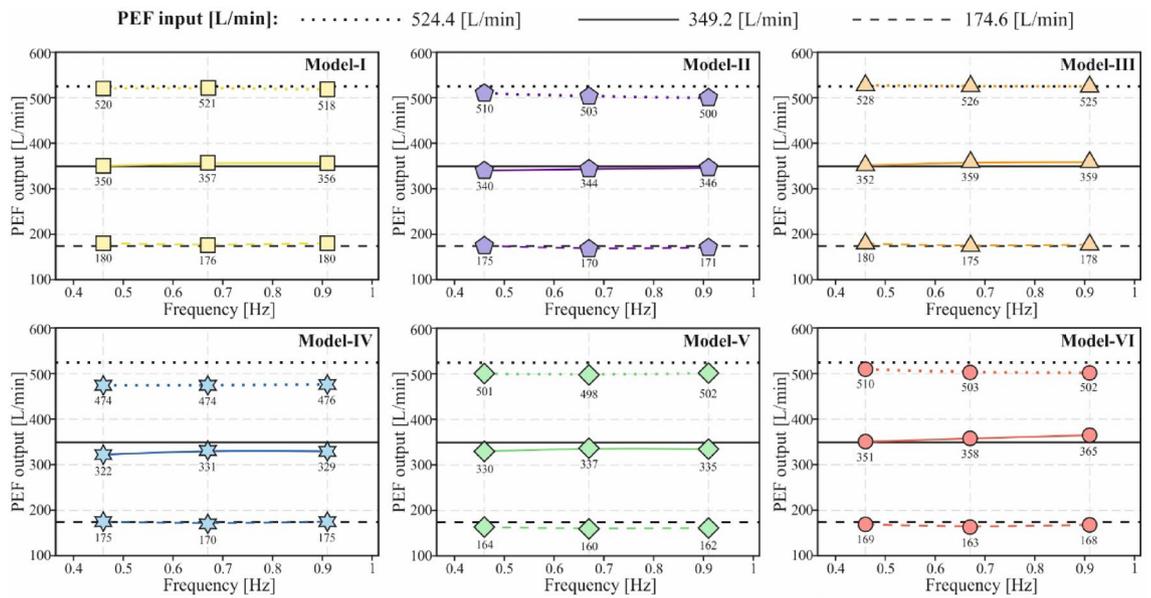
In general, for the six PEF meters analysed, very unsubstantial differences are observed, with values below 4% in all cases. Except for the Model II, the greatest differences are observed when the intermediate input flow (349.20 L/min) is administered compared to the extremes of the scale, which may indicate a greater ability to accurately register high and low airflow rates under different profile and flow conditions.

## Conclusions

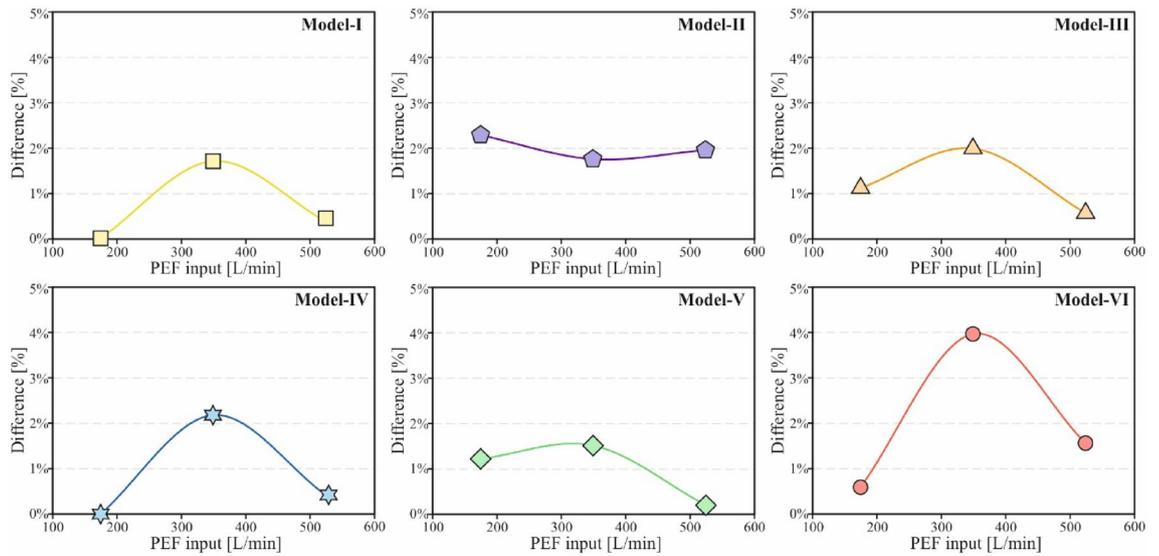
This study presents a rigorous benchmarking of six peak expiratory flow meters using a controlled spirometric test bench, revealing notable differences in precision, accuracy, linearity, inter-device variability, and dynamic



**Fig. 6.** Plots of the variability of the B meters with respect to the A meters for each reference PEF input.



**Fig. 7.** Analysis of the relationship between the peak expiratory flow readings obtained from different meters using three frequency profiles: L, M, and H.



**Fig. 8.** Difference between low and high frequency results expressed for each model evaluated.

response. Most PFMs demonstrated optimal precision and accuracy within the intermediate ranges of their scales. However, significant measurement deviations were observed at both low and high extremes, with some models consistently underestimating or overestimating PEF values. Model II exhibited the highest consistency in both accuracy and precision across the broadest spectrum of flows, whereas Models I and III showed substantial deviations, particularly at the lower and upper extremes of the flow range.

These technical limitations should be carefully considered by clinicians when diagnosing or monitoring respiratory conditions, particularly asthma, where accurate and reliable measurements are essential. Although inter-device variability tests were carried out with only two devices per model, the variability results were generally low, they nonetheless suggest caution when using Models I and III in low peak expiratory flow (PEF) populations. To reinforce this finding, additional studies involving a greater number of devices would be valuable.

In daily clinical practice, it is common to compare pulmonary function parameters over time, with variations of 10% in PEF considered clinically significant. This becomes particularly relevant when different commercial models are used interchangeably, as potential discrepancies in their measurements may compromise the reliability of the results.

Dynamic response analysis indicated that frequency variations had negligible effects on PFM readings, underscoring the robustness of these devices under differing respiratory patterns. These findings emphasize the importance of selecting PFMs based on validated benchmarking data to ensure reliable respiratory assessment in clinical and research settings.

Further investigation should address real clinical environments, particularly with asthma and COPD patients. Long-term testing evaluating aging and degradation, assessment of device durability, analysis of human factors such as usability and interpretation of results, as well as economic versus accuracy evaluations, should be undertaken. Incorporating these aspects will extend the practical applicability and robustness of the current findings, providing a roadmap for future research.

## Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

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## Author contributions

C. P. conceptualized the study and contributed to methodology. E. S. and E. P. carried out the experimental tests and wrote the original draft. A.F-V. contributed to formal analysis and supervised the study. All authors read and approved the final manuscript.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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