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Whole-body plethysmography: updated recommendations and procedure

Pletismografía corporal: actualización en las recomendaciones y procedimiento

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ABSTRACT. Body plethysmography (BP) is a lung function test that measures lung mechanics, through the measurement of functional residual capacity (FRC_{pleth}), and specific airway resistance (sRaw). It is particularly useful for confirming pulmonary restriction as well as quantifying pulmonary hyperinflation. The objective of this document is to provide an update on the procedure and recommendations for body plethysmography according to the latest international standards -American Thoracic Society (ATS) and European Respiratory Society (ERS) 2021 y 2023- as well as to issue practical recommendations for its interpretation.

Keywords: body plethysmography, lung function, lung volumen.

RESUMEN. La pletismografía corporal es una prueba de función pulmonar que mide la mecánica pulmonar a través de la medición de la capacidad residual funcional (FRC_{pleth}) y la resistencia específica de la vía aérea (sRaw). Su uso es de gran utilidad para la confirmación de restricción pulmonar, así como para la cuantificación de la hiperinflación pulmonar. El objetivo de este documento es actualizar el procedimiento y las recomendaciones de la pletismografía corporal de acuerdo con los estándares internacionales vigentes de la Sociedad Americana del Tórax y la Sociedad Europea Respiratoria, 2021 y 2023, así como emitir recomendaciones prácticas para su interpretación.

Palabras clave: pletismografía corporal, función pulmonar, volúmenes pulmonares.

Abbreviations:

ATS = *American Thoracic Society*
ERS = *European Respiratory Society*
ERV = Expiratory reserve volume
EVC = Expiratory vital capacity
FEV_1 = Forced expiratory volume in the first second
FRC = Functional residual capacity
FRCpleth = Functional residual capacity by plethysmography
FVC = Forced vital capacity
GLI = Global lung initiative
IC = Inspiratory capacity
ITGV = Intrathoracic gas volume
LLN = Lower limit of normality
ULN = Upper limit of normality
p5 = percentil 5
p95 = percentil 95
BP = Body plethysmography
PRISm = Preserved ratio impaired spirometry
Raw = Airway resistance
RV = Residual volume
sRaw = Specific airway resistance
SVC = Slow vital capacity
TLC = Total lung capacity
VC = Vital capacity
TV = Tidal volume

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INTRODUCTION

Body plethysmography (BP) is a pulmonary function test that measures functional residual capacity (FRC_{pleth}), also known as intrathoracic gas volume (ITGV), as well as specific airway resistance (sRaw)[1] (see supplementary material). It confirms the presence of pulmonary restriction and, in obstructive disease, quantifies pulmonary hyperinflation.[2,3]

The values obtained in BP depend on the distensibility and elasticity of the rib cage and lung parenchyma, as well as the integrity of the respiratory musculature. Distensibility is the ease with which a body stretches or deforms (change in volume observed by change in pressure), while elasticity is the opposition of a body to being stretched (ability to return to its original shape).[4]

BP measurement is based on Boyle-Mariotte's Law: «the volume of a gas is inversely proportional to the pressure to which the gas is subjected under isothermal conditions; therefore, during compression of a gas under these conditions, the product of pressure and volume remains constant».[5] The aim of this review is to update the document published in 2019 on plethysmography procedure and recommendations, in accordance with current international standards-ATS [American Thoracic Society]/ERS [European Respiratory Society] 2021 and 2023-[6,7] and provide practical recommendations for its interpretation.

DEFINITION

BP is a pulmonary mechanics test that measures lung volumes, quantifies the total amount of gas in the thorax (whether in direct communication with the airway or not),[5] and measures total lung capacity (TLC), which is subdivided into four volumes and four capacities shown in *Figure 1* and their definitions are summarized in *Table 1*.[7,8]

The cardinal measurement of BP is FRC, which requires that the end-expiratory air volume at tidal volume (TV) remain stable. According to the ATS 2019 spirometry standard, this stability is defined as the presence of at least three breaths at TV with a difference between maximum and minimum end-expiratory lung volume within 15% of TV.[9]

FRC_{pleth} includes ventilated and non ventilated lung compartments, and its results may be higher than those obtained by dilution or gas washout methods in the presence of severe obstruction, bullae, or emphysema. Although theoretically FRC_{pleth} may be increased by abdominal gas, the amount of abdominal gas is small (~100 mL) and larger volumes appear to have no effect on FRC measurement.[10] In cases of severe obstruction FRC_{pleth} may be overestimated when the respiratory rate (RR) during the gasping maneuver is > 1 Hz (60 breaths/min) because mouth pressure underestimates the absolute change in alveolar pressure.[7,11]

After measuring FRC, an inspiratory capacity (IC) maneuver is required to measure TLC, followed by a slow expiratory vital capacity (EVC) maneuver until the residual

