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Repeatability and reproducibility of inspiratory capacity measurement by spirometry and body plethysmography

Repetibilidad y reproducibilidad de la capacidad inspiratoria medida por espirometría y por pletismografía corporal

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ABSTRACT. Introduction: the variability between measurements of inspiratory capacity (IC) by spirometry or plethysmography have not been completely described. The objective of this study was to describe the repeatability between the different IC maneuvers measured by slow spirometry and its reproducibility compared with body plethysmography. **Material and methods:** this is a descriptive, cross-sectional and prospective study of a sample of healthy adults who completed IC measurements by slow spirometry by two different maneuvers and by body plethysmography. **Results:** a total of 49 participants (27 men and 22 women) with a mean age of 33.2 ± 8.3 years (26 to 65 years) were included. The repeatability of the IC was ≤ 150 mL in 96% of the subjects for spirometry maneuvers while for plethysmography it was 78% of the participants. The correlation (Pearson's r) was 0.95 between slow spirometry maneuvers and 0.87 and 0.88 compared with plethysmography. The agreement between measurements showed potential errors of up to 576 mL between spirometry and up to 936 mL with plethysmography. **Conclusions:** the IC measurement by slow spirometry reached a repeatability of 150 mL or less in 96% of the participants, while by plethysmography it was only in 78% with potential errors close to one liter compared to plethysmography. This study supports the current recommendation of repeatability of 150 mL for the IC measurement by spirometry.

Keywords: inspiratory capacity, spirometry, repeatability.

RESUMEN. Introducción: la variabilidad entre mediciones de capacidad inspiratoria (IC) por pletismografía o espirometría no han sido completamente descritas. El objetivo de este estudio fue describir la repetibilidad entre las diferentes maniobras de IC medida por espirometría lenta y su reproducibilidad comparada con pletismografía corporal. **Material y métodos:** se trata un estudio descriptivo, transversal y prospectivo de una muestra de adultos sanos, quienes completaron mediciones de IC por espirometría lenta por dos maniobras diferentes y por medio de pletismografía corporal. **Resultados:** se incluyeron un total de 49 participantes (27 hombres y 22 mujeres) con una edad promedio de 33.2 ± 8.3 años (26 a 65 años). La repetibilidad de la IC fue ≤ 150 mL en 96% de los sujetos para las maniobras de espirometría, mientras que para la pletismografía fue de 78% de los participantes. La correlación (r de Pearson) fue de 0.95 entre las maniobras de espirometría lenta y de 0.87 y 0.88 comparado con pletismografía. La concordancia entre mediciones mostró errores potenciales de hasta de 576 mL entre espirometría y de hasta 936 mL con pletismografía. **Conclusiones:** la medición de IC medida por espirometría lenta alcanzó una repetibilidad de 150 mL o menos en 96% de los participantes, mientras que por pletismografía fue sólo en 78% y con errores potenciales cercanos a un litro comparado con pletismografía. Este estudio soporta la recomendación vigente de repetibilidad de 150 mL para la medición de IC espirométrica.

Palabras clave: capacidad inspiratoria, espirometría, repetibilidad.

Abbreviation:

Vd = volume difference
EELV = end expiratory lung volume
COPD = chronic obstructive pulmonary disease
FEV_1 = forced expiratory volume in one second
FRC = functional residual capacity
FRC_{pleth} = plethysmograph RFC
FVC = forced vital capacity
IC = inspiratory capacity
RV = residual volume
TLC = Total lung capacity
VC = Vital capacity