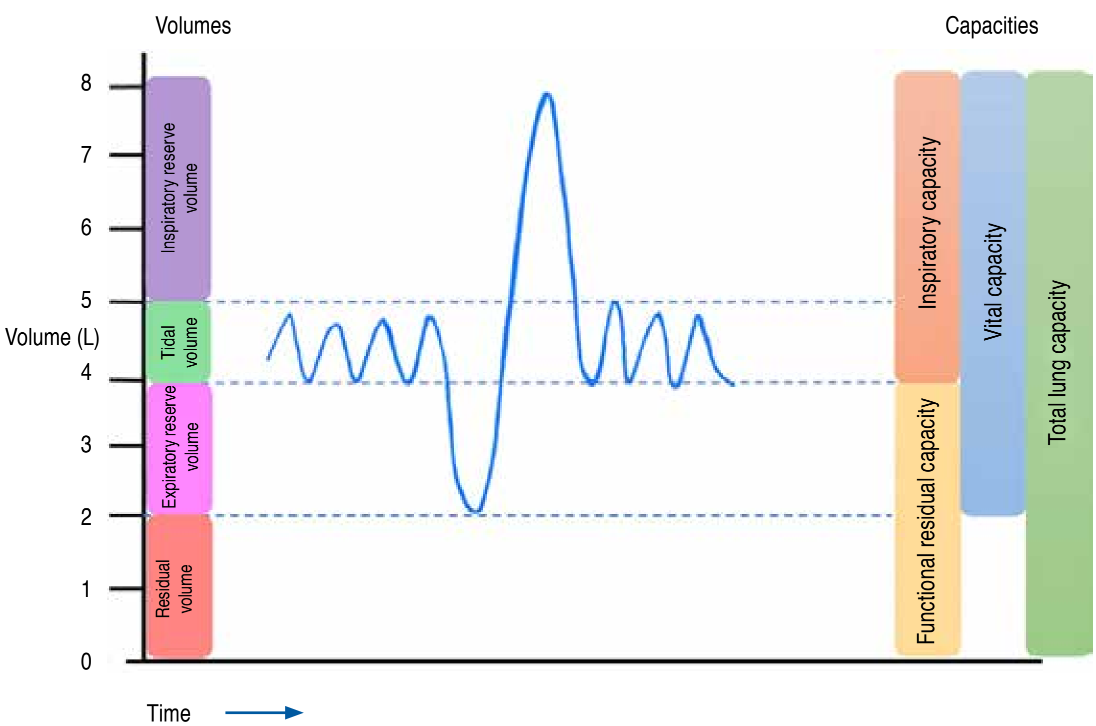

Figure 1:

Static lung volumes and capacities based on a volume-time spirogram.

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Table 1: Lung volumes and capacities.

Lung volumes	
Tidal volume (TV)	It is the volume of gas inhaled or exhaled during the normal respiratory cycle
Inspiratory reserve volume (IRV)	It is the maximum volume of gas that can be inhaled from the tidal volume at the end of inspiration.
Expiratory reserve volume (ERV)	This is the maximum volume of gas that can be exhaled from the tidal volume at the end of expiration, i.e. from FRC to RV
Residual volume (RV)	This is the volume of gas that remains in the lung after a maximum exhalation
Lung capacities	
Vital capacity (VC)	It is the maximum change in volume that can be exhaled or inhaled between the positions of full inspiration (TLC) and full expiration (RV). It corresponds to the sum of the displaceable volumes (VT, IRV and ERV)
Inspiratory capacity (IC)	It is the maximum volume of gas that can be inhaled from the FRC to the TLC. It is the sum of IRV and VT
Functional residual capacity (FRC)	It is the volume of gas present in the lung at the end of passive expiration, of a normal respiratory cycle. It is the sum of ERV and VR
Total lung capacity (TLC)	It is the total volume of the lung at maximum inspiration. It is the sum of all the RV, ERV, VT and IRV volumes, and can also be calculated by the sum of the IC and the FRC or the RV with the VC

volume (RV) is reached, without removing the mouthpiece.[7] It is important to emphasize the slow EVC maneuver, since a forced maneuver can cause premature closure of the dependent airway and generate overestimation of the RV *(Figures 2 and 3)*.[7]

To perform the calculation of TLC and RV it is required to report the pulmonary subdivisions, for this purpose it is important to measure vital capacity (VC) and one of its subdivisions, such as IC (inspiratory capacity) or expiratory reserve volume (ERV); the repeatability of both HF and ERV will be determined in part by the repeatability of FRC.[7]

Linked (associated) spirometry is ideal; unlinked spirometry is not a recommended option for plethysmography.[7]

INDICATIONS FOR BP

Indications are detailed in *Table 2*.[1,12] We recommend measuring lung volumes in individuals with abnormal spirometry results (decreased forced vital capacity [FVC], e.g., probable mixed pattern, PRISm).[6]

CONTRAINDICATIONS TO BP

They are similar to the rest of the contraindications for the other respiratory function tests *(Table 3)*.[6,13] Some risks during the performance of BP are: hypoxemia in subjects in need of supplemental oxygen, anxiety, distress, claustrophobia and dyspnea.

EQUIPMENT AND CONSUMABLES FOR BP

The plethysmograph is an airtight chamber with a volume ranging from 700 to 1,200 L (larger volumes are used for obese, very tall, or wheelchair-bound patients). Its airtight design allows it to maintain a constant volume. As a result, changes in thoracic volume, which occur during the compression or decompression of pulmonary gas during respiratory maneuvers, can be calculated by measuring the changes in cabin pressure.[7]

The plethysmograph requires: software and hardware conforming to ISO 26782, mouth pressure transducer (≥ ± 50 cmH_2O; minimum 8 Hz response) and flow sensor meeting the standards presented for spirometry. It should measure changes in cabin pressure accurately within ± 0.2 cmH_2O. Changes in temperature can cause a pressure change of up to 1 cmH_2O, requiring a wider working range of the transducer.[7,14]

A time constant of 10 s (range 5-25 s) is ideal for controlled leakage (minimizing slowly occurring pressure changes). Temperature changes inside the cabinet are common and can be detected from the volume-pressure graph *(Figure 4)* during occlusion, which shows a systematic difference in slope between compression and expansion.[7,14]

Manufacturers should specify the response frequency of their systems and how to verify it. The response frequency should be a minimum of five times the frequency of the signal being measured, in this case, for a maximum acceptable breath-hold of 1.5 Hz (90 breaths/minute) this means a minimum acceptable response frequency of 8 Hz.[7,14]

It is crucial that the equipment be networked to transmit results to electronic records and to facilitate access to clinical information, as well as to collect data for research.

Other necessary consumables are listed in *Table 4*.

PERSONAL PROTECTION

Hand washing (40-60 seconds) or use of alcohol gel (20-30 seconds) before and after the test is required for both the

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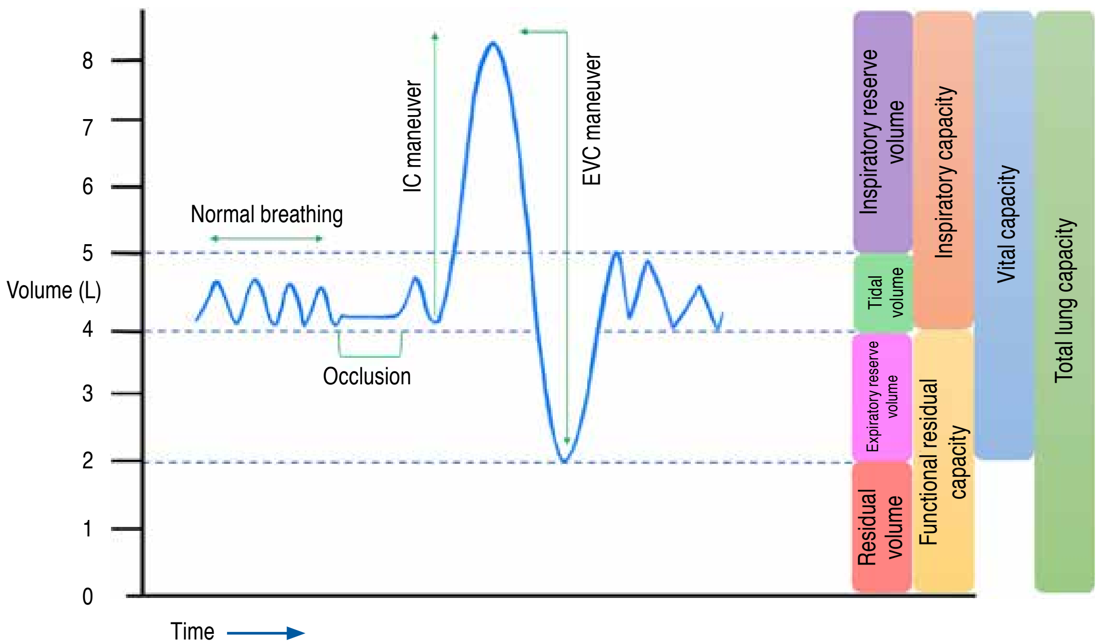

Figure 2: Body plethysmography (BP) maneuver for lung volumes. Volume-time graph showing the sequence of quiet breathing until a stable level of FRC (functional residual capacity) is reached at the end of expiration, then the shutter is closed (for a short period, approximately 2 to 3 s) to measure the intrathoracic gas volume. The shutter is then opened and the patient performs an IC (inspiratory capacity) maneuver followed by an EVC (slow expiratory vital capacity) maneuver. As a variation it is also allowed for the subject to take one breath after the shutter and then IC followed by an EVC maneuver. In this maneuver all lung volumes are calculated, the patient must remain connected to the mouthpiece with a tight lip seal throughout the measurement and specifically while the shutter is closed.

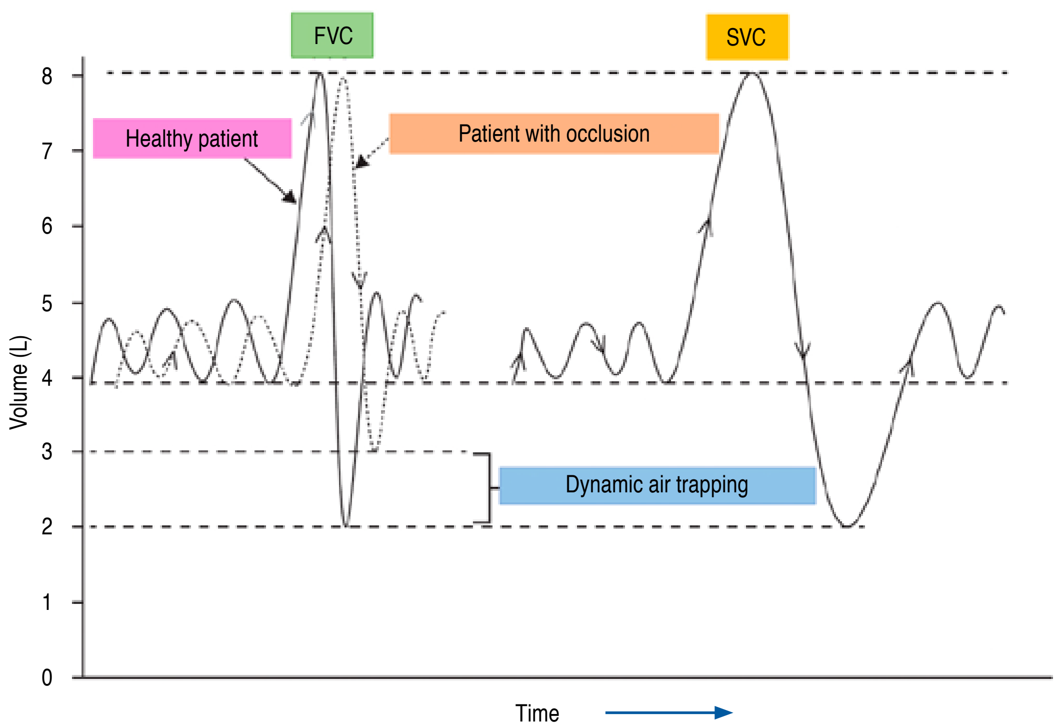

Figure 3:

Vital capacity (VC) maneuver in a healthy subject and in a subject with obstruction. In a healthy subject, the expiratory vital capacity maneuver performed in a forced (FVC) or slow (SVC) manner is expected to give the same result. However, in a subject with an obstructive ventilatory defect, there is a potential for dynamic air trapping and overestimation of residual volume with a forced maneuver.

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Table 2: Indications for body plethysmography.

Confirmation and quantification of pulmonary restriction
Confirmation and quantification of pulmonary hyperinflation and air trapping, especially in patients with dyspnea disproportionate to the degree of obstruction by FEV_1
Preoperative evaluation of volume reduction surgery
Monitoring and surveillance of disease for clinical or research purposes
Patients with any of the following functional patterns by spirometry: suggestive of restriction, PRISm, probable mixed
Dyspnea or exercise intolerance

FEV_1 = forced expiratory volume in the first second. PRISm = *preserved ratio impaired spirometry.*

Table 3: Relative contraindications for body plethysmography (BP).