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INTRODUCTION

Inspiratory Capacity (IC) is the maximum volume of air that can be inhale continuously from one point to the end of a normal exhalation (tidal volume) to a point of maximum inhalation or total lung capacity (TLC).[1,2] The initial point on inhalation of the IC corresponds to the functional residual capacity (FRC), it is a static volume which is also called end expiratory lung volume (EELV). In patients with limited expiratory airflow due to obstructive pulmonary diseases, the EELV is determined by the time constant, tidal volume and the expiratory time.[3] Changes in any of these variables that increase the EELV causes an IC decrease. This is functionally relevant because the IC represents a reserve for the tidal volume and, thus, for minute ventilation in exercise conditions.[4] IC measuring has been frequently used for investigation purposes; it can be more sensitive than the forced expiratory volume in one second (FEV1) for the quantification of the functional improvement after different therapeutic interventions in patients with chronic obstructive pulmonary disease (COPD). IC predicts dynamic hyperinflation and exercise limitations,[5-7] it correlates with syndromes such as dyspnea, bronchodilators response, and exercise tolerance.[6,8-17] IC has been use as an improvement indicator in pulmonary rehabilitation programs that involve upper and lower limbs, with or without oxygen therapy[18-20] in non-invasive mechanical ventilation[21] and in surgery of volume reduction.[22] Similarly, IC has been used to define the pulmonary hyperinflation like the relation IC/TLC below 25%. Conceptually, this indicator represents the pulmonary inspiratory fraction and has been described as an important predictor of mortality in patients with COPD.[23] IC can be measure by both vital capacity (VC) by body plethysmography. Even when the repeatability and reproducibility of the IC has not been fully explored, the standard of the American and European Societies (ATS/ERS) recommend an IC repeatability of less than 150 mL or less based on the experience of the group and following good practices.[2] The objective of this study was to describe the repeatability and reproducibility of the different IC measurement techniques, both by slow spirometry and by body plethysmography in a sample of healthy adults.

MATERIAL AND METHODS

A descriptive and prospective study with a convenience sampling was conducted, according to the availability of the laboratory of pulmonary function for the participants studies, who were healthy subjects; most of them workers of the institution, over 18 years of age, without any acute nor chronic respiratory disease history, without respiratory symptoms and without a history of active smoking (less than 400 cigarettes throughout their lives); all of them signed an informed consent form. Subjects who were unable to perform the acceptable maneuvers of forced spirometry, slow spirometry or body plethysmography were removed. Respiratory function tests were always performed in the same order (slow spirometry, forced spirometry and body plethysmography) and as indicated by the ATS/ERS 2005 standards, in force at the time of the study.[24] All the tests were performed by expert technicians from the laboratory of pulmonary function and subsequently qualified by the same observer to ensure the criterion of acceptability and repeatability was met. One equipment of respiratory function tests (MasterScreen Body, Jaeger, Hochberg, Germany) was used for all tests. The equipment was calibrated for volume with a three-liter syringe daily before the start of the day. The maximum variability accepted was ± 3%. The subjects were instructed to perform the maneuvers and later a technician demonstrated each maneuver. All subjects performed a forced spirometry, sitting down and in all a minimum of three acceptable maneuvers were obtained, for which up to eight attempts were made. The spirometry must fulfill the repeatability criterion, defined as a difference of less than 150 mL between the two highest values of force vital capacity (FVC) and the two highest values of FEV_1.

Inspiratory capacity measurement (IC). Once the subject is seated, the nasal clamp and the mouthpiece of the spirometer were placed, avoiding the presence of air leakage. The individual had to be relaxed and it was requested a normal breathing, for at least three respiratory cycles or until we obtained a stable level of FRC. Two different maneuvers have been described to measure the inspiratory capacity. Maneuver 1 is performed with an IC after reaching a stable level of FRC (no movement of FRC up or down from the level at the end of expiration), the subject should inhale rapidly to the point of TLC (maximum inspiration), followed by a relaxed maximum exhalation until reaching to residual volume (RV). In the maneuver, after obtaining a stable FRC, the subject is asked to exhale completely and in a relax way until a plateau of one second is achieved; after that it is asked to completely inhale until reaching TLC (inspiratory VC) and to exhale completely again in a relaxed way and until reaching a plateau of at least one second (expiratory VC). All subject were able to complete at least three acceptable measurements of VC for both maneuvers with a repeatability less than 150 mL.

Body Plethysmography. The participants were placed inside the cabin sitting straight, and the mouthpiece was adjusted to the appropriate height of the mouth, without bending the neck. The door of the chamber was closed and it was given enough time, usually one minute, for the temperature to equilibrate and the individual to feel comfortable. Afterwards the correct position of the mouthpiece and the nasal clamp was explained; then, it

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Table 1: General characteristics of the studied population.

Variable	Men (n = 27)	Women (n = 22)	Total (n = 49)
Age, years	33.7 ± 7.3 (26-51)	35.1 ± 0.07 (27-65)	33.2 ± 8.3 (26-65)
Weight, kg	78.5 ± 10.5 (63-116)	62.5 ± 9.1 (46-82)	71.1 ± 12.8 (46-116)
Height, m	1.75 ± 0.05 (1.64-1.87)	1.59 ± 0.06 (1.49-1.81)	1.67 ± 0.10 (1.49-1.82)
BMI, kg/m^2	25.7 ± 3.1 (21.6-38.3)	24.6 ± 2.8 (20.0-30.1)	25.2 ± 3.0 (20-38.3)
*Participants with BMI ≥ 25 kg/m^2	14 (51.8%)	10 (45.5%)	24 (50.0%)
*Participants with BMI ≥ 30 kg/m^2	1 (3.7%)	1 (4.5%)	2 (4.0%)
Forced spirometry maneuver	4.4 ± 1.3 (3-8)	4.3 ± 1.5 (3-7)	4.3 ± 1.3 (3-8)
FVC, L	5.24 ± 0.65 (3.78-6.54)	3.55 ± 0.8 (2.66-4.65)	4.46 ± 1.01 (2.66-6.54)
FVC, %p	110.0 ± 12.3 (80-139)	103.9 ± 11.3 (92-128)	109.3 ± 11.9 (80-144)
FEV_1, L	4.23 ± 0.51 (3.13-5.43)	2.91 ± 0.43 (2.02-3.98)	3.62 ± 0.82 (2.02-5.43)
FEV_1, %p	105.1 ± 11.8 (79-144)	109 ± 11.9 (78-130)	104.3 ± 11.8 (79-144)
FEV_1/FVC, %	81.8 ± 5.2 (70.7-92.6)	83.3 ± 5.1 (74.1.6-92.0)	82.6 ± 5.1 (70.7-92.6)

Values are expressed in mean ± standard deviation (minimum and maximum value), and others in n (%)*.
%p = percent predicted. BMI = body mass index. FVC, forced vital capacity. FEV_1 = forced expiratory volume in the first second.

was asked to breath normally (tidal volume) until the FRC was stable, normally between three to 10 breaths. At the end of a normal tidal volume exhalation (FRC level) the obturator occluded, for two to three seconds, and it was requested to performed a series of gentle panting breaths at an approximate frequency of one breath per second. When the obturator reopened, a VC maneuver was completed; equal to the maneuver 1 of slow spirometry. An acceptable maneuver was defined by: 1) stable FRC before occlusion; 2) the difference of volume (DV) at the level of FRC at the time of the valve occlusion should be less than 200 mL; 3)both ends of the plethysmographic FRC curve (FRC_{pleth}) should be visible on the graph; 4) the respiratory rate during the obturation should be approximately 60 breaths per minute (30-90); 5) The FRC_{pleth} curve should be regular and with minimal hysteresis (the inspiration and expiration phases should be practically superimpose); 6) the slope of the measurement line should be parallel to the expiratory part of the FRC_{pleth} curve; and 7) at least, three acceptable FRC_{pleth} maneuvers should be obtain. For the VC maneuver, a plateau of at least one second without change in volume should be reached. Repeatability of the plethysmographic was calculated after obtaining three acceptable maneuvers. The FRC_{pleth} should have a variance of less than 5%. [(higher FRC_{pleth}-lower FRC_{pleth})/ average FRC_{pleth}]. Moreover, the VC must be repeatable at less than 150 mL between the two of the highest values.

Data Analysis. For the general description of the variables, averages and standard deviation (SD) or, proportions according to the type of variables. The IC variability in mL and in percentage between the two highest values of each test (spirometric and plethysmographic) was quantified as average values in mL and in percent, as well as 90 and 95 percentiles. Additionally, the coefficient of correlation (Pearson r) and graphical concordance analysis was calculated with the Bland *et al.*[25] test for the IC measurements of the spirometry and plethysmography.

RESULTS

A total of 56 participants were included, four subjects who could not perform acceptable forced spirometry maneuvers, two other subjects by IC maneuver 2 and one by plethysmography were eliminated, so the final sample was 49 participants, 27 men and 22 women, with an average age of 33.2 ± 8.3 years (26 to 65 years). *Table 1* shows the general, anthropometric characteristics and forced spirometry results of the population studied. Overall, all presented FVC, FEV_1 and FEV_1/FVC ratio values within baseline limits.

Table 2 shows the repeatability of IC maneuvers performed by slow spirometry and by body plethysmography. The total number of maneuvers performed to obtain a minimum of three acceptable efforts were on average 4.5 ± 1.0 (three to eight efforts) for IC maneuver 1 and 4.5 ± 0.9 (three to eight) for maneuver 2; for plethysmography 5.0 ± 1.1 (three to seven efforts) were performed. In addition, the repeatability values of each test are shown as averages, percentages, and 90 and 95 percentiles (p90, p95). The repeatability of IC was ≤ 150 mL in 96% of participants or ≤ 5% in 98%

of subjects for spirometry maneuvers 1 and 2, while for plethysmography it was 78 and 80%, respectively.