Recent heart attack (< 4 weeks)
Heart failure
Cardiovascular instability
Tachycardia at rest (HR > 130 bpm)
Chest or abdominal surgery < 4 weeks; eye or ear surgery < 8 weeks
Active pulmonary tuberculosis
Acute respiratory tract infections in the last two weeks
Hemoptysis
Aneurysm (of large arteries, cerebral)
Late pregnancy (third trimester) or complicated pregnancy
Poor health
Tracheostomy
Chest tube
Continuous requirement for supplemental oxygen that cannot be discontinued during the test
Subject conditions that do not allow him to be introduced into the cabin, such as claustrophobia, body paralysis, parenteral solutions or medical devices that cannot be introduced into the plethysmograph cabin

HR = heart rate. bpm = beats per minute.

operator and the subject. A surgical mask (preferably N95), short hair or hair clipped, gloves (when there is any skin lesion), and eye protection are recommended. Ensure good ventilation and the use of antimicrobial filters.[15]

INSTRUCTIONS TO THE SUBJECT BEFORE BP[13]

The main indications are described in *Table 5*.

EQUIPMENT PREPARATION BEFORE THE BP

Quality control and calibration:[14]

1. Calibration check of the body plethysmograph.
   a. Calibration verification: procedure that establishes a relationship between the volume or flow measured by the sensor and the actual flow or volume of the calibrator (syringe). Perform calibration verification of the cabinet at least once a day, so that the software will calculate the correction factors.[9,16]
   b. Perform calibration verification of the plethysmograph flow sensor for volume with a 3 L syringe at least once a day with three maneuvers at different flows in the range between 0.5 and 12 L/s (injection of 3 L in 0.5 to 6 s). Check that the volume at each flow meets the accuracy requirement of ≤ 3%, be sure to save the results (see supplementary material for detailed information).[9,16]

BP PROCEDURE[5,7,13,14]

1. The laboratory staff receives the patient, verifies their identity, and ensures that the request matches the patient's information and the study requested.

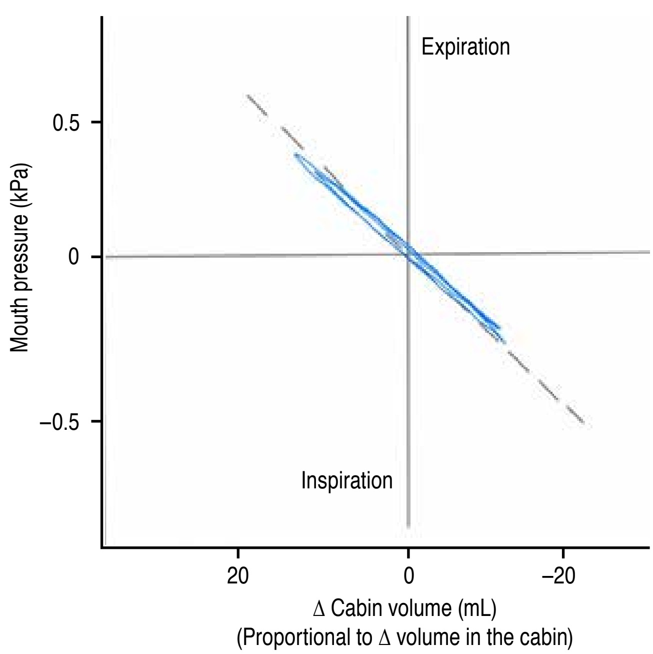

Figure 4: Gasping maneuver. A correctly performed gasping maneuver is visualized as a series of nearly overlapping straight lines, separated only by a small thermal change. The target gasping frequency is between 0.5 and 1 Hz. Δ: change in gasping frequency.

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Table 4: Body plethysmography (BP) consumables.

Extra BP consumables
3-liter syringe with an accuracy of ± 0.5% of the absolute volume (15 mL), calibrated and with a valid calibration certificate
Reusable consumables: • Flow sensor • Adapters
Disposable consumables: • Disposable filter with efficiency > 99% for filtration of viruses, bacteria and mycobacteria; dead space < 100 mL and resistance less than 1.5 cmH_2O at a flow rate of 14 L/s • Mouthpieces of various sizes • Nose clip • Silicone mouthpieces
Calibrated scale and stadiometer
Anthropometric belt
Thermometer, hygrometer, barometer or local barometric pressure source, for manual adjustment of ambient conditions.

Table 5: Instructions for the subject before performing body plethysmography.

Avoid smoking and vaping two hours before
Avoid wearing restrictive chest garments, such as vests, corsets or very tight clothing
Maintain your baseline medication. Bronchodilators and inhaled steroids modify the measurement, so the decision to suspend or continue these medications should be made by the requesting physician and the technician should report the time of the last dose
Fasting is not required for the test, but a light meal is recommended four hours before
You should avoid strenuous exercise on the day of the test

2. If the patient speaks a language other than English, a family member or translator must accompany the patient to explain the procedure.
3. Check for contraindications; if there are any, notify the physician to evaluate whether the test is appropriate.
4. Explain the procedure and the risks before performing the test and offer clarifications if required. The following explanation to the patient is recommended: «Plethysmography is a test to measure the size of your lungs, it is very similar to spirometry, but to perform it you have to be inside this closed cabin for approximately 15 minutes. Don't worry about being inside the booth; you won't feel discomfort, and I will be observing and guiding you throughout the procedure.
5. Enter the patient's data into the computer: full name, date of birth, biological sex at birth, weight and height. See supplementary material for taking anthropometric values.
6. Select the appropriate reference equation for the subject.
7. Introduce the patient into the plethysmograph cabinet, seat the patient in an upright position and adjust the chair so that the feet are flat on the floor. Adjust the height of the flow sensor so that the patient can reach the nozzle without extending or flexing the neck.

Instruct and demonstrate how to perform the BP: use of mouthpiece, use teeth without biting, seal lips, use nose clip, hold cheeks without raising arms; demonstrate gasping by obstructing the back of the mouthpiece and advise that the door will remain closed during the test.

Recommendations: explain to claustrophobic patients that the door can be opened at any time during the test. Verify that thoracic expansion is not limited by the use of girdles, corsets, etcetera. In the case of the use of well-fitting dentures they are usually left in place, otherwise it is better to remove them.

BP MANEUVER[7]

1. Close the cabinet door and wait for the pressure and temperature to stabilize.
2. Set the flow sensor to zero.
3. Instruct the patient to put on the mouthpiece, nasal clamp and hold their cheeks with their hands. Holding the cheeks is particularly important in cases of airflow obstruction, where it reduces, but does not eliminate, the impact of higher gasping frequencies.
4. Instruct him to breathe quietly until a stable end-expiratory lung volume (stable FRC) is achieved, usually three to 10 breaths at stable VT. *Figure 2* exemplifies the BP maneuver.
5. Occlude the obturator at end-expiration (when the patient is at the stable FRC level) for approximately 2 to 3 s, during which time the patient performs gentle panting against the closed obturator (~ ± ± 1 kPa [~ ± 10 cmH_2O]) or at a rate between 0.5 and 1.0 Hz (30 to 60 breaths per minute) and maximum 1.5 Hz (90 breaths per minute).
6. Note: panting frequencies > 1.5 Hz may lead to an overestimation of FRC. This effect increases as the obstruction worsens. Panting frequencies:

- Record acceptable gasping maneuvers (a series of two or three nearly overlapping straight lines, with minimal hysteresis between inspiration and expiration), on the pressure-volume graph *Figure 4*.
- During gasping with the obturator closed, check that the maneuvers are acceptable. Verify the

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automatic adjustment of the difference between ITGV and FRC_{pleth} on the spirogram trace. The gasp frequency for each maneuver should be shown on the numerical report.
- When the shut-off valve opens, IC maneuver should be performed, followed by slow EVC to RV.

7. Note: patients with severe dyspnea may have difficulty performing a IC maneuver immediately after the gasping maneuver against the closed obturator. To overcome this, instruct them to remain in the mouthpiece and breathe two or three times after the gasp maneuver, before performing the IC and EVC maneuvers *(Figure 2)*.

- Airway resistance measurements should not be performed during the same maneuver used to measure lung volumes, as the optimal gasping frequencies differ. Additionally, prolonged time with the mouthpiece increases the risk of leaks, which may compromise the accuracy of lung volume measurements. We recommend doing the measurement of airway resistances at the end, once we have already selected acceptable and repeatable maneuvers.
- Finish the maneuver, allow the patient to recover and repeat the process; in case of a failed maneuver, repeat the instructions and demonstrate the test again.
- Obtain three maneuvers with acceptability criteria and assess repeatability (see section: BP assessment).
- If you have finished the study, support the patient's exit from the cabin, save the results to generate the study report. At the end, clean and disinfect the plethysmographic booth and the patient care area.

EVALUATION OF THE BP[7]

The ERS/ATS 2023 standard for lung volumes[7] proposes the following classification based on FRC and linked spirometry.

1. Acceptable: meets all quality criteria.
2. Usable: reported and used with caution.
3. Not acceptable or rejected: consider not to report.

Criteria for acceptability

Table 6 lists the acceptability criteria for the FRC_{pleth} measurement *and Table 7* lists the acceptability criteria for the linked spirometry maneuver.

Table 6: Acceptability criteria for measurement of intrathoracic gas volume (functional residual capacity).

Tidal volume breathing before shutter closure and gasping	
Acceptable	**Before shutter closure:** • Stable end-expiratory tidal volume **During shutter closure:** • Gasping maneuvers • Superimposed straight lines without hysteresis • Parallel straight lines with minimal hysteresis • Gasping respiratory rate between 0.5 to 1 Hz or between 1.0 and 1.5 Hz with normal spirometry or mild obstruction
Usable	Any of: **Before shutter closure:** • End-expiratory tidal volume unstable, but no significant change in either direction **During shutter closure:** • Partially closed gasping maneuver • Partially overlapping straight lines • Parallel straight lines with hysteresis • Respiratory rate >1.5-2.0 Hz with normal spirometry or mild obstruction
Not acceptable or rejected	Any of: **Before shutter closure:** • Unstable end-expiratory tidal volume with significant change in either direction (e.g., increase in end-expiratory lung volume with each breath) **During shutter closure:** • Gasping maneuver with mouth opening • No straight lines • Excessive hysteresis • Force to perform the gasping maneuver exceeded the range of the oral pressure transducer • Gasping respiratory rate < 0.5 Hz, > 2 Hz with normal spirometry or mild obstruction or > 1.5 with significant obstruction

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Table 7: Acceptability criteria for the linked spirometry maneuver.

Spirometry maneuver after functional residual capacity (FRC) measurement.	
Acceptable*	**Linked spirometry** • If > 6 years, SVC ≥ (FVC–150 mL) • If ≤ 6 years, SVC ≥ (FVC–100 mL) or (FVC – 10% of FVC), whichever is lower
Usable‡	**Any of:** • If > 6 years, SVC ≥ (FVC–250 mL) • If ≤ 6 years, SVC ≥ (FVC–200 mL) or (FVC – 10% of FVC), whichever is less
Not acceptable or rejected	**Any of:** • Spirometry not linked to PC • If > 6 years, SVC < (FVC–250 mL) • If ≤ 6 years, SVC < (FVC–200 mL) or (FVC – 10% of FVC), whichever is lower

FRC = functional residual capacity. FVC = forced vital capacity. SVC = slow vital capacity.
* Meets American Thoracic Society (ATS)/European Respiratory Society (ERS) criteria for within-maneuver assessment of inspiratory capacity and SVC. If forced spirometry is not performed in the same session as lung volumes, an alternative is to obtain at least three vital capacity measurements that meet ERS/ATS acceptability criteria for within-maneuver assessment and the largest of these vital capacities is a surrogate for FVC in this table.
‡ Interpret with caution.