Figures 1 to 2 show the correlation graphs and Bland and Altman graphical analysis of IC between spirometry maneuvers 1 and 2 *(Figure 1)*, as well as maneuvers 1 and 2 versus plethysmography *(Figure 2)*. The CI values with the three measurements were highly correlated (Pearson r) with a correlation coefficient of 0.95 between maneuvers 1 and 2; 0.87 between maneuver 1 and plethysmography, as well as 0.88 between maneuver 2 and plethysmography). However, concordance between measurements (Bland and Altman analysis) showed potential errors of up to 576 mL between maneuvers 1 and 2, 954 mL (maneuver

Table 2: Repeatability of the inspiratory capacity tests.

	Inspiratory Capacity (IC)		
Parameter	**Maneuver 1**	**Maneuver 2**	**Plethysmography**
Number of maneuvers	4.5 ± 1.0 (3 to 8)	4.5 ± 0.9 (3 to 8)	5.0 ± 1.1 (3 to 7)
Average IC, L	3.12 ± 0.78 (2.03-5.24)	3.17 ± 0.74 (2.11-5.32)	3.15 ± 0.95 (1.09-5.76)
Repeatability in mL	69.0 ± 68.1 (0-420)	72.3 ± 50.2 (0 a 210)	108.5 ± 100.0 (0 a 420)
Percentile 90, mL	122	130	244
Percentile 95, mL	150	146	318
≤ 100 mL, n (%)	38 (77.6)	35 (71.4)	28 (57.1)
≤ 150 mL, n (%)	47 (95.9)	47 (95.9)	38 (77.6)
≤ 200 mL, n (%)	48 (98.0)	48 (98.0)	41 (83.7)
Repeatability in %	2.3 ± 2.5 (0-15.3)	2.4 ± 1.8 (0-7.4)	3.4 ± 3.2 (0-10.8)
≤ 3 % mL, n (%)	22 (44.8)	20 (40.8)	30 (61.2)
≤ 5 % mL, n (%)	48 (98.0)	48 (98.0)	39 (79.6)
≤ 10 % mL, n (%)	49 (100)	49 (100)	45 (91.8)

Except when otherwise noted, values are expressed in mean ± standard deviation (minimum and maximum value).