Repeatability criteria

Obtain three acceptable FRCpleth (ITGV) values that agree within 5%. Calculate the repeatability:

[(ITGV major − ITGV minor) / ITGV average] × 100.

If you do not achieve this value, a value of 10% may be usable.

GRADING OF BP QUALITY[7]

The grading system considers the number of acceptable maneuvers for FRCpleth, SVC and repeatability. The final quality grade of the test is determined by the lowest grade obtained, for example; with ≥ 3 acceptable maneuvers for FRC and SVC with repeatability between 5 and 10%, the test is classified as C *(Table 8)*.

In grades D, E and U (usable) a report is issued, but should be interpreted with caution.

BP REPORTING[7]

Maneuvers selection

If you obtain ≥ 2 acceptable maneuvers that meet 5% FRC repeatability, these and your linked spirometry maneuvers should be used to report FRC and other lung volumes.

The value reported for FRC is the average of the technically acceptable FRC measurements used for the TLC calculation.

TLC is the average of the sum of the technically acceptable FRC values and linked CI maneuvers.

RV is the value reported for TLC minus the largest measured SVC. We recommend that all methods link spirometry maneuvers with FRC measurement to calculate TLC and/or RV.[7] For details, see supplementary material. *Table 9* shows the information that should be contained in the report.

INTERPRETATION OF THE BP

The ERS/ATS 2021 standard recommends using the lower limit of normal (LLN) and upper limit of normal (ULN) or percentile 5 (p5) and percentile 95 (p95), respectively. The predicted percentile is no longer taken as a reference.[6]

It recommends using the Global Lung Function Initiative (GLI) reference values, which integrate measurements according to sex, age range 5-80 years, from 11 countries with the limitation of being predominantly for European populations.[6]

We have analyzed GLI reference values in Mexicans living at moderate altitude (1,500-2,500 m above sea level) finding higher lung volumes and, therefore, poor adjustment of this equation to our population. It is important to analyze the fit of the different equations in each region. For interpretation purposes use biological sex at birth and not gender.

The updated algorithm for PC interpretation is shown in *Figure 5*.[6]

Start with TLC, if restrictive pattern (left side of algorithm).

Once restriction is diagnosed, assess the FRC/TLC or RV/TLC ratio. If these ratios exceed the LSN or p95, evaluate the patient's spirometry FEV1/FVC ratio. If the FEV1/FVC ratio is below LIN, it indicates a mixed pattern: restriction by plethysmography and obstruction by spirometry.

If the FEV_1/FVC ratio is not < to LIN or p5, it is a complex restriction.

If FRC/TLC or RV/TLC is not > to LSN or p95, it is a simple restriction.

On the other hand, go back to the beginning of the algorithm and check TLC, if TLC is not < to LIN or p5 (right side of the figure), proceed to see if it is > LSN or to p95, if it is not above these either, analyze the FRC/TLC or RV/TLC ratio and see if it is > ULN or p95, if it is not above, it is normal lung volumes.

If the TLC is not > ULN or at p95, but the FRC/TLC or RV/TLC ratio is > p95 it is hyperinflation or air trapping.

If from baseline the TLC is > ULN or p95 it is possible hyperinflation, proceed to look at the FRC/TLC or RV/TLC ratio, if it is not > ULN or p95 it is large lungs.

If in this same part of the algorithm, the FRC/TLC or RV/TLC is > ULN or p95 hyperinflation is confirmed.

Hyperinflation may occur with TLC, FRC and RV, or only with FRC or only with RV; in the former situation, increased TLC indicates loss of elastic retraction, so it is probably due to emphysema; whereas, in the latter situation, increased FRC or RV without increased TLC may be observed in chronic bronchitis or asthma, indicating the presence of air trapping.

CONCLUSIONS

BP represents an invaluable diagnostic tool in the classification of ventilatory disorders. In light of the updates

Table 8: Grading of body plethysmography.

Grading system for a lung volume test using BP			
Grade	Number of FRC measurements	Number of SVC measurements	FRC repeatability
A	≥ 3 Acceptables	≥ 3 Acceptables	Within 5%
B	≥ 2 Acceptables	≥ 2 Acceptables	Within 5%
C	≥ 2 Acceptables	≥ 2 Acceptables	Within 10%
D	1 Acceptable and ≥ 1 usable	1 Acceptable and ≥ 1 usable	Within 10%
E	1 Acceptable and 0 usable	1 Acceptable and 0 usable	NA
U	0 Acceptable and ≥ 1 usable	0 Acceptable and ≥ 1 usable	Within 10%
F	0 Acceptable 0 usable		

FRC = *functional residual capacity.* NA = not applicable. SVC = *slow vital capacity*

Table 9: Elements that the body plethysmography report must contain.

Report content
Full name of the patient
Birthdate
Identification number
Anthropometric parameters (age, sex, weight and height)
Reference equation
Absolute values of lung volumes and capacities in liters, with two decimal places and under ambient pressure and body temperature conditions (BTPS)
Absolute values, percentages of predicted; and LLN and Z-score (ERS/ATS 2021) of the three acceptable ITGV-VC maneuvers, including FRC_{pleth}, IC, ERV, VC, TLC and RV
The average value of three acceptable maneuvers for FRC_{pleth}, IC, ERV and TLC (calculation: IC + FRC)
The highest value of VC
RV = average TLC minus the highest value of VC
Spirogram graphs showing that the maneuver was performed in a linked manner and ITGV maneuvers
Optional: Last calibration date and environmental data

ATS = *American Thoracic Society.* BTPS = *body temperature, pressure, saturated* ERS = *European Respiratory Society.* ERV = *expiratory reserve volume.* FRC_{pleth} = *functional residual capacity* . IC = *inspiratory capacity.* ITGV = *intrathoracic gas volume* . LLN = lower limit of normality. RV = residual volume. TLC = *total lung capacity* . VC = *vital capacity.*

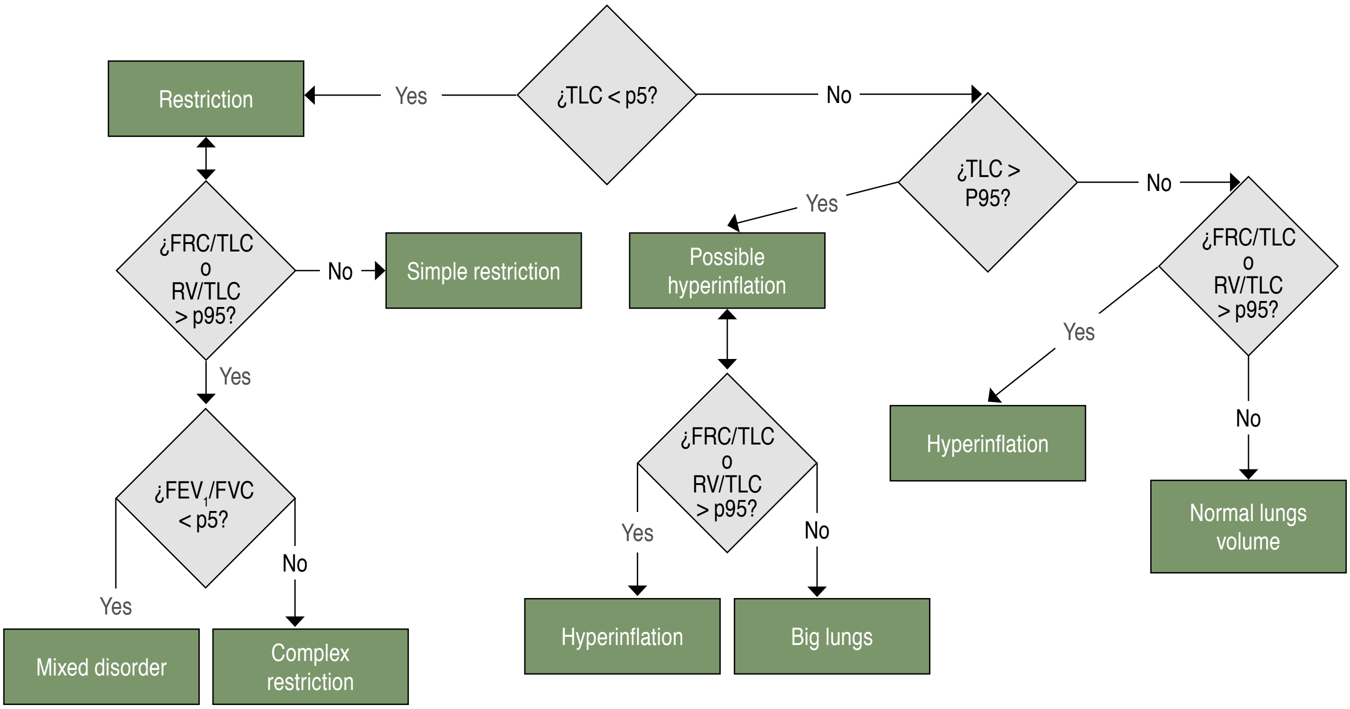

Figure 5: Algorithm for interpreting lung volumes.
FEV_1 = forced expiratory volume in the first second. FRC = functional residual capacity. FVC = forced vital capacity. p5 = 5th percentile. p95 = 95th percentile. RV = residual volume. TLC = total lung capacity.

in the technique of performance and interpretation, it is imperative that health professionals adapt and apply these innovations, in order to improve the accuracy of the measurements, deepen the understanding of their results and thus facilitate better clinical decision making. We still need to work on a reference equation that better fits the Mexican population.

Supplementary material

Specific resistance of the airway

In fluid mechanics, resistance is defined as the ratio of driving pressure (pressure difference that drives a fluid to move from one point to another) to flow. The higher the pressure required, the greater the resistance. In the respiratory setting, airway resistance (Raw) is the ratio of the pressure difference between the alveoli and the mouth (the latter is constant during free breathing) to the flow rate determined at the mouth.[5] Body plethysmography (BP) assesses airway resistance, but the primary measure recorded is specific airway resistance (sRaw), which, despite its name, is not a direct measure of resistance.[17]

Since alveolar pressure cannot be measured during free breathing, a surrogate marker of airflow resistance is used, relating flow rate to displacement volume or cabin pressure, both of which are directly measurable. This displacement volume reflects the changes in thoracic volume required to create driving pressure in the lung.[18]

The relationship between displacement volume or, equivalently, cabin pressure and flow rate, expressed in appropriate units is called «specific airway resistance, sRaw». Plotting flow vertically against displacement volume horizontally yields «closed curves» indicating sRaw *(Figure 6B)*. In healthy subjects, these curves are nearly straight, whereas in patients with respiratory pathologies they show patterns useful for differential diagnosis *(Figure 6)*. A flatter curve suggests higher sRaw. It is important to differentiate these curves as «specific resistance loops» and not simply «resistance loops», as this distinction affects data interpretation.[1,19]

The following example illustrates how sRaw is affected by lung volume and airway resistance. Consider two patients with identical lung volumes and resistances, both generating the same alveolar pressure and airflow, resulting in identical breathing loops or sRaw. However, if one lung is twice as large as the other, this patient will require twice the displacement volume to generate the same pressure, doubling his sRaw despite having the same resistance. Similarly, if the volumes are equal but the resistance of one is twice that of the other, the patient with the greater resistance

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will require twice the change in alveolar pressure, resulting in a shallower loop and double the sRaw. This demonstrates that sRaw varies with lung volume and airway resistance, and that breathing loops can be similar with different resistances if the volume and resistance ratios are inverse.[1]

PREPARING THE EQUIPMENT BEFORE THE TEST

Quality control and calibration[14]