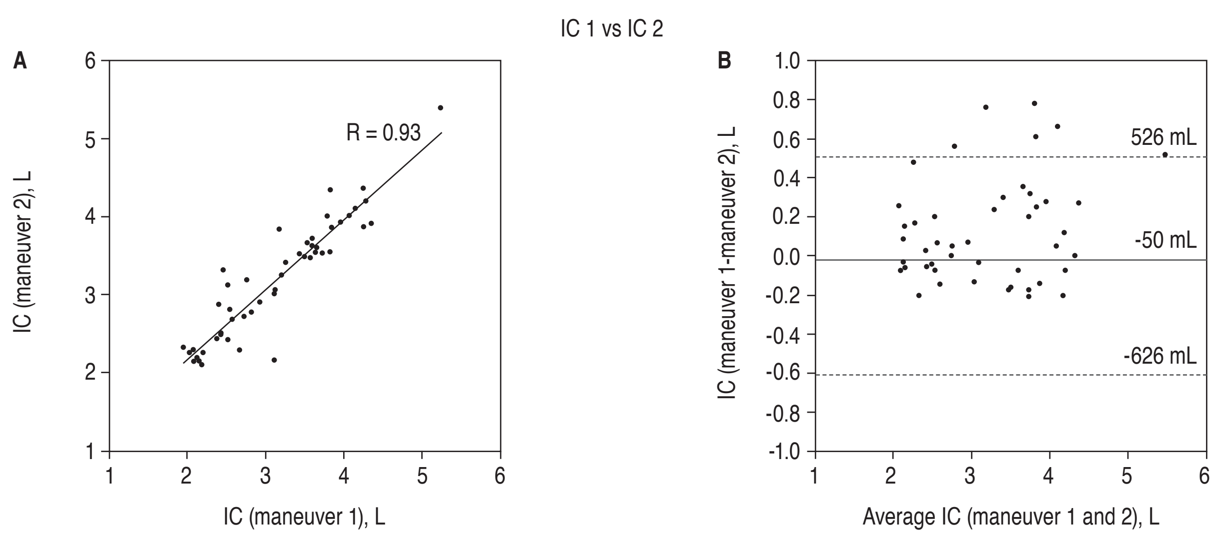

Figure 1: Graph **A** presents the correlation between inspiratory capacity (IC) measurements measured by slow spirometry. Maneuver 1 or IC 1 corresponds to the CI measured posterior to tidal volume (onset from residual functional capacity) and maneuver 2 (IC2) corresponds to the measurement with inspiratory vital capacity maneuver followed by expiratory vital capacity. Graph **B** shows the agreement analysis of Bland and Altman; the average of both measurements (IC1 and IC2) is plotted against the difference between the two. This analysis summarizes the potential differences or errors between both measurements which, in this case, is -50 ± 576 mL (average and two standard deviations).
IC = inspiratory capacity. L = liters