1. Daily calibration check of the body plethysmograph.
   a. Perform calibration check of the mouth pressure transducer on a daily basis.
   b. The plethysmography signal is calibrated daily using a volume signal with magnitude and frequency similar to those that will be recorded with patients.
   c. During calibration check and use, avoid rapid changes in room pressure and vibrations (examples: abrupt door closures, changes in room air currents from HVAC, and high-efficiency particulate air filter systems). Strong winds and direct sunlight may also affect measurements.[7]
   d. Ensure that the mouth occlusion shutter offers minimal resistance to opening and closing (i.e., does not jam).
   e. Follow the manufacturer's instructions for setting up the equipment.
   f. Perform monthly precision validation of the determined volume, with a lung or container model with a compression-decompression frequency of 0.5 to 1 Hz. Plethysmograph precision must be maintained at ± 50 mL or 3% of the volume of the model used (whichever is greater) based on the average of five determinations.
   g. It is convenient to have healthy biological controls, capable of achieving maneuvers with a coefficient of variation < 5% for FRC and TLC; who are tested monthly; in the event of software updates or suspicions of equipment error, measurements outside of two standard deviations of the usual merit exhaustive verification of the equipment in search of errors and corrective maintenance.
   h. Verify that the acceptability criteria are within acceptable limits (according to the manufacturer's instructions):
      h.1. QPB = quality factor (coefficient of variation) of cabin pressure.
      h.2. Tau verification (time constant (Tau) = half-life in seconds).
      h.3. KPB = calibration factor.

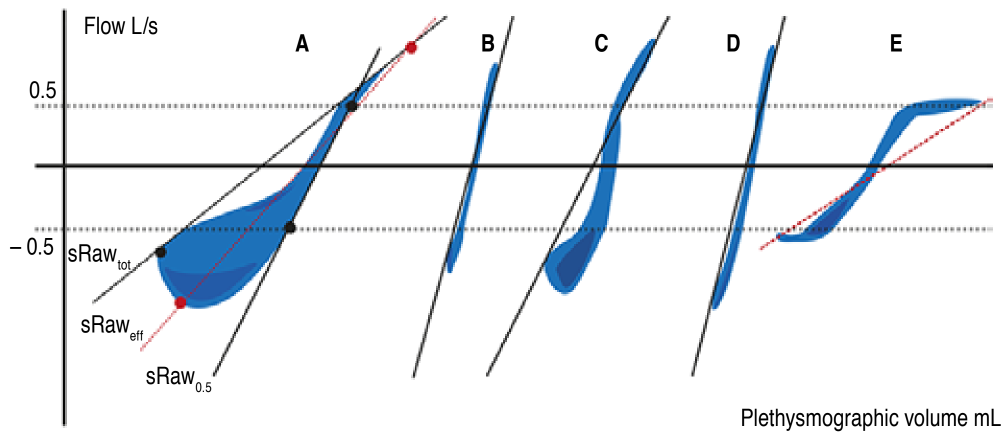

Figure 6: Plethysmographic flow-volume graph. **A)** Resistance curve in a subject with chronic obstruction where large volume changes are primarily generated during inspiration for small flow changes. The proposed calculations of the slope that best describes the curve are presented.
- sRawtot is determined as the slope of a straight line drawn between the maximum points of inspiratory and expiratory volume change. It represents a maximum value and is sensitive to changes in the small airway; however, it has a wide variability.
- sRaweff is the specific effective resistance that corresponds to a dimensional analysis of the curve, from which a representative slope is also reported. Its measurement is less variable, it is considered to be composed mainly of resistance of the central airways.
- sRaw0.5 consists of drawing a line between the points of +0.5 L/s and –0.5 L/s. Generally this portion of the graph is more linear so it has less variability and is also considered representative of the central airway. Its flow adjustment allows to eliminate artificially high values due to the presence of turbulence.

B) Normal resistance curve, healthy subjects require small volume changes to generate inspiratory and expiratory flow during tidal volume breathing, sRaw values are very similar in the three calculations. **C)** Representative curve of patients with acute obstruction. **D)** Resistance in a patient with restrictive disease, note how high flows are generated for small volume changes. **E)** sRaw of a patient with tracheal stenosis, large volume changes are required to generate low flows both in inspiration and expiration.
Adapted from: Guerrero-Zúñiga S et al. Body plethysmography: recommendations and procedure. Neumol Cir Thorax. 2019;78(Suppl 2):S113-S123.

BP PROCEDURE

Anthropometric measurements

1. Record weight in kilograms, to the nearest 0.5 kg; measure height with the individual barefoot, fully erect, heels together, and facing forward.
2. For patients who are unable to stand or who have a rib cage deformity, arm span measurement can be used to estimate standing height: measure the distance between the tips of the middle fingers (arm span).
3. For Caucasian men: height = arm span/1.03; for African-American men: height = arm span/1.06; and for women height = arm span/1.01.
4. In the case of patients who cannot be measured standing and also do not have an arm, the average span can be measured as the distance between the tip of the middle finger and the prominent cervical vertebra and multiplied by 2. And if a patient presents with significant deformity of body posture in whom it is not possible to measure the span in a linear manner, the composite span (segments) must be calculated.

BP REPORT

Selection of maneuvers

If at least two acceptable and repeatable FRC maneuvers are not obtained, all maneuvers with acceptable or usable FRC and that meet repeatability of at least 10% should be used for the calculation. If three or more maneuvers are considered (e.g., one acceptable and two usable) and FRC repeatability of at least 10% is not met, the maneuver with the largest difference in FRC from the mean FRC should be discarded along with its associated spirometry. FRC repeatability is then recalculated and additional maneuvers are similarly discarded until repeatability of at least 10% is met. The coexistence of two acceptable FRC maneuvers but not repeatable by at least 10% is rare; if it occurs, attempt to obtain another maneuver to determine which is the outlier.

Conflict of interests: the authors declare that they have no conflict of interests.

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