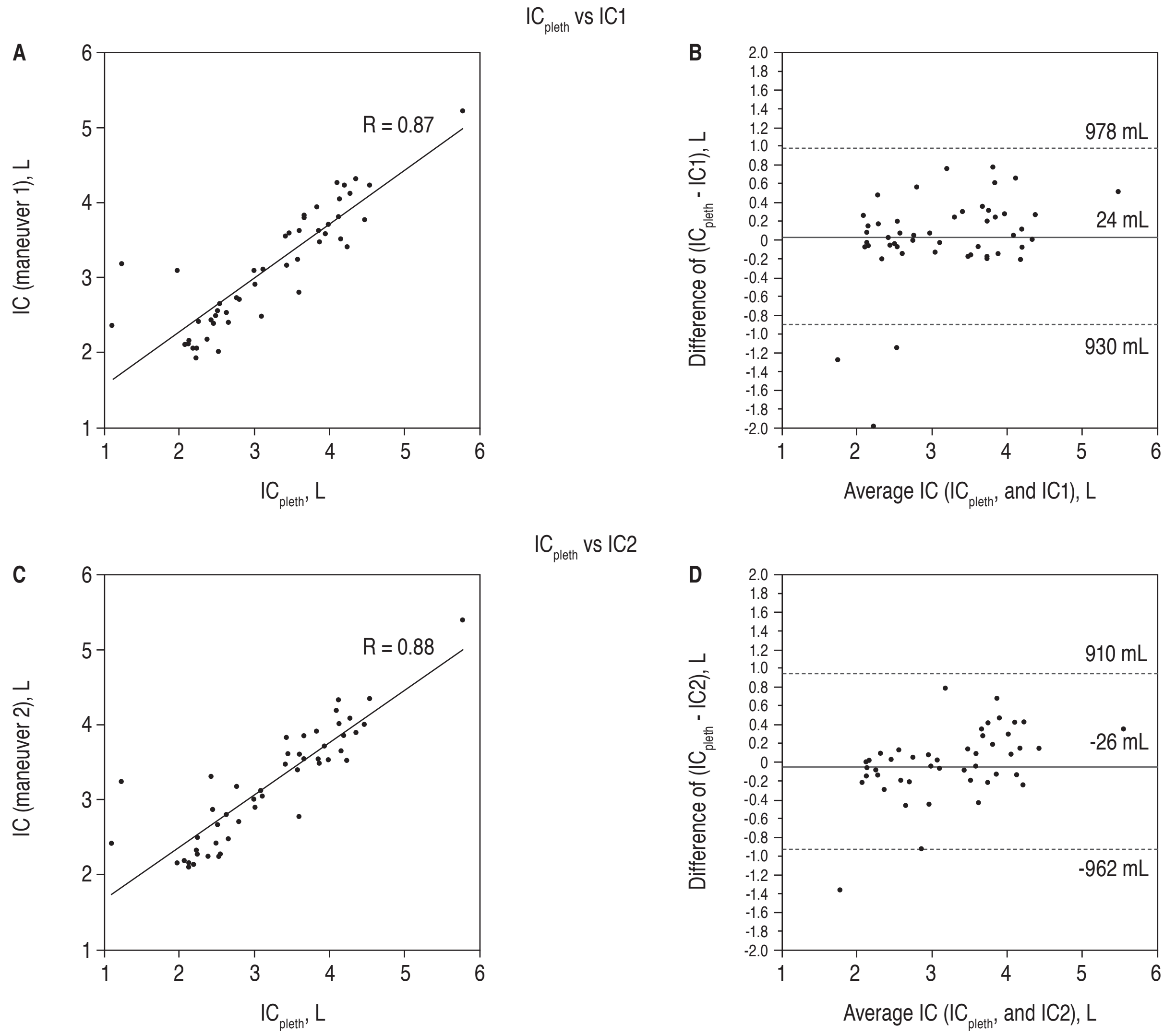

Figure 2: In the upper panel in graph **A**, the correlation between inspiratory capacity measurements measured by plethysmography (IC$_{pleth}$) compared to slow spirometry maneuver 1 (IC1) is shown. Graph **B** shows the concordance analysis (Bland and Altman); the average of both measurements (IC$_{pleth}$ and IC1) is plotted against the difference between the two, the difference or error is 24 ± 954 mL (average and two standard deviations). In the lower panel in graph **C** the correlation is shown and in graph **D** the concordance between IC$_{pleth}$ and slow spirometry maneuver 2 (-26 ± 936 mL).
L = liter.

1 versus plethysmography), and 936 mL (maneuver 2 versus plethysmography.

DISCUSSION

This study explores technical aspects and variability of IC measurement in healthy subjects, both measured by slow spirometry and by body plethysmography. The most relevant results were: 1) the vast majority of subjects were able to perform acceptable maneuvers in all tests; 2) spirometry maneuvers were more repeatable than plethysmography; and 3) in general, all IC measurements had a high correlation; however, in the concordance analysis, potential differences close to a liter are revealed when spirometry is compared with plethysmography.

Initially, the variability of the IC maneuvers obtained by slow spirometry (maneuvers 1 and 2) corresponding to the measurement of IC from FRC (maneuver 1) and measurement of IC subsequent to an inspiratory vital capacity (maneuver 2) was explored, which allowed evaluating the interchange ability of the maneuvers. Both showed similar performance based on the number of maneuvers required to achieve an acceptable test and repeatability values. The criteria for acceptability of IC are those of the slow VC maneuver already described.[2] However, the repeatability that can be achieved between maneuvers for IC has not been fully explored. Tantucci *et al.*[26] reported repeatability of 200 mL or less (< 9%) in 241 healthy subjects aged 65 to 85 years. As in any respiratory function test, it depends on the accuracy and precision of the equipment, the required respiratory maneuver, the ability of the technician and the cooperation of the people undergoing the test, as well as their interaction with the technician. Forced spirometry and slow spirometry are known to achieve high repeatability of FEV_1, FVC and VC, so repeatability of IC could be expected to be high as well. International spirometry standards ATS/ERS 2019 require repeatability of less than 150 mL for all these values. However, this value is defined based on the experience of the working group and good practices. In this study, for both slow spirometry IC maneuvers, 96% of subjects achieved repeatability of 150 mL or less and in 98% it was ≤ 5%. Consequently, it can be affirmed that any of the spirometric values (FEV_1, FVC, VC and IC) are technically very reliable for the purposes of diagnosis, monitoring and measurement of change; as is the case in the bronchodilator response test, in the monitoring of respiratory patients or in people exposed to respiratory risks, as well as in the evaluation of therapeutic interventions.

Another finding of this study is that IC measurements by spirometry achieved better repeatability than plethysmography. The IC measured by plethysmography showed higher repeatability values and with potential differences of almost one liter *(Figure 2)*. This could be explained because the IC maneuver performed by plethysmography is technically more complex and requires greater training and cooperation, as it is done sequentially with the measurement of residual functional capacity (FRC_{pleth}). Plethysmography requires a period in which there is an occlusion of the nozzle obturator (two to three seconds) where the FRC_{pleth} is measured and after that the IC maneuver is performed. In contrast, with slow spirometry, the IC maneuver is performed after a tidal volume expiration. CI values had a good correlation between slow spirometry and plethysmography measurements *(Figures 1 and 2)*. This means that the maneuvers are not completely interchangeable and for follow-up purposes the same test should always be considered, preferably by slow spirometry. The main limitation of this study is that it explores a limited number of healthy subjects and sampling of the studied population was for convenience, which might not be fully representative of the general population or patients with respiratory diseases.

CONCLUSIONS

The measurement of IC, mainly when measured by slow spirometry and with any of the accepted maneuvers, showed acceptability and repeatability of 150 mL or less in 96% of the subjects; while for plethysmography it was in 78% of the participants. Overall, all IC measurements had a high correlation coefficient. However, concordance analyses reveal potential differences close to a liter when compared to plethysmographic measurements, so they should not be considered interchangeable. This study supports the current ATS/ERS 2019 spirometry standards recommendation of requiring a repeatability of 150 mL or less for IC measurement.

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